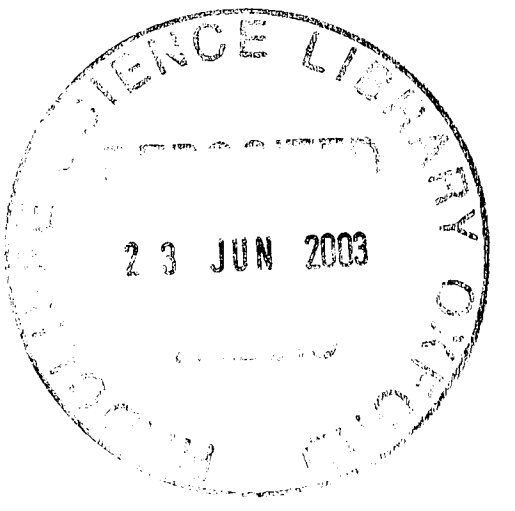


Department of Experimental Psychology

The visual perception of projectile trajectories and the guidance of interceptive behaviour

Nick Reed



Thesis submitted for the degree of D.Phil.

Trinity term, 2001

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Abstract

Experiments were conducted examining human interception of projectiles. It was found that fielders tend not maintain a linear optic trajectory (LOT) as advocated by McBeath, Shaffer, & Kaiser (1995) for interception in two-dimensions. Furthermore, it was shown that its curvature provided an ambiguous cue to action. New interception models were proposed based on optic acceleration cancellation (OAC) and the constant δ model significantly improved upon the performance of the LOT model. Awareness of interception strategy was investigated by questioning subjects about their angle of gaze variation during the ball flight. A lack of awareness of the critical information that guides interceptive behaviour was demonstrated. It is proposed that the information is stored implicitly, challenging the position of Shanks & St.John (1994). Subjects were asked to discriminate the visual information that they experienced before running to catch *real* balls to examine the validity of experiments that test human ability to discriminate the acceleration of *simulated* trajectories. Discriminative performance found to remain high even when the duration of viewed information is reduced. This intact discriminative ability led to the suggestion that trajectory discrimination occurs very rapidly after ball launch. The movement and gaze angle of fielders running to catch under conditions in which OAC cannot be sustained was analysed. Subjects showed little deviation from the strategy until the final moments of the catch. The overall conclusion to the thesis is that subjects react rapidly to the optic acceleration of a projectile to determine interceptive behaviour but may not be aware of the sensory basis of their decision and use an approximate version of the constant δ strategy to reach the interception point.

The visual perception of projectile trajectories and the guidance of interceptive behaviour

Abstract

The aim of this thesis was to investigate how human fielders use visual information when watching a projectile to produce locomotion towards the interception point. Chapter 1 introduces the areas under test whilst chapter 2 reviews two critical studies in depth, McLeod & Dienes (1996) and McBeath, Shaffer, & Kaiser (1995). Their respective qualities and failings are described and their critical differences outlined.

Chapters 3 & 4 examine the LOT and OAC models of interception. Each chapter examines experiments in which the movements of proficient human fielders moving in two dimensions to catch balls were recorded. Their behaviour and visual experience is appraised. In each experiment, a video camera recorded fielder movements from above and ball trajectory was estimated allowing analysis of the optical angles experienced. Fielders were found to run to experience constant d(tan α)/dt consistently. Multiple regression found consistent curvature of fielders' running paths to suggest lateral movement occurs prior to depth movement and that fielders use an error-nulling formula to guide interception throughout (although exceptions were observed and interpreted). The validity of optic trajectory (OT) curvature as an independent cue of depth motion and lateral motion was tested. The OT tended to curve down, irrespective of the movement required of the fielder. Curvature of tan α vs. time experienced by a fielder was significantly better at cueing the correct depth movement. In the few trials where tan α vs. time provided an invalid cue, fielders did not make movement reversals and it was suggested that these might cause the fielder

to experience a controlled change in tan α to which they can quickly respond with the appropriate movement.

An alternative formulation of the OT using angles rather than their tangents was tested in chapter 4. The OT, under this new definition, still tended to show downward curvature. A new model was proposed that suggested fielders move laterally to prevent horizontal movement of the ball across the retina. Lateral movement must occur to prevent growth of the horizontal angle through which they have turned to fixate the ball. This angle was termed δ and the model was therefore called the constant δ strategy. A computer program was written that modelled the behaviour of a simulated fielder using the constant δ and LOT strategies. The constant δ strategy was found to be significantly closer to the behaviour of the real fielders than one using the LOT strategy. However, neither model appeared to capture the true behaviour of the real fielder. The consistent tendency of fielders to move experiencing constant d(tan α)/dt was noted. This led to the hypothecation of a ring of positions centred directly beneath the ball that gives the correct value of tan α at each time interval and it was suggested that to find the true two-dimensional interception strategy, one must discover whereabouts on this ring the real fielder is positioned.

Chapter 5 examined the validity of using OT curvature as a cue to interceptive behaviour. It shows how and why fielders tended to experience its downward curvature in the experiments presented in chapter 3 and 4. The interchange of the ratio α/β with (tan α)/(tan β) is shown to be invalid. Multiple regression of the data used by McBeath, Shaffer, & Kaiser (1995) and Shaffer & McBeath (2002) to represent linearity of OT was performed, revealing significant and consistent downward curvature. The OT was found to uniquely specify the landing location of a projectile but nothing about OT curvature provides a prospective fielder with information about

appropriate interceptive behaviour. It is shown that upward OT curvature only occurs if the fielder is running so that he will finish beyond the interception point in the lateral direction. The suggestion is made that real fielders behave in this manner, thus explaining the common finding of downward OT curvature. It is also shown that the OT experienced by a fielder moving at constant speed in a straight line to the interception point shows greater linearity greater than that shown by any of the example plots presented by McBeath, Shaffer, & Kaiser (1995) as empirical evidence for the LOT model. It is suggested that a fielder following any approximately direct path to the interception point will experience an approximately linear OT, explaining the empirical evidence of McBeath, Shaffer, & Kaiser (1995). The conclusion was drawn that, although elegant, the LOT model cannot provide an unambiguous cue to interceptive behaviour.

Chapter 6 examines five proposed interception strategies in modelling the interceptive behaviour of fielders in the experiments of chapters 3 and 4 in an attempt to improve upon the LOT model of interceptive behaviour. The strategies proposed use the loci of points that give the correct value of tan α at each time interval and conformed to human-like limits on motion. This allowed revised versions of the LOT and constant δ strategies to be compared to three new models, the minimum energy strategy, the conserved alignment strategy, and the constant γ strategy. The constant γ strategy was swiftly rejected but the remaining four models produced reasonable approximations to the running paths followed by real fielders. Most effective was the constant δ strategy. Further revision allowed optimisation of parameters, introducing variation of reaction time and of the maximum speed and acceleration values. The constant δ strategy remained most effective and was the only strategy in which the mean difference between the simulated and real fielder was not significantly different

from the estimate of the error in calculating the real fielder's position. The constant δ strategy still did not capture the variation lateral gaze angle but produced a better fit to the movement of the real fielder when the average speed required to reach the interception point was greater (i.e. a catch was harder). It was suggested that real fielders use a 'loose' version of the constant δ strategy, where δ is only maintained rigorously when needed to ensure that the fielder will be able to cancel $d^2(\tan \alpha)/dt^2$ throughout the flight of the ball.

Chapter 7 examined fielders' awareness of knowledge that underlies catching and reference is made about to the position of Shanks & St.John (1994) who were unconvinced of the existence of action without concurrent awareness of the underlying knowledge. A succession of experiments increased the availability of cues to prompt subjects to demonstrate awareness of the basis of interceptive behaviour. Initially, subjects were merely asked to imagine trajectories and how the behaviour required to achieve interception would be determined. Responses were universally inaccurate. Subjects were then asked to describe variation in angle of gaze imagining a range of ball trajectories and give confidence ratings on their answers. Accurate responses were found for all trajectory types, other than when the ball would intercept their eye if they missed it. By contrast, confidence ratings were consistent across all trajectories – subjects did not realise they were making incorrect responses to that particular trajectory type. It was suggested that subjects could not break the intuition that because the ball went up and then down, their angle of gaze must do similar. In the final experiment, subjects experienced balls being thrown towards them and were instructed to concentrate on how their angle of gaze changed. Immediately after watching a trajectory, subjects had to respond with how they believed their angle of gaze changed. A Free Recall group described their variation in angle of gaze; a

Recognition group had to select the correct description from a list of seven (in which the correct description was always present). Still performance for the 'At eye' trajectory was poorer. Correlation tests revealed no effect of a subject's skill level on their response accuracy for that trial type. Modest support for the position of Shanks & St.John (1994) comes from the significantly improved performance of the Recognition group over the Free Recall group. However, over half of subjects in the Recognition group failed to select the correct response for the 'At eye' trajectory. It was therefore suggested that the information underlying catching is stored implicitly, questioning the position of Shanks & St.John (1994).

Chapter 8 examined the validity of studies that present subjects with simulated trajectories using computers (e.g. Todd (1981)). Subjects were filmed catching balls launched on one of three trajectories: lands short ('short'), would hit the fielder in the eye if missed ('at'), and lands behind the start position ('long'). A second video camera, positioned at eye-level, adjacent to the fielder start position, recorded the visual information experienced before subjects moved to catch each ball. Video footage from this camera was edited so subjects would only view the duration of trajectory until the moment that they began to move (for 'at' trials, the average duration of 'short' and 'long' trial footage was used). Subjects were positioned at a calculated distance from the monitor that gave them the same visual information watching the video footage as they experienced before moving to catch the balls for real. Subjects could accurately decide whether they would have to move forwards or backwards to catch the balls when watching the edited video footage on screen. Performance was significantly poorer when classifying 'at' trajectories. Confidence ratings reflected this decrement. It was suggested that this poorer performance was

due to greater difficulty in recognising $d^2(\tan \alpha)/dt^2$ of zero than when it is positive or negative.

Experiment 2 in chapter 8 required subjects to perform the same video clip classification task. However, video clips were cropped by different numbers of frames in an attempt to locate the boundary of optic acceleration discrimination performance. Even at the maximal frame reduction level, subjects classified trials at significantly better than chance levels. Regression of classification accuracy over frame reduction revealed that accuracy would only fall to chance levels at less than 100ms after ball launch, suggesting a high sensitivity to optic acceleration. It was proposed that subjects' poorer accuracy classifying 'at' trajectories reflected use of a servo that detects $d^2(\tan \alpha)/dt^2$ to determine interceptive behaviour, which, without any input left the subject undecided as to the correct behaviour for an 'at' trajectory.

Chapter 9 reports an experiment designed to investigate interceptive behaviour when the fielder cannot run to cancel $d^2(\tan \alpha)/dt^2$ throughout the flight of the ball. Experienced fielders were required to catch balls that will land behind their start position. To catch them, they must turn and run directly away from the launch position and take the catch as the ball comes over their head. Fielder movements were analysed using the same protocols employed in chapters 3 and 4. It was found that, unlike any other successful catching task, $d^2(\tan \alpha)/dt^2$ was positive until the ball came over the fielder's head, at which point, it collapsed. Decrease in $\tan \alpha$ only happened in the last moments before the catch was made. It was suggested that fielders ran to minimise the positive $d^2(\tan \alpha)/dt^2$ they experienced, managing to get themselves near enough to the interception point to make the catch at the last moment. Use of an alternative strategy was not encountered. The task appeared to represent the limit of performance of using an OAC model for interception.

The concluding chapter reviews the failings of the LOT model and the apparent misconceptions made my McBeath, Shaffer, & Kaiser (1995) about the OAC model. It explains why each of the proposed interception models fails to reproduce human-like interceptive behaviour and examines the validity of the modelling process. The status of implicit knowledge is reviewed and ideas for investigation into neuroscientific explanations are offered. The ability of subjects to discriminate trajectories is discussed. The results of chapter 8 are combined with the results of the implicit knowledge experiment to infer where interceptive behaviour becomes conscious. The results of chapter 9 are used to illustrate the robustness of OAC solutions. An overview combines the results of all presented experiments to predict all aspects of how a fielder determines locomotion to the interception point. Further work and modifications are proposed, ranging from ideas to improve interception models to alternative analysis software. Appendices examine the accuracy of processes recording ball and fielder movement, and include example graphs, outlines of interception model computer program code, and statistical tables.

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1. Introduction

1.1. The origins of the study of interceptive behaviour

Chapman, in his 1968 paper, 'Catching a Baseball', was the first scientist to examine how a fielder can get to the right place at the right time in order to make a catch. Taking a mathematical approach, he considered the sensory information that is available to indicate where the ball is going, looking at the theoretical situation of a ball approaching an observer with parabolic motion i.e. the only force acting on the ball is gravity. Chapman suggested the effect of air resistance on the flight of the ball was minimal and may not be important. First, Chapman determined the dynamics of a launched ball experiencing a gravitational force.

If the ball has speed V at angle θ with the ground and experiences g, the acceleration due to gravity, then at time t:

Vertical displacement, y:

$$y = (V \sin\theta)t - 0.5gt^2$$

Horizontal displacement, x:

$$x = (V \cos\theta)t$$

Time of flight, T:

$$T = \frac{(2V \sin\theta)}{g}$$

$\therefore$ Range, R:

$$R = (V \cos\theta)T = \frac{(2V^2 \sin\theta)}{g}$$

Chapman went on to examine what a fielder who was stood at range R would observe.

Visual angle of elevation of a fielder looking at the ball stood at $R = \phi$

$$\therefore \tan\phi = \frac{y}{(R - x)}$$

Through an algebraic manipulation, we find

$$\tan\phi = \frac{gt}{2V\cos\theta} = Kt$$

where K is a constant.

$\therefore$ The tangent of elevation of gaze increases uniformly with time.

Figure 1.1 on the following page illustrates an example. So Chapman noted that an observer sited at range R would experience a constant rate of increase of tan ϕ, the tangent of their angle of gaze. Furthermore, he determined that tan ϕ increased at an increasing rate for a ball that would go beyond R and at a decreasing rate for a ball that would fall short of R. These remarkable contingencies formed the basis of Chapman's hypothesis of how a fielder might determine the appropriate movement required to be in the right place at the right time to catch a ball. The strategy Chapman proposed operates as follows: A fielder at displacement s from the interception point will be in the right place at the right time if they run at a constant speed v, such that d(tan ϕ)/dt is held constant. If he[1] does so, his arrival at the interception point would coincide precisely with the arrival of the ball. Chapman noted that fielders are usually

---

[1] Throughout the thesis, fielders (real and simulated) are generally referred to in the third person as 'he', e.g. 'he ran backwards to catch the ball'. However, 'he' may be referring to 'he', 'she', or 'it'. This phrasing is not intended to suggest any gender differences in catching performance (fielders of both sexes comprise the novice and expert groups in some of the experiments) but is merely for convenience and clarity of description.

moving as they make catches, which seems to fit with his idea – they are trying to maintain constant d(tan ϕ)/dt right up to the point of the catch. Chapman suggests that a ball launched in a projection plane that is laterally offset from the position of the fielder is easier to catch because of the additional information that is available. The azimuth angle and its rate of change could be used to estimate the trajectory parameters T and R, thereby allowing fielders to generate an estimate of v, the constant speed required to reach the interception point.

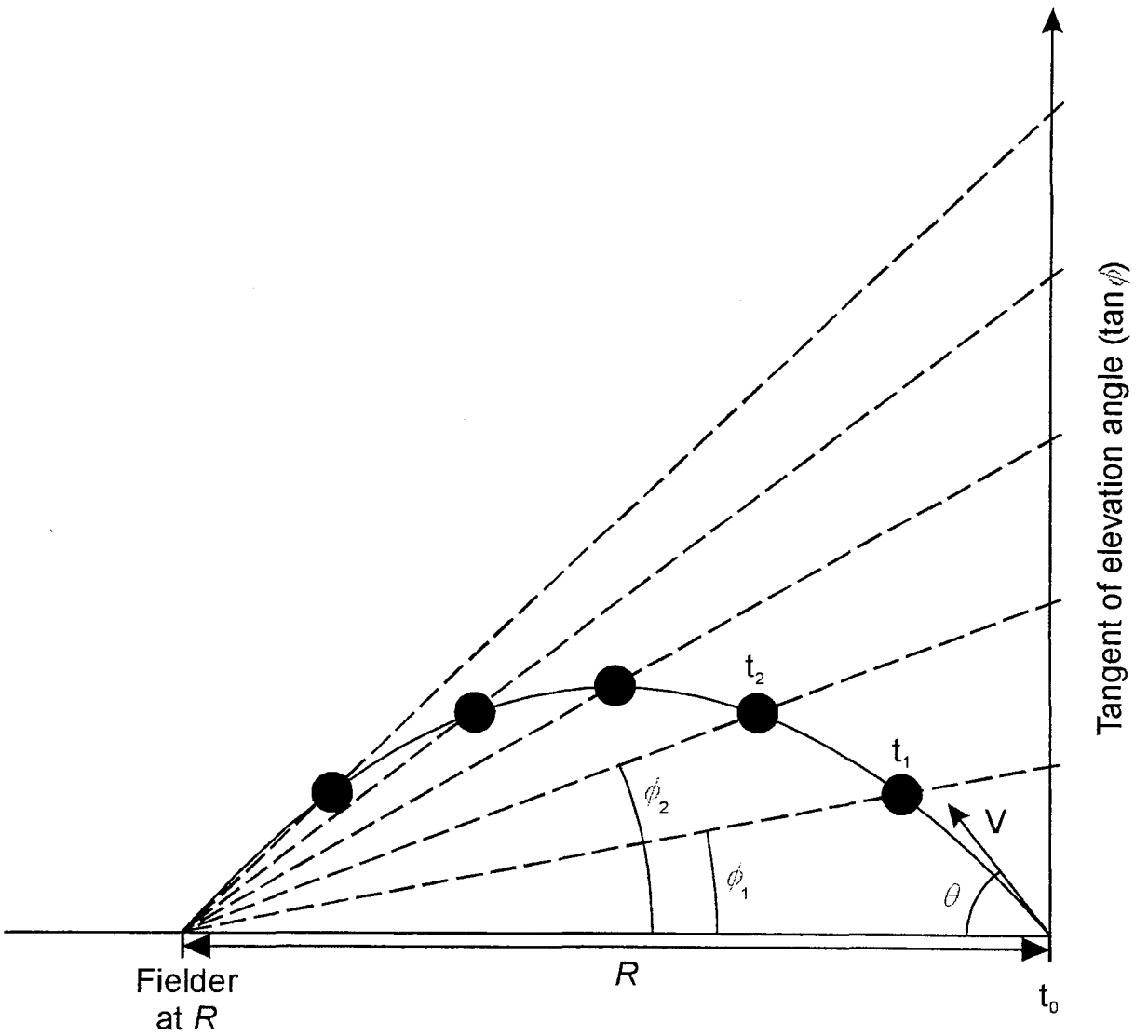


Fig. 1.1 Trajectory observed by a fielder stood at the interception point of the projectile (modified figure from Chapman (1968)).

This seminal paper presented ideas that warranted further exploration into how humans accomplish interception. For example, it seems counter-intuitive that a fielder would run at constant velocity. Firstly, humans cannot begin running at a specific

velocity instantaneously and secondly, it is unclear how a fielder could determine the correct constant velocities for the infinite number of ball trajectories that it is possible to receive. Although Chapman's paper raised interesting issues regarding catching, clearly further investigation and experimentation was required to find how the task is really performed by humans. For coherence within the thesis, the angle of elevation of gaze, referred to by Chapman as ϕ, shall henceforth be expressed as α.

1.2. Investigating the physics of interception

Brancazio (1985) published a paper that tackled flaws in Chapman's proposals directly. Entitled 'Looking into Chapman's homer: The physics of judging a fly ball', it examined the contribution of air resistance to the flight of a spherical projectile. Chapman suggested that aerodynamic forces are "...relatively small and have only a small percentage effect on the trajectory". Brancazio meanwhile, found that air resistance could reduce the horizontal displacement of a ball by more than 40%. Brancazio used the following equation for the drag force on a projectile, F_D:

$$F_D = \frac{1}{2}\rho A C_D v^2$$

where ρ is air density

A is the cross-sectional area of the sphere

C_D is the drag coefficient

and v is the speed of the projectile.

This equation gives an estimate of the drag force on a baseball moving at 80m.p.h. as being equivalent to approximately two thirds of its weight. This force is therefore likely to cause considerable departure from the parabolic ideal. Lateral wind

forces are ignored, as is any lift that a spinning object may generate through the Magnus effect. Brancazio used a computer program to generate trajectories that included a drag component. This demonstrated that the effect of air resistance on the trajectory of a baseball causes significant deviation from parabolic. To compare, Brancazio analysed the simulated trajectories of a baseball launched in a vacuum and a baseball launched in air, both given the same launch characteristics (initial velocity of 147ft/sec at 60° angle of elevation). The ball in a vacuum had a simulated total horizontal displacement of 581ft whereas the ball in air would have a horizontal displacement of only 323ft. The ball has an asymmetric trajectory, descending on a steeper trajectory than that with which it rises and therefore a fielder stood where the ball would land would not in fact experience constant $d(\tan \alpha)/dt$. Chapman's strategy is apparently confounded by this result.

Brancazio suggested that, in the early stages of the flight of a ball, the salient cue specifying which way a fielder should run is vestibular feedback gained as the fielder tilts his head backward to fixate the ball as it ascends. It was presumed that the contingency between the vestibular cue and the correct action is learnt by trial-and-error. For the later stages of the catch, Brancazio claimed that the fielders moved so that optical perpendicular velocity was reduced to zero. Brancazio's work makes the important observation that catching strategies could not be based on parabolic motion. However, his proposed strategy is based on mathematics, inference, and introspection – it is a theoretical catching strategy. To discover the true basis of human interceptive behaviour, experiments looking at real catchers catching real balls must be conducted.

1.3. Interception strategies

The current theories of how fielders locate themselves to make a catch owe a great deal to Chapman's ideas. Models of human interceptive behaviour that suggest a fielder moves to ensure constant optical velocity of the projectile are often referred to as optical acceleration cancellation (OAC) models. Michaels & Oudejans (1992) produced a study that supported use of OAC to guide interceptive behaviour. For mathematical convenience, Michaels & Oudejans used projective co-ordinates on an image plane, one unit distance from the eye for representing optical information. The projective co-ordinate technique assumes the observer fixates a point in the distance, precisely at eye level, and all angles are determined relative to this fixation point. This is somewhat at odds with what catchers actually do – fixate the ball at all times during its flight. However, figure 1.2 shows why tan α and optic height are mathematically equivalent and are therefore equally valid analysis procedures.

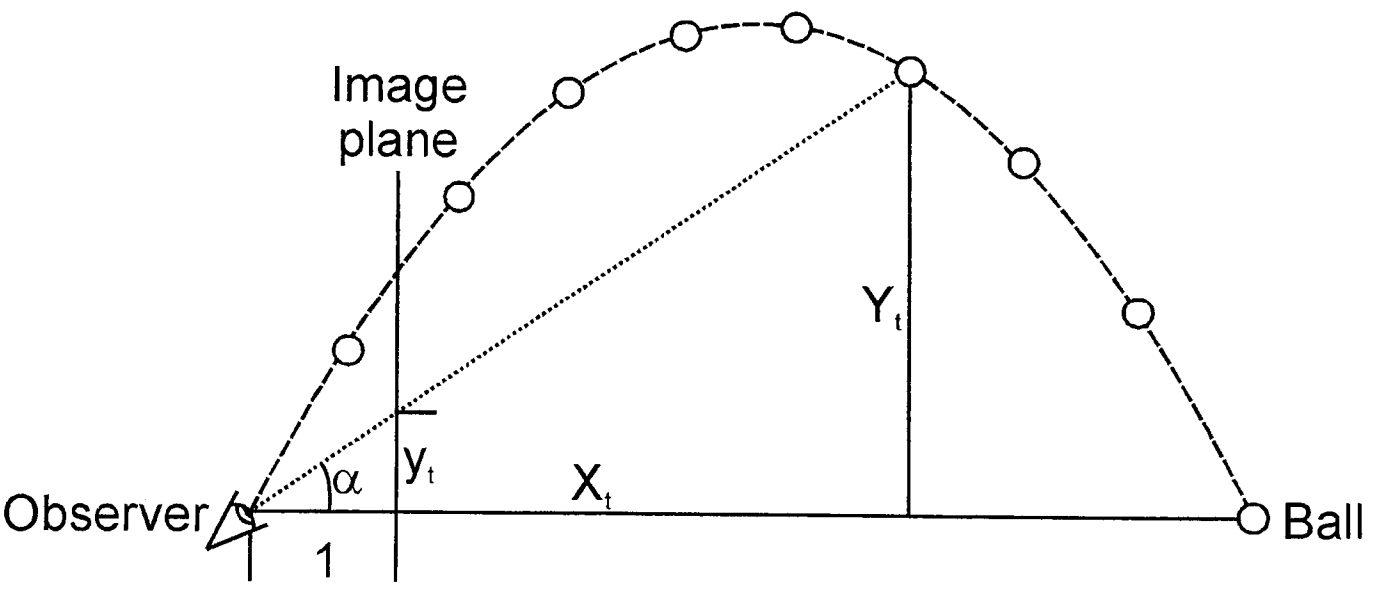


Fig. 1.2 Definition of optic height. Tan α is defined by Y_t/X_t. The optic height, y_t, on an image plane unit distance away from the observer's eye is equivalent to tan α since $\tan \alpha = y_t/1$.

Michaels & Oudejans restate Chapman, showing that a displaced fielder moving with the right velocity to intercept a projectile experiences the same variation in optical angle as a correctly positioned fielder. In both cases the relative velocity of ball and catcher are the same, a quantity they refer to as $\dot{Z}$. Their experiments investigated whether the fielder observes the visual angle of the ball rising at a constant rate as he runs to catch the ball. Michaels & Oudejans made two predictions about their first experiment. If a catcher were to use OAC, firstly they would observe constant vertical optical velocity and secondly, they would move in the correct direction soon after ball launch. They tested their predictions by filming two experienced softball players attempting to catch balls thrown to them over a variety of trajectories. The optical position of the ball was reconstructed from the position of the catcher relative to the ball on the videotape of the experimental session. Use of optical acceleration cancellation would be shown by linear change of optical height over time. Graphs of optical position against time showed a reasonably linear positive change, until the final 200-400milliseconds of the catch, at which point it deviates dramatically from linearity. This linearity was observed with all trajectories, whether the ball would have landed behind, at, or in front of the catcher's original position. This is in agreement with their first prediction. They also found evidence that fitted with their second prediction. Catchers always moved off in the correct direction and when the greatest movement was required in order to make the catch, reaction times were less than 500msec.

Michaels & Oudejans further tested the use of optical acceleration with their second experiment. Since optic velocity is available monocularly, they predicted that monocular locomotive catching behaviour could be successful. Again, they filmed two experienced softball players catching balls given a variety of trajectories. In this

experiment, a pitching machine was used to launch the balls, preventing the use of the human throwing action as a cue to trajectory. One of the catchers was instructed to practice monocular catching informally for an hour per day in the week preceding the experimental trials. In the actual experiment, there were twelve binocular and twelve monocular trials (non-dominant eye covered). The practised catcher caught the ball in all 24 trials. The unpractised catcher caught the ball in all of the binocular trials and in ten out of the twelve monocular trials. For the two that he missed, he was in the appropriate position to make the catch but made an incorrect grasp. The result is consistent with the first experiment. It appears that vertical optical acceleration is used until the final tenths of a second before the catch. Frame-by-frame analyses of the videotape were performed. They showed that catching behaviour, at least up until ball contact is imminent, does not distinguish monocular and binocular viewing. Michaels & Oudejans interpreted the results of this experiment as evidence that available monocular information is used in guidance of locomotion for catching and perception of the thrower's motion is not a necessary cue.

McLeod & Dienes (1996) extended the work of Michaels & Oudejans (1992) by showing that a fielders running to catch a balls consistently cancel optic acceleration with sufficient accuracy to be in the right place at the right time. According to McLeod & Dienes (1996), the only viable strategy for interception is the use of an algorithm that exploits the available information obtained by watching the flight of the ball. The algorithm uses this information to determine an appropriate response that will bring the fielder to the correct position. Learning to catch therefore would entail learning the algorithm. McLeod & Dienes (1996) performed two experiments, examining the behaviour of fielders moving to catch balls in the aligned plane (the vertical plane linking the fielder and the launch site). The results suggest

that fielders do indeed run to cancel optic acceleration to intercept projectiles. However, rather than run at a constant speed as prescribed by Chapman, McLeod & Dienes (1996) suggest that optic acceleration acts as the input to a servo-like mechanism that controls running speed. Fielders therefore produce varied running speed patterns dependent on the movement required to reach the interception point.

A contemporary paper by McBeath, Shaffer, & Kaiser (1995) proposed an alternative strategy for the interception of a ball projected in an unaligned plane on the premise that models of interception proposed previously are based on an 'aligned, accidental view'. It contains elements that are broadly similar to OAC strategies with some fundamental differences. McBeath, Shaffer, & Kaiser acknowledged that the only viable cue for the majority of the task is the changing position of the ball image relative to the background scenery (the optical trajectory of the ball). They suggest that fielders can normally use their vantage point outside the plane of the ball trajectory to simplify determination of interceptive action. Their theory unifies the available optical information as a 2D image. Vertical and lateral optical angles of the ball are specified by α and β respectively. The observed angle of ball movement relative to the background horizon (the optical trajectory projection angle) is called Ψ and is derived from α (the vertical optical angle) and β (the lateral optical angle).

$$\tan \Psi = \frac{\tan \alpha}{\tan \beta}$$

The McBeath, Shaffer, & Kaiser model proposes that fielders follow a running path that maintains a linear optical trajectory (LOT). The solution is based on maintaining constant Ψ, resulting in proportionate variation of tan α and tan β. To ensure that he experiences LOT, the fielder must move closer to the point of interception at all times, thus guaranteeing that they will be in the right place at the

right time. McBeath et al. performed experiments to examine the validity LOT strategy, finding that fielders tended to follow curved running paths. They suggest that curved running paths comply with the LOT model rather than their interpretation of the OAC model. A more thorough review of the work of McLeod & Dienes (1996) and McBeath, Shaffer, & Kaiser (1995) is undertaken in chapter 2, which also outlines the progress of the study of interception strategy, from Chapman onwards.

It may seem unintuitive that a fielder may use optical acceleration to guide interceptive behaviour. The validity of such a hypothesis was assessed in a study conducted by Tresilian (1995). He simulated the motion of fielders using a servo-controlled running strategy for the interception of projectiles, with $d^2(\tan \alpha)/dt^2$ as its input. His experiments examined interception in the aligned vertical plane – the 1D case, and went on to look at interception in unaligned projection planes – the 2D case. Tresilian used the McRuer-Krendel operator to model the dynamic transfer characteristics of the stimulus provided by $d^2(\tan \alpha)/dt^2$. The McRuer-Krendel operator was developed in studies of human visuomotor performance where subjects were required to act as a servo controller, making the appropriate response to null a visual error signal (McRuer & Krendel (1959)). This transfer function was found to accurately model human performance in experimental studies of single-input/single-output tasks such as compensatory tracking and vehicular control (McRuer, Graham, & Krendel (1967); Sheridan & Ferrel (1974); McRuer, Allen, Weir, & Klein (1977)). Tresilian considered it a useful starting point for the analysis of servo-control guided interception as $d^2(\tan \alpha)/dt^2$ plays the role of the single input and the McRuer-Krendel operator acts as a proportional controller. For trajectory simulation, Tresilian used a similar technique to that employed by Brancazio (1985) for the effect of air resistance on the parabolic trajectory of a projectile. Tresilian's first model gave a maximum

limit to the acceleration of the simulated fielder of $2ms^{-2}$ and the maximum speed the fielder could achieve was $6ms^{-1}$. It was assumed that the simulated fielder detected an accurate and noise-free estimate of $d^2(\tan \alpha)/dt^2$. This he termed the *ideal version*. Simulation results showed that the model was effective over a range of launch velocities and launch angles of the ball.

Tresilian notes that studies of detection of visual acceleration have shown that the human visual system is an imperfect transducer of optical acceleration, e.g. Babler & Dannemiller (1993), Todd (1981) (both are discussed in a later section). Tresilian also suggests that these studies measure acceleration detection thresholds whereas the implication in Chapman's strategy is that fielders must detect an absolute value of the visual acceleration so that they can accelerate at a proportional rate. He therefore suggests that the thresholds for detection of the amount of acceleration change may be very large. This led to the modification of the model simulating interceptive behaviour so that optic acceleration detection was limited to one of three categories: positive, negative, and zero acceleration. This model provides the fielder with only the sign of the acceleration rather than its magnitude and was dubbed the *worst-case* version. The motion of the fielder in the worst-case model was predictably more oscillatory but remained effective at reaching the interception point within the applied limits. To further test the validity of using $d^2(\tan \alpha)/dt^2$ the cue to interceptive behaviour added a noise component to the input signal to the worst-case model. This proved not to be detrimental to the performance of the model but caused an improvement over the noise-free version. The robustness of OAC led Tresilian to claim that his results in conjunction with the experimental results of Michaels & Oudejans (1992) and McLeod & Dienes (1996) confirmed it as a plausible candidate for the visual guidance of catching.

Tresilian then extended his simulation to the 2D case, where fielders must add a lateral component to their running speed in order to reach the interception point. Tresilian provides an example of why OAC alone cannot be responsible for behaviour under these circumstances. For a ball launched in an unaligned projection plane that will land behind the fielder's position in depth, the fielder would initially begin moving away from the plane of projection of the ball. This would be an inefficient system and fielders are not observed performing in this way. Tresilian modified his model in an attempt to account for fielder motion in 2D so that the fielder accelerates directly towards the ball if $d^2(\tan \alpha)/dt^2$ is negative and perpendicular to the direction of the ball if $d^2(\tan \alpha)/dt^2$ is positive. This produced performance that was markedly limited. When the simulated fielder began near to the interception point in depth, the model failed to achieve interception if the simulated fielder was more than 1m outside the plane of projection of the ball, despite ball flight lasting over 2 seconds. This effect became less pronounced as the simulated fielder's start position moved further away from the interception point producing a *zone of successful performance* (ZS) that was 'dumbbell'-shaped (with the long axis on the projection plane and it narrowed near the interception point).

Tresilian suggested two possibilities that could explain the poor performance of the model for interception in 2D. Firstly, switching to behaviour based on predictive information, engaged to make hands meet ball, may extend the range of the real fielder although Tresilian concedes that the performance advantage is unlikely to be dramatic. Secondly, the fielder may use an additional control action that tends to move the fielder toward the plane of projection of the ball. Tresilian explored the latter of the two suppositions by examining addition of a second component of acceleration to the movement of the fielder, supplementing the acceleration generated

by the pure Chapman strategy. This additional acceleration is proportional to the rate of change of direction of the ball as measured at the observer's eye and is designed to divert the running path toward the interception point rather than toward the ball. The direction in which the new acceleration is applied is specified through two McRuer-Krendel operators, the first to determine the magnitude of the Chapman strategy acceleration command and the second to determine the magnitude of the additional acceleration command. Tresilian only examined the performance of the new strategy under *ideal version* conditions, where the model has access to error-free estimates of the relevant visual cues. Tresilian found that the performance of the model showed a marked improvement over the previous incarnation of the 2D case model. The ZS was considerably larger indicating greater efficiency of interception. However, there remained pronounced narrowing of the ZS when the fielder did not have to move far in depth, giving the ZS distinct dumbbell shape. Further developments of this model failed to rectify this trait leaving Tresilian to suggest that the model could be improved by allowing extraction of greater information about the ball's trajectory. Tresilian's interpretation of Chapman's strategy appears to have handicapped his models of interception. The implication is that the acceleration experienced by a fielder using Chapman's strategy is always either towards or perpendicular to the ball rather than towards the interception point.

Tresilian's final experiment attempted to distinguish predictive strategies from OAC-type strategies by examining the variation in running path shape caused by interception of sponge balls and tennis balls. Air resistance causes each to deviate from parabolic by a different amount and the two strategies differ in the behaviour they predict the fielder would make in response to these deviations. Tresilian found

predominantly straight paths and stated that it demonstrated marginal support for Chapman's strategy.

Chapters 3 and 4 describe experiments that attempt to clarify the position of the LOT and OAC models by examining the behaviour of human fielders running to catch balls launched on a variety of trajectories. The validity of using the optic trajectory to guide interception is investigated in chapter 5 using empirical data and simulations. In chapter 6, attempts were made to produce an accurate model of human interception in 2D based on constant optic velocity. Examining the differences between the placement and visual experience of real and simulated fielders allowed conclusions to be drawn about the validity of each model.

1.4. Awareness of interception strategy

Work such as that of Michaels & Oudejans (1992) and McLeod & Dienes (1996) has demonstrated the consistent finding that a fielder catching a ball launched in the aligned projection plane uses the variation in the elevation of his angle of gaze (α) to guide his interceptive behaviour. However, when catching, one is not apparently conscious of the specific variation in α, one simply seems to 'know' the appropriate movement that is required. McLeod & Dienes (1996) claimed that learning to catch involves learning an algorithm that links visual information to action. They showed that fielders catching balls in the aligned vertical plane (linking the launch site and the fielder) run so that they null the acceleration of tan α ($d^2(\tan \alpha)/dt^2$), where α is their angle of elevation of gaze. They proposed that the link between visual information and action was represented by the equality, $d^2(\tan \alpha)/dt^2 = 0$, and that this acts as the fulcrum of a servo-mechanism controlling the running speed of the catcher. However, when learning to catch, children appear to discover

this complex stimulus structure without being given explicit instruction to null the acceleration of tan α. Consequently, fielders may lack conscious knowledge about the basis of their actions that take them to the right place at the right time to catch the ball. Such knowledge is termed *implicit*. Reber (1967) established the phrase 'implicit learning', referring to learning achieved without concurrent awareness of what is being learned. Most tasks used to study these concepts are necessarily abstract in construction. However, to a fielder, the stimulus and goal of a catching task are familiar and very clear: to *catch* the *ball*. Consequently, a fielder should have very little to consider other than the knowledge that they use to achieve interception. Little investigation has been carried out examining awareness of the basis of action with regard to motor skills. The basis of action in (aligned plane) catching tasks is well understood so awareness tests could be constructed that satisfied Shanks & St.John information and sensitivity criteria. Chapter 7 describes the results of experiments that were conducted using free and cued report measures to evaluate the level of awareness a subject has of the knowledge that they use to guide their catching behaviour and discusses the position of Shanks & St.John (1994) in the light of the results.

1.5. The τ-margin

Lee (1976) proposed the τ-margin as a cue that humans could use as an indication of the time-to-contact of an approaching stimulus. Subsequently, the τ-margin has been put forward as a possible cue for guidance of catching behaviour. Lee (1976) examined how humans may interact with moving objects in the environment, investigating how a driver might visually control braking of a vehicle in order to prevent collision. To do this, he investigated the optic array at the driver's eye and the simple visual variables that would provide the driver with sufficient

information to employ an appropriate braking strategy. Lee examined information available in the optic flow field (*o.f.f.*). Gibson argued that the *o.f.f.* provides the observer with information about the environment and the motion of the observer. The first type of information is usually referred to as motion parallax. The second type was first recognised by Gibson (1950) who termed it visual kinaesthesis. Mathematical analysis of the *o.f.f.* reveals that there are elements specifying aspects of both types of information. In studying the *o.f.f.*, Lee found that the distance and velocity of an element of a surface are not specified in absolute terms but only relative to some standard distance. However, temporal proximity, i.e. time-to-contact, is optically specified in the *o.f.f.* as the variable, τ. This can be registered as the inverse of the proportionate separation rate of the retinal images of any two points on the obstacle. Lee suggests that a strategy for braking could be based on τ. For example, braking could engaged at a critical value of τ, using the rate of separation of the brake lights on the car in front as it gets closer. Furthermore, τ could be used in timing action in sports. Lee & Young (1985) developed this sporting theme in their work examining the visual timing of interceptive action. Here they introduced the term *extrinsic timing*, meaning timing that requires predictive information about the relative motion of the organism and objects and surfaces in the environment. In sports such as cricket, they suggest a temporal accuracy of 10ms is required. Lee & Young see this as evidence that humans have evolved precise visuomotor timing devices. The optic variable, τ, is specified without the need to know distance or velocity of elements in the optic field. The claim is that it provides a more plausible explanation of skilled timing than computational models of such parameters (which necessarily calculate τ or an equivalent quantity in computation).

A dilemma for τ theories is that τ accurately specifies time-to-contact for constant velocity approaches towards the eye but is not precise for objects or surfaces that approach at changing velocity or those which do not approach the eye. Lee & Young tackle the problem of changing velocity approaches with the following propositions:

1. τ over estimates time-to-contact for an accelerating approach.
2. τ is a better estimate of time-to-contact for faster approaches due to smaller proportional increases in speed.
3. τ is a better estimate of time-to-contact as this time decreases since proportional increases in speed are less and time-to-contact is shorter.

$\therefore$ Using τ leads to interception irrespective of changes in velocity.

Lee & Young examined this hypothesis in an experiment looking at whether people gear their movements to τ or time-to-contact, observing the knee and elbow flexion of subjects jumping to punch a falling (and therefore accelerating) ball. They made two predictions:

1. As drop height increases (and therefore ball velocity at contact increases), each stage of the action will be reached earlier before contact and the total action will be more protracted (from point 2, above).
2. As the moment of contact approaches, action patterns for different drop heights will become more similar (from point 3, above).

They found knee and elbow flexion angles are not significantly different for different drop heights when plotted against τ. They also found a better fit to the timing data if a τ strategy rather than a time-to-contact strategy were used.

Lee & Young seemed to have shown that actions are geared to τ in some way. Other scientists however, have produced evidence against the use of τ, suggesting that

it is not used in interceptive timing. Tresilian (1991, 1993) discusses the limitations of τ strategies in perception of time-to-contact. Tresilian acknowledges that there is supporting empirical evidence but recognises that there have been no studies published supporting the use of a τ strategy in non-collision trajectories. Tresilian considered the interception of a ball passing at 50cm to one side of the catcher. At high ball velocities, the τ strategy produces small enough errors to produce reasonable interception. At slower speeds, errors introduced by using τ become unacceptably large, for example, a ball at $1ms^{-1}$ will have an associated time-to-contact error of 800ms. A study by von Hofsten (1983) found young infants to be far more accurate than could be accounted for by τ strategy. Tresilian also highlights the problems caused by τ strategies being formulated as a monocular cue. Time-to-contact information can be more readily computed if additional binocular cues are available. Tresilian suggests that it is unreasonable to believe that the visual system would perform the more complex operations required by the τ strategy over simpler strategies which extract the same information.

Another critical review of the use τ is that of Wann (1996). Wann investigated evidence that is often cited as strong support for use of τ and found that whilst it provides an appealing account of interceptive timing, its broad acceptance is unwarranted. Wann examined the work of Savelsbergh et al (1991,1993) who extended the τ paradigm to look at its possible use in catching. Their experiments attempted to control τ by being able to vary the size of the stimulus during its approach. More specifically, they deflated balls as they swung towards subjects on a pendulum. Savelsbergh et al (1991) found subjects delayed their grasp for deflating objects, which would suggest use of a τ-like quantity. Savelsbergh et al. proclaimed this evidence as supportive of the use of τ. However, other experiments have shown

that additional cues are also influential in the task such as binocular disparity (Judge & Bradford (1988)) and vergence (Heuer (1993)). Wann also conducted experiments that looked at the initiation of deceleration by humans running at different speeds toward a doorway. Subjects began decelerating at a critical distance from the target across speed conditions. Use of τ was not encountered.

So far, there have been no studies published that indicate positive evidence for use of τ by a fielder to get to the right place to make a catch. The evidence against the use of τ in the guidance of movement (e.g. Tresilian (1993), Wann (1996)) suggests that the τ margin is not a cue fielders use to guide their running for interception. The proposed strategies for interception work by causing the fielder to follow a path that would cause eye to meet ball. Obviously, this is not the ultimate goal of a catching task. The cue provided by τ may be critical when the strategy followed by the fielder changes from one designed to make eye meet ball to one designed to make hand meet ball in the final moments of a catch. However, the experiments conducted in this thesis investigate how a fielder uses the cue provided by the flight of a projectile to run to the interception point and do not consider this change in fielder behaviour. Consequently, use of τ is not considered further.

1.6. Examining the cues controlling interceptive behaviour

A fielder running to catch a projectile must use information gleaned from the movement of the ball to make a decision about how to run to the interception point. Various studies have examined human sensitivity to the cues that are available to a fielder. Many such studies present subjects with a computer simulation of trajectories. The subjects are then asked to decide whether they would need to move forwards or backwards if they were attempting to intercept a projectile on such a trajectory. Chapter 8 assesses the validity of this protocol by using a monitor to present subjects

with the visual information that they experienced when catching real balls. Confirming the variation in trajectory to which humans are sensitive allows progression in developing models of how a fielder might use these cues to get to the right place at the right time.

Todd's 1981 paper, 'Visual Information about Moving Objects' takes an analytical approach in trying to account for the ability of an observer to effectively interact with moving objects. The basis of investigation is the problem faced by a fielder who must move in order to get into the right position to catch a ball launched in the aligned vertical plane. The paper has two aims. Firstly, to demonstrate formally that sufficient physical variables are represented as optic variables at the retina to specify whether an observer should move forward or backward to achieve interception. Secondly, to validate that the observers are indeed sensitive to these variables. Todd simulated trajectories by presenting subjects with vertically ascending stimuli on a monitor using a computer. He found that subjects were unable to use second derivatives with respect to time as a cue to action. This presents problems for those who suggest that such derivatives are used as cues in catching strategies, e.g. Chapman (1968), McLeod & Dienes (1996). However, Michaels & Oudejans (1992) produced a study that conflicted with the results reported by Todd. They videotaped fielders as they caught balls thrown towards them and studied the forward and backward movements that fielders made attempting to catch the ball. They did not examine lateral movements because they considered the cues more obvious. They reiterated the work of Chapman, proving that a catcher stood in the correct position for interception observes zero optical acceleration of a ball given parabolic flight.

Michaels & Oudejans (1992) investigated the various monocular sources of information could be used to guide activity. Instead of vertical optical acceleration,

lower order variables, such as initial optical velocity and ball image expansion rate could be used in various ratios to provide suitable cues to catching behaviour. These may be sufficient to explain the running patterns found in their previous experiments. To examine this possibility they used a computer to simulate the rising phase of a ball projected towards the subject. Subjects were required to judge whether a simulated trajectory would 'land' behind, in front of, or at their position. Michaels & Oudejans found that subjects appeared sensitive to optic acceleration but chose not to use it in their landing judgements, contradicting the work of Todd (1981) who concluded that subjects were unable to take advantage of the optical acceleration of stimuli. Babler & Dannemiller provided a thorough appraisal of image acceleration of projectiles in their 1993 paper, in which they used a variety of computer simulation techniques to present trajectories to subjects. They begin by acknowledging the intuitive appeal of the interception strategies which use image acceleration as the primary cue (e.g. Chapman, 1968) but recognise evidence such as Todd's questioning the validity of such strategies. They found that subjects were sensitive to acceleration of the vertically ascending stimuli but the average velocity of the stimulus biased judgements. They also found that image expansion was not a necessary cue for correct judgement of the simulated trajectory. Babler & Dannemiller comment on why Todd failed to find significant acceleration discrimination. They point out that the change in acceleration in many of Todd's trials was smaller than the threshold for detection found in their experiments. This being the case, it is unsurprising that subjects in Todd's experiments failed to show significant acceleration discrimination.

Todd (1981) showed that observers were insensitive to variation in acceleration and deceleration of points ascending a computer screen. Michaels & Oudejans (1992) results contradict Todd and Babler & Dannemiller (1993) showed why Todd's

subjects failed to demonstrate sensitivity to acceleration. An important caveat can be gleaned from the results of these experiments. Todd's failure to demonstrate sensitivity to acceleration highlights the dangers of using computer simulations for studying catching behaviour. Computer simulation is an appealing method of presentation because it allows parameters to be precisely defined and controlled by the experimenter. However, although using a computer program allows easy manipulation of the stimuli, tasks performed by subjects watching a computer screen are not the same as those faced when catching a real ball. Great care must therefore be taken when extrapolating from results gained in computer based experiments to genuine interception strategies. Chapter 8 attempts to examine the validity of asking subjects to judge the landing location of a projectile when the trajectory information is presented via a two-dimensional monitor screen.

1.7. Contravening the rules of OAC

McLeod & Dienes (1996) showed that for a ball launched in the vertical plane aligned with the fielder, the fielder moves to intercept the ball so that tan α increased at a constant rate. Cricket textbooks (e.g. Richards & Murphy (1988)) describe the preferred catching technique for a fielder positioning himself to catch a ball launched on a high trajectory in the aligned plane. They suggest that fielders prefer to catch the ball facing the opposite direction to its flight and with their hands raised in front of their eyes. Utility of these techniques is perfectly acceptable if the fielder can reach the interception point comfortably. However, there are circumstances where fielders can achieve interception and yet cannot maintain $d(\tan \alpha)/dt$ at a constant value throughout the flight of the ball. These are situations where fielders cannot reach the interception point comfortably using OAC, as suggested by McLeod & Dienes, and cannot catch the ball in the preferred catching position suggested by Richards &

Murphy. Consider a ball launched in the aligned plane so that it will land behind the position of the fielder. A fielder may realise that he will not reach the interception point if he remains facing the direction of the launch position and runs backwards. To reach the interception point in time he must therefore turn through 180° and run at maximum speed (forwards) in the same direction as the flight of the ball. As the ball passes over the fielder's head, α reaches 90°. The fielder's angle of elevation of gaze, α, must decrease beyond this point, giving negative $d^2(\tan \alpha)/dt^2$. The fielder is therefore failing to cancel optic acceleration and the ball will descend vertically across his optic field. This is very different to 'normal' catching where a fielder will move so that he experiences the ball vertically ascending his optic field with no acceleration. If the fielder can run fast enough to reach the interception point he may be able to take the catch at full stretch directly in front of him ($\alpha \approx 0°$). This type of catch is probably the most difficult to accomplish successfully.

An experiment was conducted that required to fielders to make catches in this particularly difficult situation. Balls were launched in the aligned vertical plane to travel over the head of fielders who had to turn and run in the same direction of travel as the ball. The movements made by fielders as they ran to make each catch were recorded. This allowed investigation into how and when the breakdown in maintenance of constant $d(\tan \alpha)/dt$ occurred. Variation was also noted in fielders' interceptive behaviour in relation to how difficult it was to reach the interception point.

2. Extended review of the essential work under investigation

2.1. McLeod & Dienes (1996)

'Do fielders know where to go to catch the ball or only how to get there?'

This 1996 paper underpins much of the work carried out in this thesis. McLeod & Dienes investigated the behaviour of fielders when attempting to catch balls launched towards them. They begin by demonstrating the remarkable sensitivity of the system controlling the motion in depth of a fielder. The example given is that of three balls launched at 45° with three similar velocities: 22, 24, and 26ms^{-1} toward a fielder stood on level ground 45m away. The ball launched at 24ms^{-1} would land at approximately the fielder's position. The fielder would have to move about 5m forward to catch the ball given the least velocity and about 5m backward to catch the ball given the greatest velocity. A competent fielder will have started to move in the correct direction (forwards or backwards) within 840ms. However, if one examines the flights of the three balls, the difference between their positions at 840ms is very small indeed, particularly relative to the final separation of the three trajectories. McLeod & Dienes pose the question – how are fielders able to determine the appropriate movement from such a fine discrimination?

There are several essential attributes required to describe the motion of a projectile. These are its projection angle, its projection velocity, and the effects of air resistance and gravity. If a fielder could acquire this information and use it to compute the trajectory of their target then the fielder could determine where he had to be and when he had to be there to intercept it. However, McLeod & Dienes suggest that humans must have very crude estimates of these essential parameters. Consequently, it is unlikely that the fielder is able to calculate the trajectory of the ball using their estimation of these properties. Another conceivable method of acquiring a strategy of interception would be to memorise

the behaviour of all observed trajectories from an early age. When called upon to intercept a projectile, the fielder would recall the most similar trajectory that had previously been encountered and devise an appropriate running strategy based on the recalled properties of the matching trajectory. McLeod & Dienes predict that given the infinite variation in trajectory caused by variability in the flight parameters, it is impossible to explain human interceptive performance using such a system. The authors propose an alternative technique employing an algorithm that links the available visual information gained from observing a ball's motion to the appropriate required movement. The algorithm should operate efficiently irrespective of the fielder's starting position or the trajectory of the ball. Learning to catch would involve discovery and tuning of this algorithm.

2.1.1. Chapman's solution

McLeod & Dienes see the work of Chapman (1968) as offering the basis of an algorithm that satisfied the criteria outlined above. He proposed a mathematical solution to the 'outfielder problem' by analysing the visual information available to a fielder watching a ball travelling in parabolic motion toward him. The angle of elevation of gaze from the observer to the ball is represented by α and changes as the observer tracks the flight of the ball[1].

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[1] Chapman used the symbol, ϕ, to represent the angle of elevation of gaze. For continuity within the thesis, it is referred to here as α.

Chapman found a unique contingency in the special case where a fielder is located in exactly the right place to catch the ball in front of his eye as it falls (see figure 2.1). In this special case, the tangent of α increases at a constant rate. Consequently, the acceleration of tan α, $d^2(\tan \alpha)/dt^2$, is zero. Chapman supposed that a fielder might exploit this information in deriving an interception strategy. A fielder in the plane of projection of the ball but some distance from where it will land, who moves at constant velocity such that $d^2(\tan \alpha)/dt^2$ is zero will intercept the ball as it reaches eye level.

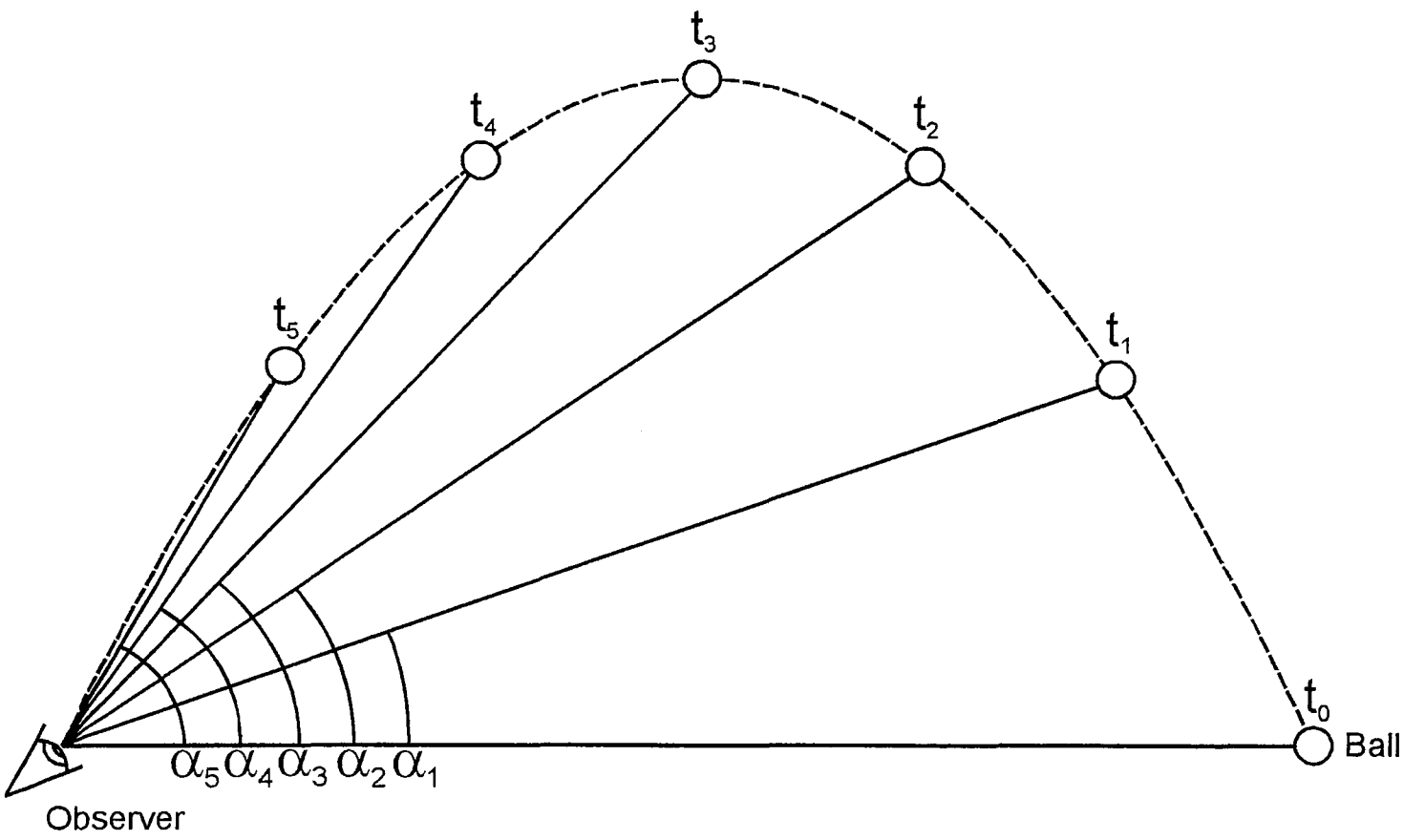


Fig. 2.1 How angle of gaze changes over time.

Although Chapman's mathematics are sound, there are issues related to the pertinence of this geometrical solution to human interceptive performance. Firstly, humans cannot instantly attain a particular velocity. There are neural and muscular delays prior to movement and the fielder must undergo a period of acceleration. A further complication is that by the time fielder reached the velocity that was initially computed to get him to the right place at the right time, the velocity required would have changed. Chapman stated that aerodynamic forces have a near-negligible effect on a trajectory.

However, air resistance causes projectiles to deviate considerably from the parabolic ideal. In a study investigating the feasibility of Chapman's proposal, Brancazio (1985) calculated the effect of aerodynamic drag on a baseball. Incorporation of air resistance led to trajectories that were not parabolic and flight distances could be reduced by as much as 40%.

With these issues in mind, Chapman's account would appear to be of questionable relevance to human interceptive performance. Nevertheless, an experiment performed by Michaels & Oudejans (1992) suggested that the geometrical solution might be applicable. Balls were launched towards fielders stood in the plane of projection of the ball and they were filmed attempting to catch the balls, running forwards or backwards to achieve interception. They found that fielders experienced an approximately linear increase in the optic height of the ball as they moved to intercept. Since optic height is mathematically equivalent to tan α (see figure 1.3, in chapter 1) and a linear increase is equivalent to zero acceleration, Michaels & Oudejans' result offers reasonable support for Chapman's (1968) proposal.

McLeod & Dienes list several valid shortcomings of the work of Michaels & Oudejans. Firstly, their evidence is obtained from limited information – their experiment covered 10 catches made by two different fielders. Secondly, they do not assess the linearity of the optic height plots with a suitable statistical test. Thirdly, in the majority of catches there are departures from linearity that occur in the latter stages of the plots of optic height against time. They did not show that Chapman's strategy would lead to interception and that these deviations were unimportant or alternatively that they were a necessary corrective measure as a result of air resistance causing the projectile to depart

from parabolic motion[2,3]. Finally, the fielder's running velocity was not analysed. Chapman's strategy relies on a fielder attaining the specific constant running velocity that holds the rate of change of optic height constant. McLeod & Dienes assert that to provide firm evidence that human fielders use Chapman's strategy, this condition must be met.

2.1.2. McLeod & Dienes' first experiment

McLeod & Dienes' work extended that of Michaels and Oudejans and addressed the criticisms raised. It examined six skilled fielders catching balls in the aligned projection plane.

2.1.2.1. Experimental set-up

Fielders stood at a distance of 45m from the ball-launching machine. Balls were projected at an angle of 45° at a random velocity between 20 and 25ms^{-1}. These parameters produced trajectories that had an unpredictable landing point within ±10m of the fielder's start position. Each fielder received about 50 balls and attempted to catch each ball. Figure 2.2 shows a bird's-eye view of the experimental set-up.

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[2] McLeod & Dienes noted that the fielders in Michaels & Oudejans experiments also experienced a catastrophic departure in the linearity of optic height against time. This is attributable to large changes in angle of gaze as the ball nears the fielder in (approximately) the final 50msec before the catch. However, by this time the fielder is in a good position to take the catch so the catastrophic departure from linearity cannot play a part in the fielder's motion to the interception point.

[3] It is quite possible that the deviations in linearity in the plots of optic height are due to increased error in the calculation of optic height as the ball approaches the fielder.

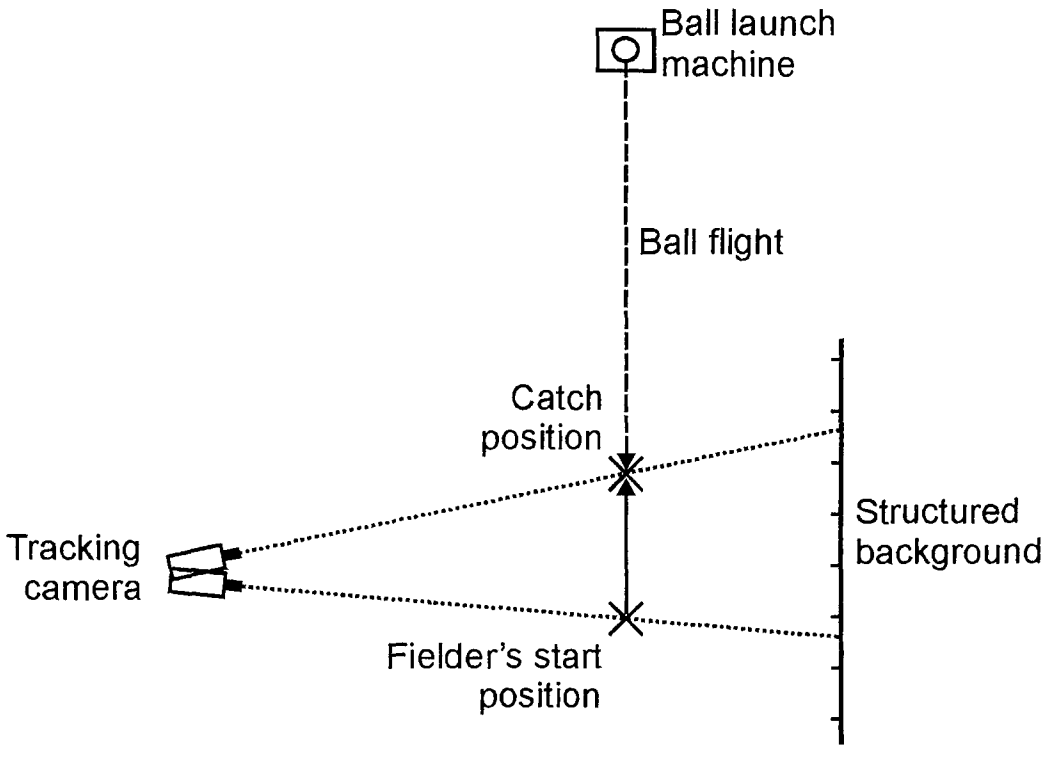


Fig. 2.2 View from above of the experimental layout.

The tracking camera could follow the fielder as he moved forward or backward, attempting to catch the ball. This had a high-speed shutter to ensure blur-free images. The fielder's position was estimated by replaying the video footage frame-by-frame and observing the markings on the background. McLeod & Dienes surmised that they could estimate the fielder's position to an accuracy of about ±3cm using this method. Since the fielder and ball start separated by 45m, this tolerance seems more than acceptable. The fielder's position was recorded every third frame giving an interval between each sample of 120ms. Position data was smoothed using a Hanning window[4]. Differentiation with respect to time gave the fielder's velocity.

2.1.2.2. Calculation of the ball's trajectory

The trajectory of the ball was calculated using four parameters. Its initial projection velocity and angle are known. A marker appeared in the field of view of the camera as the ball was launched and by seeing in which frame the ball was caught, the duration of the

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Each value is recalculated as the sum of half of itself plus one quarter of the previous value and one quarter of the following value.

flight could be estimated to within one frame (±40ms). In addition, the position of the ball in the final frame of a catch was used to give an estimate of the distance the ball had travelled (with similar error to the estimate of the fielder's position). The trajectory of the ball was then computed assuming that the ball travelled with parabolic motion transformed by an aerodynamic drag factor. This was proportional to the square of the ball's velocity, and its value gave the best fit to the observed flight distance and duration. The errors found using this technique were about 3% in the estimate of flight duration and about 1% in the estimate of flight distance. Thus, the ball position at any time between launch and catch could be calculated. Using this data in combination with the known position of the fielder's head, tan α could be calculated by dividing the height of the ball relative to the fielder's eye by the horizontal distance between fielder and ball.

2.1.2.3. Characteristics of fielders' performance

McLeod & Dienes noted some consistent features of fielders' running patterns. Firstly, fielders always had some velocity when they caught the ball. They did not run to the place where the ball was going to land and wait for it[5]. Instead, they seemed to time their run to coincide with the ball at the interception point. This observation led McLeod & Dienes to predict that fielders do not know where the ball is going to land but the information available before they start to move is merely sufficient to indicate in which direction they should start running.

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[5] In trials where the fielder had to move a trivial distance (less than 2m), the fielder often moved slowly to the interception point and waited for the ball to arrive.

They also noted that the pattern of running velocities varied across trials, seemingly dependent on the distance the fielder had to cover to reach the ball. In trials where the fielder ran more than 8m, running velocity increased in magnitude throughout the trial. When the fielder only had to move 3m, running velocity initially increased but then decreased, sometimes falling to a constant (non-zero) value. Trials where the fielder had to move somewhere between these extremes often saw the fielders' velocity increase to a constant velocity that is held until the ball is caught. This is clearly divergent from Chapman's hypothesis, since fielders are not necessarily running at constant velocity. McLeod & Dienes cite the work of Babler & Dannemiller (1993) as offering a possible solution to the problem of how the fielder is zeroing $d^2(\tan \alpha)/dt^2$ without using the constant running velocity suggested by Chapman. Babler & Dannemiller proposed that fielders use a strategy that continuously nulls optic acceleration so that the non-parabolic trajectory of the ball is approximated by parabolic segments. As the fielder adjusts to successive parabolic segments, he would need to adjust his running velocity to ensure that the new optic acceleration is zeroed. This intuitive strategy follows naturally from the work of Chapman. However, its effectiveness is not analysed by Babler & Dannemiller but suggested in their conclusions. McLeod & Dienes point out that whilst it offers a more complete explanation of the outfielder problem, it does not solve the underlying problem. That is, how does a fielder discover the correct single running velocity that will null optic acceleration to the interception point? They also question whether this amendment could account for the fielder's behaviour when called to run to the extreme distances in their experiment, where the fielder is accelerating throughout the ball's flight.

Reaction times for fielders in McLeod & Dienes first experiment were typically 0.5s i.e. the fielder waited around half a second before moving forward or backward. Confirming the data of Michaels & Oudejans (1992), they showed that fielders in their

experiment maintained $d^2(\tan \alpha)/dt^2$ roughly at zero and that they adjusted their running velocity to ensure this remained true. In an intriguing analysis, they showed that fielders were maintaining this relation with enough efficiency to guarantee that they were within catching distance of the ball as it neared the ground. McLeod & Dienes plotted $d^2(\tan \alpha)/dt^2$ against time and on the same graph also plotted lines indicating $d^2(\tan \alpha)/dt^2$ for an imaginary fielder who had run at constant velocity to the points 2m in front of and 2m behind where the ball would fall. These showed that although cancellation of $d^2(\tan \alpha)/dt^2$ was not perfect, it was accurate enough to get the fielder to within this catching range of the ball. McLeod & Dienes plotted regression lines of $d^2(\tan \alpha)/dt^2$ against time for all trials completed by a single fielder to test the claim that $d^2(\tan \alpha)/dt^2$ was zero as fielders attempted to intercept the ball. They found that only one trial had a slope or intercept that was reliably different (at the 5% level) from zero in a random sample of fifteen trials by one fielder. Analysis of the same data for the other fielders yielded similar results.

A feature of the fielders' behaviour that was common but not ubiquitous was an initial movement of a couple of steps forward immediately after the ball was released. This forward movement occurred regardless of whether the fielder needed to move forward or backward to catch the ball. McLeod & Dienes suggested that this behaviour was an artefact of the routine that cricket fielders follow when fielding at distance from the batsman. In a match, fielders are instructed to 'walk in' as the ball is being bowled to aid their movement and reflexes should the ball come their way. Not all fielders in McLeod & Dienes experiment displayed this initial movement and the authors do not attempt to explain it any further. Similar behaviour was encountered in the experiments presented in chapter 3. It is possible that the initial movements are a necessary step to

induce a controlled change in $d^2(\tan \alpha)/dt^2$, furnishing the fielder with information about the required interception strategy.

2.1.3. McLeod & Dienes' second experiment – High trajectories

The protocol for this experiment was largely the same as the first, the key differences were an increase in the projection angle from 45° to 64° and a fixed initial projection velocity of $24ms^{-1}$. This gave the ball an approximate projection distance of 36m, similar to balls projected at 45° and $20ms^{-1}$ in the first experiment. However, the fielder now had considerably longer to get to the same interception point (around 4s as opposed to around 3s). In the first experiment it was found that when fielders had less far to run they ran more slowly, rather than running to the right place an waiting for the ball to arrive. McLeod & Dienes contend that if a fielder knew where the ball were to land, it would be foolhardy to risk running to coincide with the ball. It would seem logical for the fielder to arrive with time to spare and steady himself to take the catch. However, the fielder may not have prior knowledge of where the ball will land but applies a strategy that uses changes in visual information to guide changes in motion. This experiment was designed to explore these possibilities. It was found that fielders arrived at the interception point at the same time as the ball. Although they ran there more slowly than when running to a similar point in the first experiment, they always had a positive velocity when the ball was caught. To quote McLeod & Dienes:

"The strategy [the fielder] used got him to the right place at the right time. However it did not appear to tell them where that was in advance."

Once again, McLeod & Dienes found that fielders ran controlling $d^2(\tan \alpha)/dt^2$ in such a way that they would end up within ±2m of the ball as it fell. Regressions of $d^2(\tan \alpha)/dt^2$ over time found that only one trial had a slope and intercept that was reliably non-zero. McLeod & Dienes concluded that because fielders do not use spare time to get

themselves to the interception point, it is highly likely that they did not know where it was until they made the catch. Consequently they are using an algorithm that gets them to the right place at the right time but does not give the fielder prior knowledge about where the ball will land. McLeod & Dienes concede that it is possible that fielders do know where the ball will land but choose not to use that information.

2.1.4. Missing the ball

Further to the experiments, McLeod & Dienes compared what happened to a fielder's visual information when they were successful and unsuccessful in catching balls on similar trajectories. They show two trials where the ball landed about 6m behind the fielder's start position. In the successful catch, the fielder accelerated backwards for around half the trial before settling at a roughly constant velocity until the catch was made. In the unsuccessful catch, the fielder was slower to move off backward and although he accelerated backward throughout the trial, he failed to get to the interception point in time to make the catch. More interesting than the fielder's running patterns are the changes in $d^2(\tan \alpha)/dt^2$ generated in attempting to catch the ball. In both the successful and unsuccessful catch, $d^2(\tan \alpha)/dt^2$ initially increased from a positive value, as one would expect for a ball on a trajectory which will finish behind a stationary observer. However, after half a second the successful catcher had accelerated backward, reducing $d^2(\tan \alpha)/dt^2$ until it had been attenuated to zero after one second. From that point on, $d^2(\tan \alpha)/dt^2$ hovered around zero until the catch was made. Control was not perfect, but sufficient to bring the fielder within range of the ball when it fell. After half a second, $d^2(\tan \alpha)/dt^2$ was still increasing for the unsuccessful catcher. By one second, the fielder had begun accelerating backward and $d^2(\tan \alpha)/dt^2$ started to decrease. However, he could not run backward fast enough to null $d^2(\tan \alpha)/dt^2$ and it remained positive

throughout. Failing to null $d^2(\tan \alpha)/dt^2$ led to unsuccessful interception – the ball flew over the fielders outstretched hand.

2.1.5. A servo to direct running

Given the evidence from their two experiments and their analysis of what happened when a fielder misses the ball, McLeod & Dienes claimed that a fielder uses the sign of $d^2(\tan \alpha)/dt^2$ as the input to a servo that controls running speed. The logic of the servo is outlined below:

Initial $d^2(\tan \alpha)/dt^2$	*Direction of running*	*Subsequent –ve* $d^2(\tan \alpha)/dt^2$	*Subsequent +ve* $d^2(\tan \alpha)/dt^2$
Positive	Backward	Decelerate backward running	Accelerate backward running
Negative	Forward	Accelerate forward running	Decelerate forward running

Table 2.1 Logic of servo controlling interceptive motion

A fielder engaging this servo who can run fast enough to null $d^2(\tan \alpha)/dt^2$ will coincide with the ball as it falls to eye-level. A topic not tackled by McLeod & Dienes is the question of sensitivity of the servo. How far does $d^2(\tan \alpha)/dt^2$ have to deviate from zero before a fielder will begin to accelerate in the appropriate direction to null the deviation? In fact, the question of human sensitivity to acceleration has been raised as a criticism of McLeod & Dienes' concept (McBeath, Shaffer & Kaiser, 1995). Furthermore, Todd (1981) found when subjects experienced stimuli simulated to approach with projectile motion they were apparently unable to take advantage of second derivatives with respect to time. However, Tresilian (1995) simulated interception of projectiles by a fielder using a servo-control strategy with $d^2(\tan \alpha)/dt^2$ as the input and found that performance was sufficient when the input signal for the servo was restricted

to merely the sign of the acceleration. Servo-control by $d^2(\tan \alpha)/dt^2$ appears to be a valid model of interception.

2.1.6. How to intercept a projectile and why $d^2(\tan \alpha)/dt^2$ is useful

McLeod & Dienes explained the rules that govern interception of a projectile. To summarise, if a fielder is in the right place at the right time to intercept a projectile launched in the aligned plane, the horizontal disparity between the fielder and ball must tend to zero at the same time as the vertical disparity. If this is true then at the point of contact, α will be between 0° and 90°. If the ball falls in front of the fielder then α falls below 0°. Conversely, if the ball goes over the fielder's head, α increases beyond 90°. So long as the fielder can keep α between 0° and 90°, interception is certain. Keeping $d^2(\tan \alpha)/dt^2$ at zero results in interception because it guarantees that α will be between 0° and 90° throughout the flight of the ball. If $d^2(\tan \alpha)/dt^2$ is zero then for a ball launched from ground level, $d(\tan \alpha)/dt$ will be increasing at a constant rate. Consequently, at the end of the flight of the ball $\tan \alpha$ must be positive and finite. The tangent of 0° is zero and that of 90° is ∞ so if $\tan \alpha$ is positive and finite then α is between 0° and 90°.

The evidence from the experiments of McLeod & Dienes and Michaels & Oudejans (1992) confirms that human fielders (intentionally or otherwise) hold $d(\tan \alpha)/dt$ constant for the majority of the flight when intercepting a projectile. Outwardly, this appears to lend support for Chapman's hypothesis. However, the motion of fielders in McLeod & Dienes' experiments conflicts with how one would expect them to move if a Chapman-style strategy were assumed. Real fielders did not move toward the ball at a specific constant velocity that holds $d^2(\tan \alpha)/dt^2$ at zero. Chapman noted that an observer moving with such motion would intercept a projectile. For any projectile there is a specific velocity that a fielder could maintain which would null $d^2(\tan \alpha)/dt^2$ and therefore get

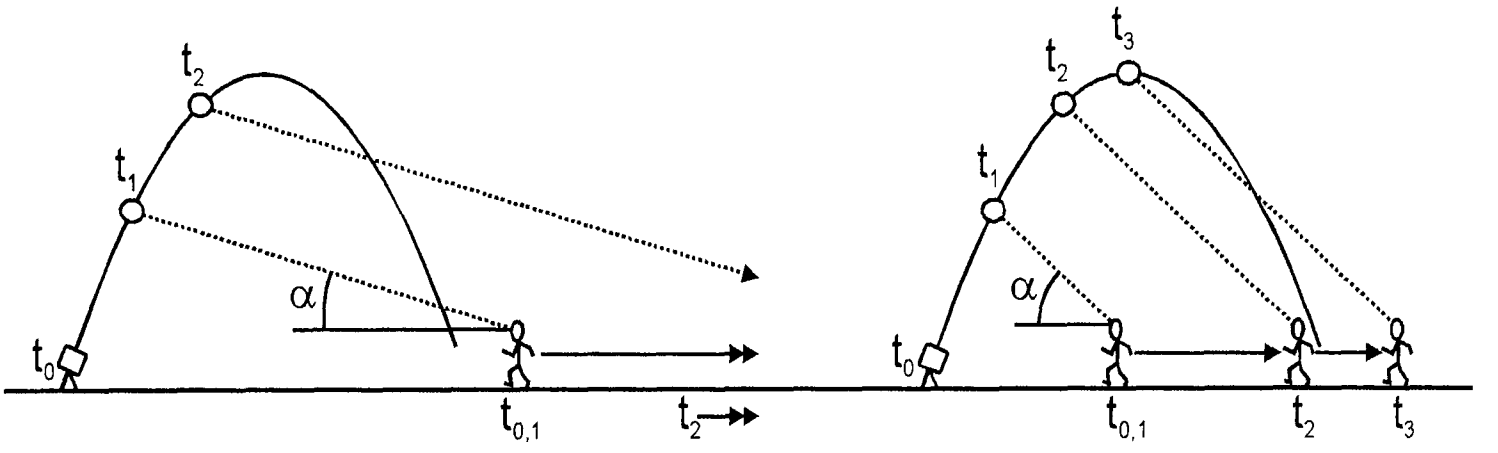
him to the right place at the right time. For a fielder to intercept a projectile in this way, he must have access to the specific running velocity that corresponds to the $d(\tan \alpha)/dt$ he experiences. This is tantamount to knowing when and where the ball will land, given any launch characteristics. As was discussed earlier, McLeod & Dienes predict that given the infinite variation in trajectory, it would be impossible for a fielder to have access to all such information. Their idea that $d^2(\tan \alpha)/dt^2$ is the input to a servo that can continuously vary motion eliminates this requirement. When a ball is launched towards a fielder it will generate $d(\tan \alpha)/dt$ and so long as the fielder can run so that it is held constant, he will be in a position to catch the ball as it falls to earth. Depending on when the fielder starts to run, a different running pattern will ensue but he will make the catch.

2.1.7. Alternative strategies

McLeod & Dienes showed that interception is guaranteed if a fielder can follow a strategy that keeps α between $0°$ and $90°$. They proposed an efficient strategy that achieves this by keeping $d^2(\tan \alpha)/dt^2$ at zero. That a fielder could solve these complex equations on the fly might seem a little implausible. They examined two simpler strategies that, although they achieve interception mathematically and may seem more plausible, are shown less effective than the one they propose.

2.1.7.1. Constant α

The simplest strategy to ensure that $0° < \alpha < 90°$ is to hold α constant – in other words hold $d(\tan \alpha)/dt$ at zero.



i). Ball lands ahead of start position ii). Ball lands behind start position

Fig. 2.3 The constant α strategy.

Figure 2.3 illustrates the limitations of the constant α strategy. In both cases, at t_1 the fielder has used the constant α strategy to decide which way to run and is moving to maintain α. In i), the ball is going to land in front of the fielder's start position. However, to maintain α the fielder has to move backward, away from the eventual interception point. If he continues to follow the constant α strategy he will achieve interception but this will involve a reversal of movement to recover ground lost whilst running in the wrong direction. In ii), the ball is going to land behind the fielder. This time, the fielder is sent initially toward the interception point. By t_3 however, the fielder has been sent beyond the interception point and to achieve interception a reversal of movement will again be required.

A fielder usually has a relatively short amount of time to decide which way to run and to arrive at the interception point simultaneously with the ball. It is essential that he begin running in the correct direction as soon as possible and throughout the flight of the ball. The constant α strategy is a mathematical solution to the 'outfielder problem' but is inefficient because it requires the fielder to recover ground lost whilst moving away from the interception point. By allowing α to increase, the $d^2(\tan \alpha)/dt^2$ nulling strategy does not face this problem and keeps the fielder moving toward the interception point at all times. It is therefore more effective and bears more resemblance to human performance.

2.1.7.2. Constant $d\alpha/dt$

McLeod & Dienes demonstrated in their analysis of the constant α strategy the importance of allowing α to increase throughout the flight of the ball. An alternative to cancellation of $d^2(\tan \alpha)/dt^2$ that also allows α to increase is the constant $d(\tan \alpha)/dt$ strategy, nulling the acceleration of α rather than $\tan \alpha$. The inherent danger with this strategy is that the fielder may select a rate of change of α that will cause α to exceed 90° before interception is achieved. For example, a fielder stood close to a ball projected at high velocity with a steep launch angle will experience a large initial $d\alpha/dt$. If the fielder ran holding this constant, it is likely that α would exceed 90° by the time the ball fell to earth. Dienes & McLeod (1993) showed that the constant $d\alpha/dt$ strategy caused simulated fielders to run backward too slowly to intercept balls landing behind their start position. Their experiments have shown that skilled human fielders were able to catch balls on the trajectories missed by the simulated fielders. Nulling $d^2(\tan \alpha)/dt^2$ avoids the risk of α exceeding 90° because $d\alpha/dt$ will decrease as α approaches 90°. As explained in section 2.1.6, if the fielder can run to maintain $d^2(\tan \alpha)/dt^2$ at zero, α can never exceed 90°. McLeod & Dienes confirmed that $d\alpha/dt$ decreases as α increases for real fielders in their first experiment by finding highly significant negative quadratic components to multiple regressions of α on time. Fielders are not holding the rate of change of α constant. They conclude that whilst the strategy of holding $d^2(\tan \alpha)/dt^2$ at zero may seem intrinsically complex there are good reasons why it has evolved to be so.

2.1.8. Learning to catch

McLeod & Dienes suggest that children learning to catch are capable of passively acquiring the fact that for all projectiles that land in their arms α was between 0° and 90°. They also presume that children will be able to exploit this relation in running to intercept

a ball that will land somewhere other than where they are. McLeod & Dienes quote their findings from Dienes & McLeod (1993) to explain how children might discover that nulling $d^2(\tan \alpha)/dt^2$ is an efficient method keeping α between 0° and 90°. For a ball that will land in front of a stationary fielder, $d^2(\tan \alpha)/dt^2$ is almost always negative whilst for a ball that will land behind a stationary fielder, $d^2(\tan \alpha)/dt^2$ is almost always positive. Therefore, $d^2(\tan \alpha)/dt^2$ is correlated to the catchability of a particular trajectory of ball flight and this cue is available to a stationary child. Whether mere exposure to this cue is sufficient for the child to acquire the strategy is a question McLeod & Dienes acknowledge remains unanswered.

2.1.9. Is $d^2(\tan \alpha)/dt^2$ computed by a human fielder

McLeod & Dienes' experimental data support Michaels & Oudejans' (1992) work that fielders null $d^2(\tan \alpha)/dt^2$ and they show that this is an effective strategy for achieving interception. However, neither propose any mechanism of how $d^2(\tan \alpha)/dt^2$ is kept at zero. McLeod & Dienes admit there might be scepticism that the human nervous system is capable of solving an equation involving the second differential of the tangent of an angle. They cite the work of Todd (1981) as offering an alternative solution that uses optic size to generate a cue equivalent to that provided by $d^2(\tan \alpha)/dt^2$. However, McLeod & Dienes make the observation that fielders start to move toward the interception point soon after the target is projected, even when the ball is launched from as far as 50m away. They question whether the extreme sensitivity to optic size that would be required to exploit such a cue from that range is any more plausible than computing $d^2(\tan \alpha)/dt^2$. It is also suggested that fielders may null $d^2(\tan \alpha)/dt^2$ by systematically reducing $d(\alpha)/dt$ as α increases, eliminating the obligation to compute tan α.

McLeod & Dienes' final remarks question whether the human visual system can cope with the sensitivity to acceleration required to maintain $d^2(\tan \alpha)/dt^2$ at zero. However, in defending the exploitation of an acceleration cue, they quote work by Tresilian (1995) and Babler & Dannemiller (1993), showing that the performance of human fielders observed in the experiments by Michaels & Oudejans (1992) and McLeod & Dienes (1996) is possible within the limitations of the visual system.

2.1.10. Questions arising from McLeod & Dienes (1996)

Several issues arise from McLeod & Dienes' 1996 paper. McLeod & Dienes offer a thorough analysis of how a fielder gets to the right place at the right time when intercepting a ball launched in the aligned plane. However, they do not make any attempt to explain how a fielder might intercept a ball launched in an unaligned plane, other than to refer the reader to other work examining the extra cues that are available in this scenario[6]. To complete the explanation of human interceptive behaviour an additional or a single unified theory is required to account for fielders' sideways motion to supplement or replace McLeod & Dienes' algorithm. Chapters 3, 4, & 6 examined this issue and found that the addition of a second control variable to guide lateral movements implemented alongside produced an accurate fit to the behaviour of real fielders intercepting projectiles. It would also be of interest to study what fielders know of what they are doing when they are running to catch a ball. Do they have any awareness of the strategy being implemented as they close in on the ball? This possibility is investigated in chapter 7.

Finally, McLeod & Dienes (1996) do not shed any light on how a fielder might appraise the available visual information. They point to the studies of Babler &

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[6] Regan, Beverly, & Cynader (1979); Regan, (1993); Regan & Kanshal, (1994).

Dannemiller (1993) and Tresilian (1995) as offering evidence that the human visual system has sufficient acceleration sensitivity to achieve interception using the strategy they propose. Opposing this view is the work of Todd (1981) who found that when subjects observed simulated stimuli approaching on parabolic paths they were unable to use acceleration cues. Chapter 8 investigated this divergence of opinion, by examining the information available to a fielder before he starts to move. Subjects' performance was consistent with their efficient detection of changes in $d^2(\tan \alpha)/dt^2$ adding weight to the theory that control of running using $d^2(\tan \alpha)/dt^2$ is a valid model for human interception.

2.2. McBeath, Shaffer and Kaiser (1995)

'How baseball outfielders determine where to run to catch fly balls'

The following section reviews a much-cited paper that advocates unification of the horizontal and vertical visual angles generated by a ball travelling in an unaligned plane into an optic trajectory and bases interceptive behaviour on variation in this trajectory.

2.2.1. Information for guiding action

The paper begins:

'Even recreational baseball outfielders appear to know virtually from the moment of bat contact where to run to catch a fly ball.'

It is difficult to say to what extent a fielder 'knows' where to run. This is a rather contentious point and is investigated in the chapter 7. It depends on the degree of knowledge that it is presumed the fielder has of where to run. It is unlikely that the authors predict that fielders have an immediate conscious awareness of exactly where they need to go to intercept a projectile. However, as chapter 7 shows, it is unclear whether fielders have any conscious awareness at all of their interception strategy. The authors go on to acknowledge the utility of cues such as stereo disparity, accommodation, image expansion rates, and occlusion for fine motion adjustments in the final moments of interception. The paper is therefore a study of interceptive strategy between the moment the target is launched until the moments before interception is achieved (or not). As in previous studies of interception, it was assumed that because of factors such as drag, spin and wind effects, deriving an interception strategy from a computed parabolic trajectory is unlikely to be the method used by human fielders. Instead, they come to the same conclusion as McLeod & Dienes (1996) – that the only viable information that could be used to achieve the goal is the optical information provided by the changing position of

the ball image relative to the background scenery. A fielder running to catch a ball must use that information to control his movement.

2.2.2. Appraisal of the Optical Acceleration Cancellation (OAC) model

McBeath et al. reject models that are based on maintenance of constant d(tan α)/dt, referred to as optical acceleration cancellation (OAC) models. They acknowledge that there is empirical support for OAC models, notably papers by Michaels & Oudejans (1992) and McLeod & Dienes (1993), but consider them to be inadequate for several reasons. First, they correctly point out that constant d(tan α)/dt results in decreasing d(α)/dt so the rate of change of the available optical information is not constant but diminishing. The second flaw McBeath et al. find in OAC models relates to the human ability to discriminate accelerations. They believe that fielders have insufficient discriminative ability to account for the accuracy of their performance. A further problem with OAC models cited by McBeath et al. is one of projection. They state that the optical angular information available to the fielder is in the form of a spherical projection, whereas maintenance of lateral alignment with the projectile necessitates use of an orthographic projection. McBeath et al. also take issue with previous work which has focussed on balls being projected toward fielders aligned with the plane of projection of the ball. Whilst this simplifies analysis by reducing the variables an experimenter has to consider, McBeath et al. suggest that it complicates matters for a fielder. They believe that the extra information afforded by a viewpoint outside the ball's projection plane simplifies the task of interception.

The criticisms of OAC appear valid but most can be answered simply. Their first criticism is levelled at the usage of d(tan α)/dt. However, it is a consistent finding of studies tackling interception strategy that fielders appear to have a remarkable ability to

cancel the optical acceleration of their target. This may seem unintuitive but has been a consistent finding of such interception studies and therefore must be considered. Secondly, McBeath et al. question whether humans possess a sufficiently precise ability to discriminate acceleration to successfully null this quantity when running to catch. They admit that the evidence confirming or refuting this is far from concrete. However, Tresilian (1995) showed that a simulated fielder could achieve a level of interceptive performance that is qualitatively similar to that of a human if the only discrimination given to the simulated fielder is the sign of optical acceleration. Tresilian suggested that the result validated the OAC model for visual guidance of catching. The third criticism relates to the optical projection available to the fielder. McBeath et al. state for a fielder to maintain lateral alignment with a moving projectile, they would require an orthographic projection. This is perhaps true in optical terms but it is a patently simple task for a human to decide whether they are in line with the plane of flight of a moving projectile or not. If the approaching target moves to the left of the observer's mid-line, the observer must move left in order to maintain alignment and vice versa.

2.2.3. The Linear Optical Trajectory (LOT) model

The model of interception proposed by McBeath, Shaffer, & Kaiser combines the vertical and horizontal components of optical information that are available to a fielder watching a projectile. They specify the vertical and horizontal optical angles as α and β. The angle α represents the angle through which the observer has had to raise their line of sight from horizontal in order to fixate the ball. The angle β represents the horizontal angle subtended by the initial optical position of the ball and the current position of the ball from the point of view of the observer. A third angle, Ψ, is specified by α and β. This represents the observed angle of ball movement relative the background scenery. Figure 2.4 illustrates how Ψ is derived from α and β.

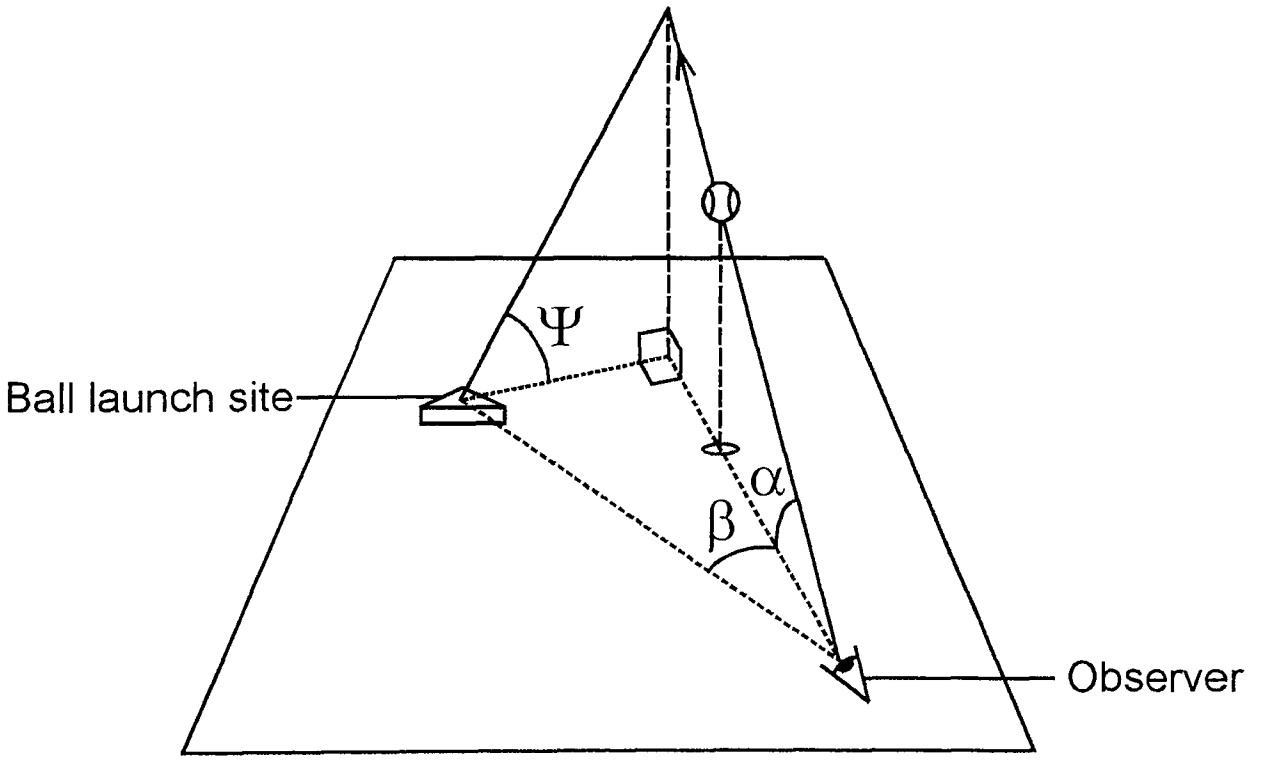


Fig. 2.4 The optical trajectory projection angle, Ψ.

The right-angle triangles that specify α, β and Ψ form a right-pyramid such that:

$$\tan \Psi = \frac{\tan \alpha}{\tan \beta}$$

The LOT model, proposed by McBeath, Shaffer & Kaiser, states that a fielder chooses a running path that maintains a linear optical trajectory of the ball relative to the home-plate (where the ball was projected from) and the background scenery. Keeping the optical trajectory linear is mathematically equivalent to keeping Ψ constant. Given the above relation, if the fielder keeps Ψ constant, tan α and tan β must increase in proportion with one another. The solution is based on the fielder maintaining a balance between the vertical and lateral optical angular change. Since the model is based on these optical angular changes, it does not require the fielder to possess any knowledge of the distance to the ball or its origin. The authors claim that one reason why the LOT model is better suited to human interception than the OAC model is because the fielder is required to discern optical curvature rather than optical acceleration. At the same time, maintenance of a LOT achieves OAC via control of the shape of the ball trajectory image.

McBeath, Shaffer & Kaiser argue that, although the constraints of the LOT model require that tan α and tan β must increase proportionally and not necessarily linearly, fielders tend to follow LOT solutions in which show linear increases in tan α and tan β. These solutions require keep the bearing of the running path roughly constant and minimises the overall running speed.

Figure 2.5 extends figure 2.4, showing how a fielder using the LOT model achieves interception (α and β are shown for t_1).

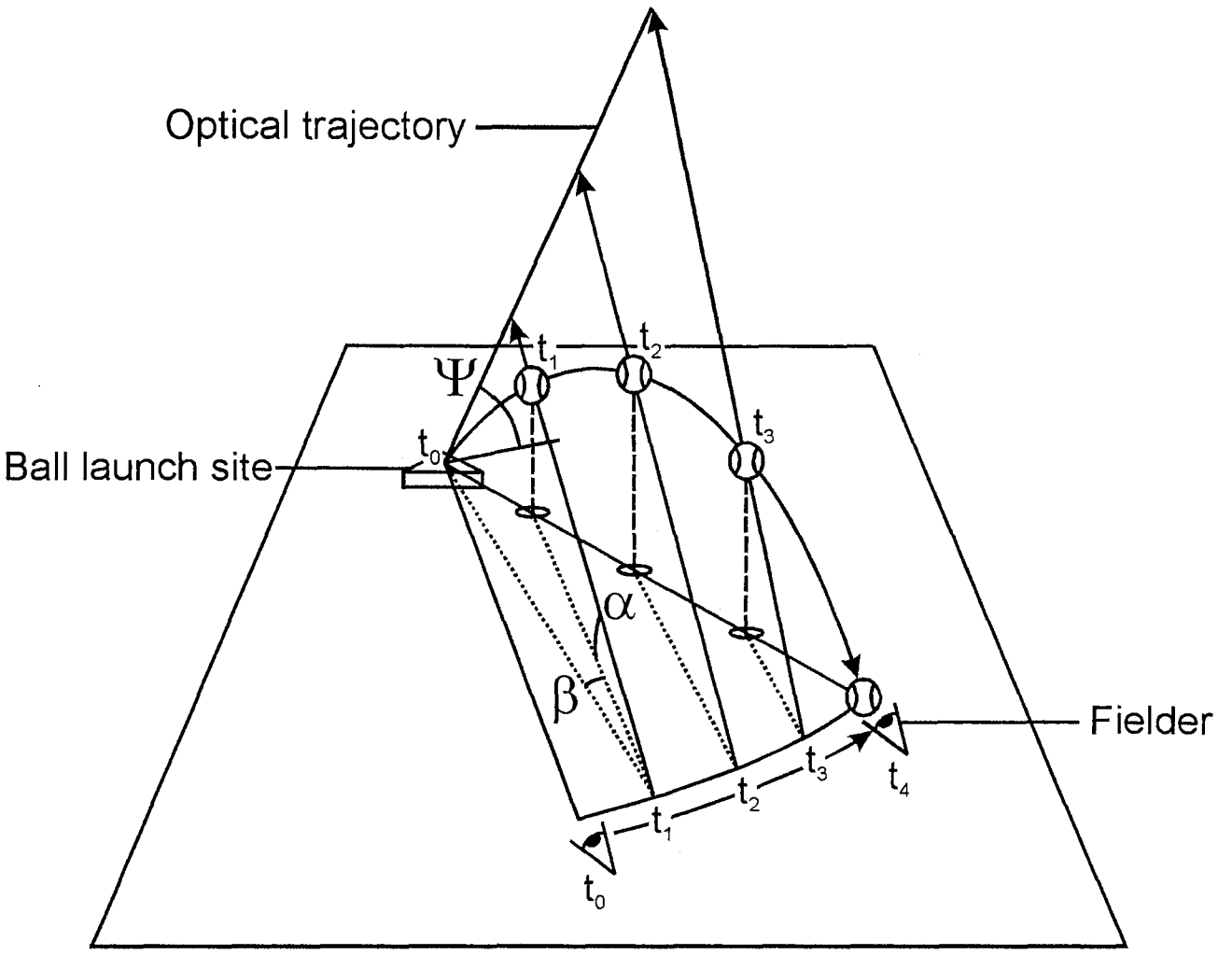


Fig. 2.5 A fielder using the LOT model.

In section 2.1.6, it was shown why ensuring that tan α increases at a constant rate guarantees that the fielder will be in the right place at the right time to intercept a projectile. McBeath, Shaffer, & Kaiser extend this premise stating that if the fielder maintains a linear increase in tan β, he will achieve approximate lateral alignment with catchable trajectories. The authors express the relation governing the LOT model mathematically. This is as follows:

$$\tan\psi = \frac{\tan\alpha}{\tan\beta} = \frac{C_\alpha f(t)}{C_\beta f(t)} = C_\psi$$

where C_α, C_β, and C_Ψ are constants and the function of time, $f(t) = t$ = time since trajectory initiation. Although $f(t)$ could be any monotonically increasing

function, McBeath, Shaffer & Kaiser suggest that $f(t) = t$ gives the most appropriate running paths for approximately parabolic trajectories.

To maintain a constant optical trajectory projection angle, Ψ, there is no constraint on tan α and tan β to increase linearly, just that they increase in proportion with one another. A linear increase in both tan α and tan β would produce a constant optical speed. McBeath, Shaffer & Kaiser hypothesise that fielders tend to choose running paths that produce constant optical speeds because solutions with variable optical speeds require running paths with extremes of curvature and acceleration. They also confirm that because it links visual information to running strategy, the LOT model, like the OAC model, is an error-nulling strategy. Deviations in trajectory caused by e.g. wind, ball spin, are compensated for as the fielder runs.

2.2.4. Predictions about performance by the OAC model

McBeath, Shaffer, & Kaiser ran two experiments to test the validity of the LOT and OAC models. They summarised the predictions of the OAC model for their experiments as follows:

"...the OAC model predicts that fielders select a running path that is straight with constant speed, resulting in a curved optical ball trajectory."

In fact, these are not the predictions of the OAC model. Chapman (1968) first proposed a mathematical solution to the outfielder problem that was based on optical acceleration. He found that a fielder aligned with the plane of projection of the ball would intercept a ball on a parabolic trajectory, if he moved at the constant speed that caused the tangent of his angle of elevation of gaze to increase at a constant rate. However, Chapman did not test that fielders actually did perform as his solution predicted and only made the brief suggestion that fielders attempting to catch a ball in the unaligned plane would move laterally to hold its bearing constant. For a projectile

following parabolic motion, this would result in the fielder moving laterally at a constant velocity.

Aggregating Chapman's ideas into a coherent model of how fielders move in two dimensions intercept a projectile would lead to a model that predicts fielders do indeed run at constant speed in a straight line to intercept projectiles, as McBeath, Shaffer & Kaiser suggest. However, further studies based on Chapman's hypotheses have shown that, although his idealised mathematical solution is correct, it is not applicable in the real world and that fielders do not run at constant speed to intercept projectiles. Brancazio (1985) showed that air resistance causes balls to deviate markedly from parabolic motion. This means that fielders would have to vary their running speed in order to null optical acceleration continuously. Furthermore, Dienes & McLeod (1993) (and subsequently McLeod & Dienes (1996)) showed that fielders intercepting balls projected in the aligned plane did not run at a constant speed but always moved so that the tangent of their angle of elevation of gaze increased at a constant rate. Consequently, a fielder running to intercept a projectile in the aligned plane can run at different speeds (depending on when they begin running and how they accelerate) whilst still holding the rate of change of tan α constant. Dienes & McLeod made no explicit predictions about how a fielder might move laterally to intercept a projectile but suggest, like Chapman, that a fielder might keep the ball at a constant left-right bearing throughout its flight. Given the variation in running speed shown by Dienes & McLeod and the variation in trajectory caused by air resistance shown by Brancazio, it is clear that constant running speed is not a prediction of the OAC model. Furthermore, it is not clear from any of these studies whether the motion resulting from the strategy governing lateral movement and motion resulting from the

requirement to keep tan α increasing at a constant rate occur simultaneously. This would be essential in generating a straight constant speed running path.

To conclude, McBeath, Shaffer & Kaiser appear to have misjudged the predictions of the OAC model of interception. Its predictions regarding lateral movement are not rigorously specified so making comparisons with the LOT model are not necessarily valid. This must be considered when interpreting the results of their analyses attempting to separate the LOT and OAC models.

2.2.5. Experiments to test the validity of the LOT and OAC models

2.2.5.1. Experiment 1

McBeath, Shaffer, & Kaiser ran two experiments to evaluate the models in question, both using college students with moderate experience of ball games. In their first experiment, they were filmed catching by a video camera mounted on a tower above and behind their position. Balls were projected at a variety of launch velocities and angles from a distance of 50m with the fielders running forward to catch in most trials to optimise camera angle. They analysed movement in 31 trials in which fielders caught the ball. Of these, there were three trials in which the ball was launched in the same vertical plane as the fielder. McBeath, Shaffer, & Kaiser regarded the behaviour of fielders to be significantly different in these trials and so were discarded from the analysis. In the remaining 28 trials, fielders had to run between 2 and 15m in various directions in order to catch the balls.

McBeath, Shaffer, & Kaiser used regression analyses to interpret their results. They found that 71% of running paths (20 of the 28) curved significantly and that in 75% of trials (21 of the 28), the running speed of fielders varied significantly. Only in 3% of trials (1 of the 28) did the fielder demonstrate constant running speed

behaviour. They suggested that the results provided evidence supporting the LOT model over the OAC model. However, as was discussed earlier, the OAC model makes no such prediction about running speed. Consequently, the analysis does not favour either model.

2.2.5.2. Experiment 2

In their second experiment, the relative positions of the ball launch apparatus and fielder were the same as their first experiment. The launch parameters of the balls were also approximately the same. However, in this experiment the fielders carried a shoulder-mounted camera that was aimed toward the ball as they ran to make a catch. To optimise filming, fielders again ran forward in the majority of trials. There were 31 trials in which fielders caught the ball and kept the ball within the field of view of the camera and it is these that were selected for analysis. As before, trials in which the ball was launched in the projection plane aligned with the fielder were discarded, leaving a remainder of 27 trials. From the position of the ball in the video footage, McBeath, Shaffer & Kaiser were able to determine Ψ and the optical speed of the ball.

It was found that there was a significant decline in optical speed in 60% of trials. This appears to refute the hypothesis that fielders move to maintain a constant optical speed. However, McBeath, Shaffer & Kaiser go on to show that, on median, a linear function accounts for 99% of the variance in tan α (consistent with the OAC model) and 97% of the variance in tan β. They state that 'the fielders chose paths with lateral change matching the vertical rate'. In this instance, it is more correct to say that fielders chose paths with lateral rate of change proportional to vertical rate of change. They go on to say that the LOT model accounted for a median of 96% of the variance of the optical projection angle, Ψ and additional quadratic curvature for 2%.

They plot some typical results in their figure 4. Somewhat confusingly they plot α against β rather than tan α against tan β and add straight lines the data points of each trial to indicate the proportional changes in each angle. Given that in the LOT model they propose that tan α changes in proportion to tan β, presenting a figure that shows α changing in proportion to β is of questionable relevance. One can only assume that they are using the approximation that, for small angles, α(radians) $\approx$ tan α. Re-plotting their data using the tangents of each of their angles (see figure 2.6) reveals greater linearity of the relative variation in the two components of the optic trajectory angle, adding to the confusion of why McBeath, Shaffer, & Kaiser plot α against β.

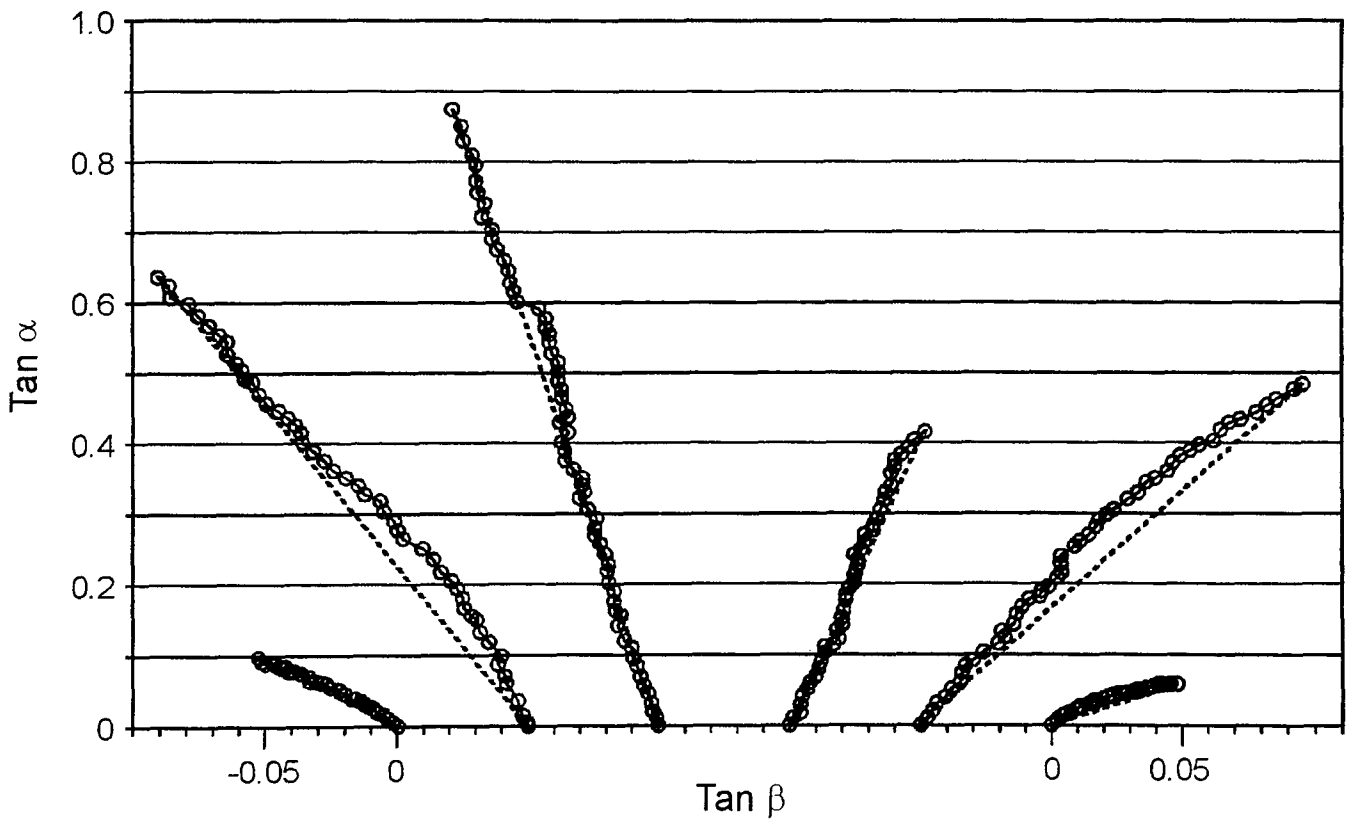


Fig. 2.6 Graph of tan α vs. tan β for the example plot shown in McBeath, Shaffer, & Kaiser (1995).

A further problem with their original figure is that each set of data points appears to show slight downward curvature. Although the straight lines added by the authors are intended to show constancy of Ψ, they also demonstrate a consistent

deviation of the optical trajectory away from linearity. Significantly, they do not say whether a curved fit was significantly better than the linear fit to the changes in tan α or tan β over time. This is excusable because the linear fit explained 97% of the variance. However, it is still possible that a curved would significantly improve the regression model and could be responsible for the observed curvature of the optical trajectory. Furthermore, it is unclear whether plotting the tangents of the visual angles rather than the angles themselves would eradicate or exacerbate this apparent curvature.

2.2.6. Conclusion

McBeath, Shaffer, & Kaiser conclude that fielders combine the change in the vertical and horizontal optical angles into an optical trajectory and use this spatial cue, rather than just temporal cues, to guide their interceptive behaviour. They provide evidence from the animal kingdom of the use of optical angles to guide tracking movements and suggest fielders use a similar strategy. They believe that once a fielder establishes a LOT solution, he knows that he can control his running strategy to get to the right place at the right time to catch the ball. The LOT model does not provide the fielder with explicit information about where or when that will be. McBeath, Shaffer, & Kaiser claim that this is why a fielder attempting to catch a ball does not run to the interception point and wait for the ball to arrive. They also suggest that the LOT model provides a cogent explanation as to why it is easier to catch balls launched in the unaligned plane. The claim is that for a ball launched in the aligned plane, a fielder must rely on a weak ability to discriminate acceleration (using the OAC model). The trajectory does not generate a lateral optical angle and therefore the fielder cannot use their robust ability to discriminate curvature (as they would in the LOT model). Finally McBeath, Shaffer, & Kaiser confirm that the LOT model is an

error-nulling strategy that can correct a fielder's running strategy for minor deviations in the trajectory of the ball.

McBeath, Shaffer, & Kaiser's LOT model offers a mathematical solution to the 'outfielder problem' but the contradictions in their experimental evidence supporting it suggest that further work is required to show whether the LOT model is employed by fielders as they run to catch a ball.

2.3. Responses to McBeath, Shaffer, & Kaiser (1995)

A technical commentary on McBeath, Shaffer, & Kaiser (1995) entitled 'On Catching Fly Balls' (*Science* (1996)) critically reviewed the LOT model. Two sets of authors gave their impression of the proposed interception strategy, whilst McBeath, Shaffer, & Kaiser answered their criticisms.

2.3.1. Dannemiller, Babler, & Babler

In their response to the McBeath, Shaffer, & Kaiser article, Dannemiller, Babler, & Babler raised three issues. These are as follows:

1. OAC requires the fielder to precisely discriminate optical accelerations, a task at which, according to McBeath, Shaffer, & Kaiser, humans are not very good.
2. Poor sensitivity to acceleration leads fielders to convert the problem from the temporal one of detecting velocity differences into a spatial one of detecting optical curvature, a task at which McBeath, Shaffer, & Kaiser suggest humans are very good.
3. Maintaining the two-dimensional projection of the ball on a LOT is sufficient to get the fielder to the right place at the right time to catch the ball.

In response to the first statement, Dannemiller, Babler, & Babler claim that the first statement is incorrect when one considers the velocities and accelerations

typically encountered by a fielder trying to catch a ball. They also claim that although the second statement may be correct, it is not supported by the research to which McBeath, Shaffer, & Kaiser refer. The cited research (Riggs (1973); Watt & Andrews (1982); Hopkins et al (1976)) required subjects to discriminate straight and curved lines. Dannemiller, Babler, & Babler suggest that, because projectiles do not leave trails in the sky, sensitivity to curvature of a line (a spatial problem) is of questionable relevance to trajectory curvature sensitivity (a spatiotemporal problem). They cite a study by Werkhoven, Snippe, & Toet (1992) as more relevant data. It shows that humans require a deviation of approximately 5° at low temporal frequencies to detect perturbation from a straight path for a slow moving object. It is unclear whether sensitivity at this level is sufficient to allow the LOT model to operate adequately.

In responding to the third statement, Dannemiller, Babler, & Babler conducted a study that simulated a fielder running to a catch a ball projected from a distance of 67m and would land 23.1m from the fielder's start position. They found that the simulated fielder could run on a path that ensured Ψ remained constant ($\tan \alpha$ and $\tan \beta$ changed in proportion) but left the fielder out of range of the ball as it fell to earth. Initially, the simulated fielder experiences a proportional increase in $\tan \alpha$ and $\tan \beta$ at a decreasing rate. Eventually, this trend reverses and $\tan \alpha$ and $\tan \beta$ decrease proportionally through the same values over which they increased. The fielder would experience a linear optic trajectory and consequently, according to the LOT model, the fielder would receive no signal to indicate that he would end up some distance from the eventual interception point. To prevent this behaviour materialising, McBeath, Shaffer, & Kaiser added the constraint that $\tan \alpha$ and $\tan \beta$ should increase monotonically. Dannemiller, Babler, & Babler question how a fielder would realise that the optical projection was increasing monotonically if he is just monitoring

linearity of the optical trajectory. They state that unless the fielder also nulls variation in the rate of change of the vertical optical angle, he may follow a LOT solution that does not necessarily get him to the landing site of the ball. The authors conclude that the OAC model is a more appealing model of human interceptive behaviour because the linear increase in the vertical optical angle is a direct prediction of the model. By contrast, in the LOT model this is a curiosity that must be explained by extra-perceptual constraints.

2.3.2. Jacobs, Laurence, Hong, Giordano, & Giordano (1996)

The authors examined the performance of outfielders participating in a similar experiment to that conducted by McBeath, Shaffer, & Kaiser (1995). Their intuition was that fielders ran to catch the ball so that they achieved alignment with its projection plane, reducing β to 0°. This would violate the premise that fielders move to keep the ratio tan α/tan β constant. Their analysis revealed that although fielders moved so that tan α increased linearly for the majority of the ball's flight, in some trials, tan β was observed to increase linearly initially but then decreased to zero before the ball was caught, confirming the hypothesis of Jacobs et al. This directly contradicts the LOT model, which predicts that the fielder always keeps the ball to one side of his body to ensure that tan β is increasing (through holding Ψ is constant). Jacobs et al. suggest that fielders control movement using the relative velocity of the ball perpendicular to the line of sight (v_p), such that β and v_p fall to zero at the same time. They conclude that, although LOT model has some intuitive appeal, it does not reflect how human fielders intercept projectiles.

2.3.3. The response of McBeath, Shaffer, & Kaiser

McBeath, Shaffer, & Kaiser responded to the criticisms raised by Dannemiller, Babler, & Babler, insisting that the LOT model is preferable because the OAC model restricts fielders to straight, constant speed running paths. This, as described earlier, is not a constraint of the OAC model. They hold that they never suggested that the LOT model was a sufficient condition for interception, more that it is a cue that fielders use to guide their interceptive behaviour and that OAC is a secondary cue that fielders may also engage. They defend their position that human fielders have insufficient ability to discriminate accelerations, suggesting that the family of sensors that register trajectory acceleration assist in the detection of trajectory curvature, which therefore must have greater sensitivity.

McBeath, Shaffer, & Kaiser suggest that the OAC model is flawed because it requires fielders to run so that α is increasing at a decreasing rate since they must keep the rate of change of tan α constant. They concede that this effect is negligible at small angles because $\alpha \approx \tan \alpha$, but becomes substantial at larger angles. Given this criticism of the OAC model, it is difficult to understand why they presented a figure of α against β rather than tan α against tan β in order to illustrate constancy of Ψ. McBeath, Shaffer, & Kaiser illustrate their apparent confusion as to the true specification of the OAC model when they cite evidence of non-constant speed running paths of fielders from McLeod & Dienes (1993). The main thrust of the McLeod & Dienes paper was that although fielders do not use the unique constant speed OAC solution (as suggested by Chapman (1968)), they consistently run so that the optical acceleration is cancelled.

Given the evidence provided by Jacobs et al., McBeath, Shaffer, & Kaiser accept that the LOT model is an overly conservative description of interceptive

behaviour, which they suggest would be better served by a model that is more loosely specified. They suggest that a model to supersede one based OAC or LOT should account for the following empirical findings:

1. Balls hit to the side seem easier to catch.
2. Fielders generally run along curved paths with ∩-shaped speed functions.
3. Spatial strategies are noted in other domains of tracking.

McBeath, Shaffer, & Kaiser contend that the LOT model addresses these findings. In defending the criticisms of Jacobs et al., McBeath, Shaffer, & Kaiser suggest that their model was never intended to explain fielder behaviour in the final moments before interception, where cues other than the optical ball trajectory can be exploited. They reject the use of v_p because this abandons use of α, which is optically specified.

McBeath, Shaffer, & Kaiser contend that, in the example trial presented by Jacobs et al., the fielder maintains linearity if the optical trajectory for 2.5s of a trial lasting 3.8s. However, this is based on a plot α against β, rather than tan α against tan β. It is unclear how linear the optical trajectory would be if the plot was constructed on these axes. Furthermore, McBeath, Shaffer, & Kaiser go on to claim that the LOT model is based on a constant ratio of α and β and that non-linearity is to be expected since α reaches 70° where α is a poor approximation of tan α. This remarkable assertion is a direct contradiction of the LOT model, as specified in the original paper.

2.4. The state of the LOT model

McBeath, Shaffer, & Kaiser's LOT model remains a widely cited explanation of human interceptive performance. However, the authors do not provide a convincing argument as to why the OAC model is invalid since the only restraint imposed by the

OAC model is not violated in any of their experiments (or those of the responding authors). The OAC model for interception in two dimensions that McBeath, Shaffer, & Kaiser claim to improve upon is not current. Their belief that it predicts straight running paths that fielders run along at constant speed is not in fact stipulated. It appears that where the OAC model under-specifies interceptive behaviour, the LOT model seems to over-specify the fielders' movements. There is confusion over the ratio that fielders are supposed to hold constant as they run. In the original paper, they authors provide a lucid explanation and a clear figure showing that in the model, fielders hold tan α/tan β constant, giving constant tan Ψ (and therefore constant Ψ). However, they also present a figure that shows linearity (and therefore a constant ratio) of α vs. β. Furthermore, in their reply to technical comments on the LOT model, they appear to suggest that fielders hold the ratio α/β constant. Experiments presented chapters 3 and 4 of this thesis examined the optical experience fielders. Results show that neither of these ratios provided a consistently accurate cue to interceptive behaviour. Chapter 5 examines the cue provided by curvature of the optic trajectory finding that it can be ambiguous in the action it specifies to a prospective fielder. In chapter 6, alternative interception models were constructed and their performance guiding a simulated fielder was compared to a simulation of a fielder following the LOT model. The result of this analysis produced further evidence to suggest that fielders do not attempt to induce linearity of the optic trajectory that they experience to guide their catching behaviour.

3. Interception in the unaligned plane

3.1. Introduction

3.1.1. Considerations in past studies of interception

Past studies of interception (Chapman (1953), Michaels & Oudejans (1992), McLeod & Dienes (1993,1996)) have tended to focus on how a fielder determines whether to move forward or backward toward a target projectile that may land directly in front or directly behind their start position in the aligned vertical plane. For a fielder attempting to intercept such a projectile, deciding the correct course of action in this plane of motion has always been considered a more complex task than the decision of whether to move left or right. When a projectile has a component of horizontal velocity (i.e. left or right relative to the plane vertically aligned with the fielder), the direction in which the fielder must move in the left-right axis is immediately apparent from the motion of the target relative to the fielder's mid-line. If the target is observed moving left, the fielder should move left, if the target is observed moving right, the fielder should move right. For a target moving in the aligned vertical plane, the cues determining appropriate behaviour are not so apparent. The height attained by a projectile does not indicate how fast the fielder should move forward or backward to intercept it. Similarly, the launch velocity of a projectile is not necessarily a valid cue to its landing location. The angle of projection will have a dramatic effect on its trajectory.

McLeod & Dienes (1996) have shown that the rate of change of the tangent of the observer's angle of gaze ($d(\tan \alpha)/dt$) provides the observer with salient information about the landing location of the projectile (reviewed in chapter 2). If $d(\tan \alpha)/dt$ is decreasing then the projectile will land in front of the observer and if

d(tan α)/dt is increasing then the projectile will land behind the observer. However, this relation is less precise when one considers a projectile launched with a component of horizontal velocity. A stationary observer will experience a decreasing d(tan α)/dt as the ball falls to earth. The ratio of the height of the ball above the fielder's eye to the horizontal distance between the ball and the fielder will reach a maximal value. From then on, tan α, must decrease. The cue provided by d(tan α)/dt does not indicate whether the fielder must run left or right to reach the interception point. It only shows that the fielder is not in the right place to make the catch. The comparative simplicity of the left-right decision has lead to its neglect as studies attempt to minimise variables to concentrate on the forward-backward running decision.

3.1.2. Aims of the experiment

This experiment was designed to examine the cues available to fielders to guide motion in two dimensions to reach the interception point. McBeath, Shaffer, & Kaiser (1995) advocate that cues to lateral and depth movement are integrated within a universally applicable strategy. They suggest that fielders running to intercept projectiles maintain a linear optical trajectory (LOT) of the ball relative to the launch site of the ball and the background scenery. The angle formed between the horizontal and the optic trajectory they term Ψ. The angle Ψ is formed from the vertical visual angle α and the lateral visual angle β, such that:

$$\tan \Psi = \frac{\tan \alpha}{\tan \beta}$$

If a fielder runs so that Ψ (and accordingly tan Ψ) is constant, then tan α and tan β must increase proportionally to each other. The motion of fielders in this experiment was examined to investigate whether this principle was observed. The LOT model they propose is detailed in chapter 2. Alternatively, it is possible that movement resulting from the more complex and perhaps more time consuming forward-backward decision is superimposed onto initial left/right movement. This would result if the fielder simply started to move left or right cued by the relative lateral displacement of the ball then followed, for example, a McLeod & Dienes (1996) strategy to guide forward/backward movement. Tresilian (1995) advocated a strategy of this nature. Should the LOT model fail to explain interceptive behaviour satisfactorily, observations of fielder movements will allow proposal of novel interception strategies.

3.2. Method

3.2.1. Experimental apparatus

VHS video camera recording at 25 frames per second, standard tennis balls.

3.2.2. Subjects

6 university graduates (5 male, 1 female) all experienced at ball sports (played a ball sport at a representative level).

3.2.3 Interception

3.2.3.1. Experimental set-up

Each subject stands at a start position 13.40m from a building. At the top of the building (at a height of 14.75m) are the thrower and a video camera angled down to view the 'catching area' (see figure 3.1).

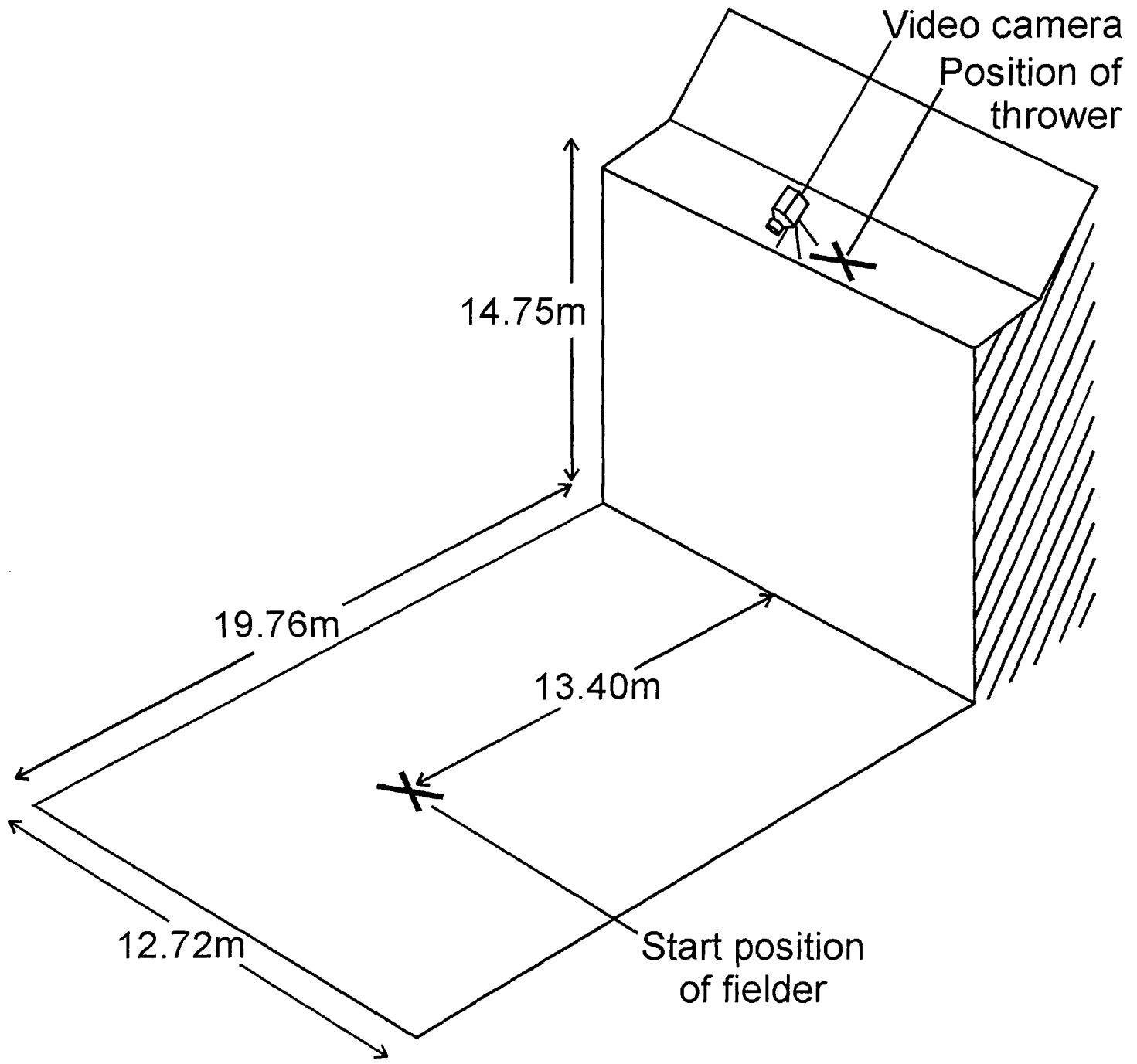
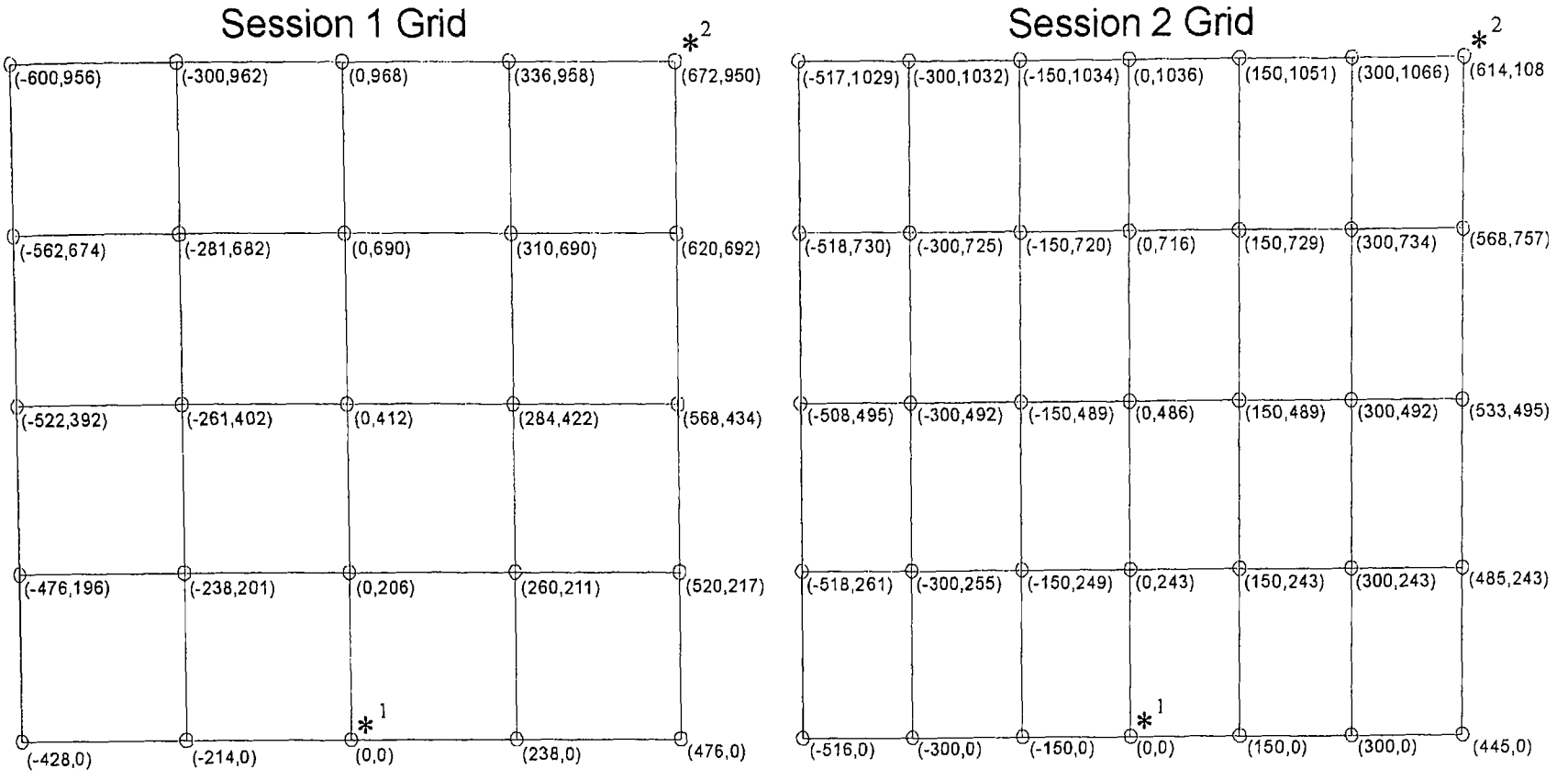


Fig. 3.1 Experimental set-up (approximate scale).

The camera shutter speed was set to its fastest possible level, which was $1/500^{th}$ of a second, to minimise blur of the ball and fielder on the video footage. The field of view of the camera approximates the fielding 'envelope' of the catcher, i.e. the maximum distance which a fielder could run to intercept a ball launched from the thrower's position.

3.2.3.2. Recording of fielder movement

The computer program 'Vidi-Clik' was used to record the position of fielder and ball within the field of view of the camera. Vidi-Clik allows video footage to be played through a computer and maps the monitor screen relative to two user-defined reference points. Any point on the screen then has a co-ordinate defined by Vidi-Clik. However, the co-ordinates specified by Vidi-Clik do not accurately represent true positions in the space shown in the video footage. Equations were created that produced an estimate of the true position of any Vidi-Clik co-ordinate. To calibrate the equations, the Vidi-Clik co-ordinates of known positions were required. The positions of tennis balls arranged in a grid within the field of view of the camera were measured and recorded. In the first session of the experiment the grid was a 5×5 arrangement of balls. To improve the resolution of the grid, in the second session the balls were arranged in a 5×7 grid. The position of each ball in the grid was measured relative to the position of the video camera. These true positions were compared with the Vidi-Clik positions of the head of an experimenter, stood at each ball. The co-ordinates of the experimenter's head, stood at the bottom-centre and top right tennis balls of the grid were used as the reference points for Vidi-Clik. Figure 3.2 shows the layout of the grids used for each session. Analysing fielders' movements using such a grid allowed independent analysis of position and motion in X and Y-axes.



*[1] First reference point for Sigma-Plot
*[2] Second reference point for Sigma-Plot

Fig. 3.2 Layout and the measured, true positions of the ball grids in sessions 1 and 2. The bracketed values next to each node show the relative position of each ball (in centimetres) to the first reference ball at the bottom-centre of the grid.

3.2.3.3. Equations for conversion of Vidi-Clik co-ordinates to true co-ordinates

Using the computer package, SigmaPlot, equations were generated to convert Vidi-Clik co-ordinates into true positions. The equations compensates for the grid distortion caused by the camera being at an angle relative to the catching area and for distortions due to the camera lens itself. Separate equations were required for x and y co-ordinates. See appendix A1 for full details of the origin, format, and accuracy of the equations used.

3.2.3.4. Format of the catching trials

Subjects each participated in around 50 trials. A trial consisted of a ball being launched by the thrower to land within field of view of the camera and the subject setting off from the start position in an attempt to catch it. A second experimenter,

positioned next to the video camera swept his hand in front of the lens to coincide with the release of the ball so that for an instant, his hand appears on the tape in synchrony with its release. This marked the start of a trial for analysis. Admittedly, this technique of recording trial onset was a somewhat crude affair. However, more precise methods were developed in later experiments and checks of internal consistency across techniques showed that timing inaccuracies introduced by the simpler technique were not severe (see chapter 4 and appendix A1).

Ball trajectory was essentially random, with the constraint that the ball had to land within the catching area. A small initial upward vertical velocity could be applied to the ball if it was intended to land in the extreme corners of the catching area to give subjects more time to reach the interception point. If the fielder managed to get their hand to the ball before it landed, the trial was considered valid. If the catch wasn't made, but the fielder got their hand to the ball, this was considered a failure of the mechanisms controlling grasp that govern the final moments before contact with the ball (see Peper, Bootsma, Mestre, & Bakker (1994)). The trial was still considered valid because the fielder moved successfully to the intercept point. If the fielder did not reach the ball before it landed then the trial was considered invalid.

To aid the timing of ball launch, the launch location is relatively unconventional in relation to the experience that the subjects have had in the normal course of participating in ball sports. Given their naivety to this trajectory type, the subjects might choose a different method for running to the interception point. However, the flight path of the balls in the experiment can be thought of as an abbreviated version of a trajectory launched from ground level, where the subject has not seen the initial portion. Subjects did not report finding the task especially difficult and there was no

reason to believe that they deviated from their usual interception strategy when running to catch this type of trajectory.

3.2.4. Movement analysis

3.2.4.1. Basis of video analysis

The video footage of subjects' attempts to intercept each ball was analysed using the Vidi-Clik computer program. This entailed first, calibrating Vidi-Clik using the reference points, then advancing through every frame of each valid trial clicking the cursor on the head of the fielder. Vidi-Clik records this information as a series of co-ordinates. The position of the ball in the final frame of the trial was also recorded. The co-ordinate data provided by Vidi-Clik was converted to true positions using the equation generated using SigmaPlot, so that for each frame the position of the catcher is known. A VisualBasic computer program was written to calculate the position of the ball for each video frame of its flight. The program was based on the equations and physical constants used by Brancazio (1985) in his paper examining the physics of catching and projectile motion. See appendix A3.1 for details of the program.

3.2.4.2. Factors affecting simulated ball trajectories

There are five factors that must be taken into consideration in simulating the trajectory of each trial.

- Firstly, the program used the number of frames each trial took, from the sweep of the hand in front of the camera until the ball makes contact with the fielder's hand. The camera runs at 25 frames per second so each frame is 0.04 seconds apart. Hence, a simple calculation allows the duration of the flight to be estimated.
- The initial ball position was required. This meant using the position of the release point of the ball relative to the grid which had been set up to estimate the fielder's

position. The release point was 940cm directly in front of the (0,0) ball and 1475cm above the ground. The final position of the ball in each trial was also required. This was relatively easy to obtain using its Vidi-Clik position and the conversion equations.

- A slight adjustment was included in the program to shift the position of the ball compensating for the fact that the ball wasn't always caught at eye level. The grid on Vidi-Clik and the conversion equations gave the true position of anywhere on screen at eye level. However the scene is being viewed from an angle and not directly above, when the ball is not at eye level the conversion equations will not give an accurate estimate of ball position. This was fixed using an estimate of the ball's height in the final frame of the trial and some simple trigonometry.
- Chapman (1968) reported a mathematical proof that a ball projected toward a fielder in the plane of projection would be intercepted if the fielder moved to maintain constant $d(\tan \alpha)/dt$. This claim was based on parabolic projectile motion, Chapman suggesting that "aerodynamic forces are relatively small and have only a small percentage effect on a trajectory". Brancazio (1985) modelled the effect of air resistance on a projectile using known physical constants and formulae to test Chapman's assertion. Brancazio estimated that, at ball velocities typical of baseball, air resistance could cause the distance achieved by a projectile to be reduced by as much as 40%. It was therefore vital that this be included in the trajectory simulation for this experiment. Although Brancazio's calculations relate to a baseball, most of the formulae and constants remain valid for this experiment. Brancazio used imperial measures throughout so conversion of the constants to their metric equivalents was required. The forces acting on a ball in flight are shown in figure 3.3.

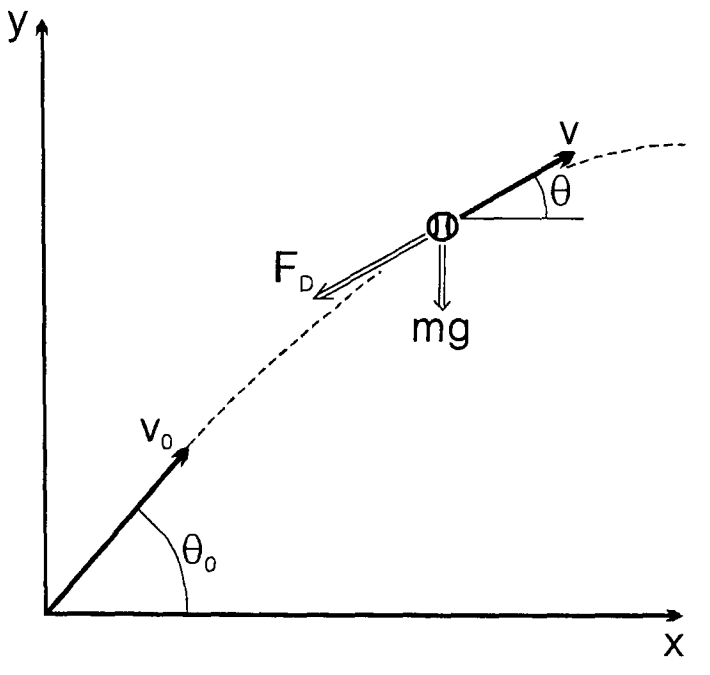


Fig. 3.3 The forces on a ball launched from (0, 0) with velocity, v_0 (reproduced from Brancazio (1985)).

The aerodynamic force, F_D, on a sphere under the conditions of projectile motion as found in this experiment is given by the equation

$$F_D = \frac{1}{2}\rho A C_D v^2,$$

where ρ is the air density, A is the cross-sectional area of the sphere, C_D is the drag coefficient and v is the speed.

The force experienced by the projectile in each dimension can be written as follows:

$$m\ddot{x} = -F_D \cos\theta = -F_D (v_x / v),$$
$$m\ddot{y} = -F_D \sin\theta - mg = -F_D (v_y / v) - mg,$$

where v_x is the horizontal component and v_y is the vertical component of the ball's velocity, v, at any given instant. It is assumed that the spin on the ball in flight is insufficient to generate significant lift through the Magnus effect. Combining the equation for the drag force, F_D, with the equations of motion:

$$\ddot{x} = -Kvv_x, \qquad \ddot{y} = -kvv_y - g,$$

where $K = \rho A C_D/2m = 7 \times 10^{-5}\text{cm}^{-1}$.

This value of K is adapted from Brancazio's value (which was $1.6 \times 10^{-3}\text{ft}^{-1}$) incorporating the lower mass of a tennis ball compared to a baseball and conversion to metric units. It is not possible to solve these equations analytically but it is possible to approximate their solution by integrating over small increments, using the third order derivative:

$$\Delta x = v_x \Delta t + \frac{1}{2}\ddot{x}(\Delta t)^2 + \frac{1}{6}\dddot{x}(\Delta t)^3,$$

$$\Delta y = v_y \Delta t + \frac{1}{2}\ddot{y}(\Delta t)^2 + \frac{1}{6}\dddot{y}(\Delta t)3,$$

where

$$\dddot{x} = -K(\dot{v}v_x + v\ddot{x}), \qquad \dddot{y} = -K(\dot{v}v_y + v\ddot{y}),$$

$$\dot{v} = (v_x\ddot{x} + v_y\ddot{y})/v$$

The equations for Δx and Δy give the change in position of the ball over each time increment.

New values of v_x and v_y can then be calculated using

$$\Delta v_x = \ddot{x}\Delta t + \frac{1}{2}\dddot{x}(\Delta t)^2, \qquad \Delta v_y = \ddot{y}\Delta t + \frac{1}{2}\dddot{y}(\Delta t)^2.$$

Tresilian (1995) also used this technique for trajectory estimation.

- The gravitational constant, g, was estimated as 981cms^{-2}.

3.2.4.3. Procession of the program

Given these factors, the program engages an iterative process, varying launch angle and launch velocity, to find the parameters that minimised error between the endpoint of this simulated trajectory and the known final ball position. The program is shown in appendix A3.1.

3.3. Results

The 6 subjects received a total of 281 trials. Of these, 165 (59%) were valid.

3.3.1. Performance of trajectory estimation program

The trajectory estimation program produced trajectories that obeyed the factors described in 3.2.4.2 and gave a prediction about the position of the ball in each frame of each trial. The only times at which an estimate of the position of the ball was available was in the first frame (the launch position) and the final frame, when its position could be recorded using Vidi-Clik. The duration of the flight and these two positions were used to calculate a best-fit trajectory. The data below summarises the difference between the position of the ball in the final frame using the trajectory estimation program and the estimate of its true position using Vidi-Clik.

N = 165

Minimum error = 0.18cm

Maximum error = 6.99cm

Mean error = 2.06cm

SD = 1.22

See appendix A1 for further error considerations.

3.3.2. Curvature of running paths

McBeath, Shaffer, & Kaiser (1995) studied fielders running forwards to catch baseballs. They observed running paths that showed slight concavity relative to the origin of the ball. Figure 3.4 shows that for the example trials shown, running paths were also concave relative to the origin of the ball when the fielder ran forward, matching the results of McBeath, Shaffer & Kaiser (1995). The examples also illustrate the convex running paths observed when the fielder ran backwards.

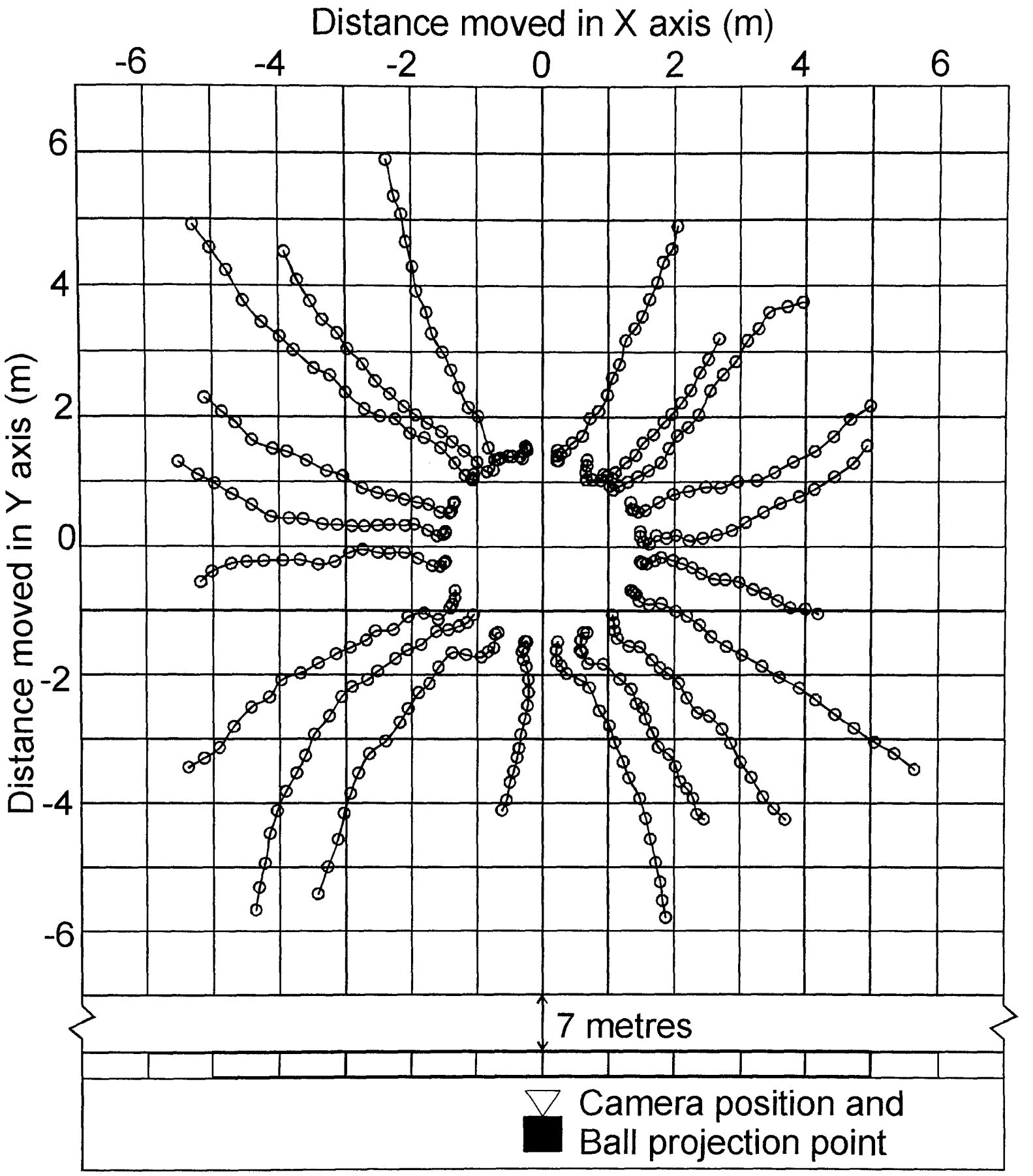


Fig. 3.4 A plan view of 20 examples of the interception paths followed by subjects in the experiment. The fielders' start positions for each of the trials have been displaced from the actual start position (which was common to all trials) for ease of viewing.

To investigate this phenomenon more thoroughly, a regression technique was used to assess the curvature of running paths. Fielders' X-Y positional data was cropped before the analysis took place. Data from the first ten frames of every trial was removed so that fielders' initial reflexive movements did not contaminate the

regression. Linear and quadratic regression lines were computed for the selected X-Y positional data in each trial. Although the quadratic fit will always explain more of the variance, an F-test determines whether the improvement in fit is significant. If the improvement in fit to the running path was not significant using the quadratic model then the linear fit was considered the most appropriate. This suggests that the running path was straight. If the improvement in fit was significant, the sign of the parameter of the squared component indicates the direction of curvature of the model. A positive component means the model curves up and predicts that the running path is convex relative to the origin of the trajectory. A negative component means the model curves down indicating a concave running path. An example of this regression analysis is shown in appendix A3.2 and the results are summarised in Table 3.1.

		Running path (relative to wall)			
		Concave	Straight	Convex	Total
Fielder moved	Forward	76	17	4	97
	Backward	1	9	58	68
	Total	77	26	62	165

Table 3.1.

This pattern of results is consistent with an interception strategy where lateral motion (movement in the X-axis) occurs before depth motion (movement in the Y-axis). The r^2 values for both the linear and quadratic were reasonably high. They are summarised in Table 3.2.

Fielder ran	Model	N	Mean	Minimum	Maximum	SD
Forward	r^2 (linear)	80	.94	.10	.99	.12
	r^2 (quadratic)	80	.98	.52	1.00	.066
Backward	r^2 (linear)	59	.89	.29	.99	.15
	r^2 (quadratic)	59	.97	.84	1.00	.034

Table 3.2.

To further evaluate how the curvature of fielders running paths is generated, relative movement in the X and Y-axes was investigated. A two-tailed t-test was conducted on fielders' time to attain a criterion velocity in the correct direction for movement in each axis. The chosen criterion velocity was 50cm/s. The t-test reveals a significant difference in the time fielders take to reach the criterion velocity in each direction. For the 165 trials, the mean time to attain the criterion velocity in X was 0.22seconds. In Y, the mean time to attain the criterion velocity was 0.44seconds[1]. The large number of trials resulted in a highly significant result ($t = -20.82$, $df = 164$, $p < 0.001$). Further confirmation of this result is the finding that fielders reached the criterion velocity in X prior to reaching it in the Y direction in 161 out of the 165 trials. This suggests a simple explanation as to why the running paths are curved in the nature observed – some distance is covered in the X direction before movement has begun in the Y direction. The outcome being concave paths when running forward and convex paths when running backward.

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[1] These values for fielder response time seem remarkably low, demonstrating the problems of recording the start of a trial accurately. However, since timing is consistent from trial to trial and it is the comparison of response times that is of interest, the analysis is not invalidated.

3.3.3. Changes in tan α and tan β over time

In order to produce a LOT, tan α must change in proportion to tan β over time. Multiple regression was used to investigate changes in tan α and tan β over time using a similar method as used to investigate curvature of running paths. Linear and quadratic models were fitted to plots of tan α against time and tan β against time. The data was analysed up to the point 200msec before the catch was made to ensure that variation in the visual angles was not corrupted by dramatic changes experienced as the ball is caught. F-tests were again used to determine whether the improvement in fit gained by adding a squared term to the regression model was significant. If the improvement in fit was not significant then the linear fit was considered the most appropriate. However, if the improvement in fit was significant, the sign of the parameter of the squared component indicates the direction of curvature of the model. A positive component means that d(tan α)/dt is increasing. A negative component means that d(tan α)/dt is decreasing. If a linear optical trajectory is to be observed, one would expect tan α and tan β against time to show the same curvature in any given trial since they should be changing in proportion to each other. Table 3.3 summarises the curvature of tan α and tan β in each trial.

		tan α vs. time			Total
		curved down	was straight	curved up	
tan β vs. time	Curved down	25	1	10	36
	was straight	7	1	0	8
	curved up	52	12	57	121
	Total	84	14	67	165

Table 3.3.

In some trials, there was a significant quadratic component to the regression of tan α vs. time for the duration of the trial. These are trials where the fielder has, by choice or by necessity, taken the catch at a non-optimal position – not at eye level in front of them. When the fielder ran forwards, the regression of tan α against time had a significant negative component in 84 trials. These are trials where the fielder has taken the catch at lower than eye level and might be expected of trials where a fielder is struggling to reach a catch ahead of them. Of these 84 trials, tan β had a significant negative quadratic component in 25 trials, a significant positive quadratic component in 52 trials, and no significant quadratic component in 7 trials. When the fielder ran back, there was a significant positive quadratic component to tan α vs. time in 67 trials. These are trial where the fielder has taken the catch above eye level and might be expected of trials where a fielder is struggling to reach a ball that will land behind them. Of these 67 trials, there was a significant positive quadratic component to tan β vs. time in 57 trials and a significant negative quadratic component in 10 trials. In the remaining 14 trials, the regression of tan α vs. time showed no significant improvement using a quadratic regression model, i.e. it increased linearly. Of these 14 trials, tan β vs. time showed a significant negative quadratic component in 1 trial, showed a positive quadratic component in 12 trials had no significant quadratic component in 1 trial.

In total, the curvature of tan α matches that of tan β (and is therefore compatible with the LOT model) in 83 of 165 trials – only half of all trials. It appears that fielders are not necessarily running so that they experience proportional changes in tan α and tan β as McBeath, Shaffer, & Kaiser would predict. Tan β vs. time curves upwards 121 times out of 165 trials, whereas tan α vs. time only curves up 67 times out of 165

trials. Tan β vs. time is tending to curve up, regardless of the variation in tan α vs. time.

3.3.4. Using tan α vs. tan β as a cue to motion in depth

The current claim by McBeath et al. is that a fielder attempts to maintain a LOT in running to catch the ball. Curvature of the OT therefore provides the signal to move so that the curvature can be corrected. The optic trajectory is defined by the ratio of tan α to tan β, therefore tan α vs. tan β should consistently curve one way when the fielder should run forwards and curve the other way to indicate that the fielder should move backwards. A multiple regression technique similar to that described above was used to investigate the curvature of tan α vs. tan β up to the point at which the fielder had begun to move in the correct direction in the Y-axis to intercept the ball. For the purposes of analysis, a fielder was said to have begun correct depth movement when he had attained a velocity of greater than 50cm/s in the appropriate direction. Only trials that showed significant curvature in tan α vs. tan β up to that point were examined. McBeath, Shaffer, & Kaiser (1995) claim that if a fielder must run forwards to reach the interception point then he shall experience an optic trajectory that curves down, providing a cue for the fielder to take the appropriate action to move toward the interception point. Conversely, if a fielder has to run backwards, the optic trajectory should curve upwards, indicating the required action.

The performance of tan α vs. tan β in predicting fielder depth motion was assessed in relation to that of tan α vs. time as a comparison of the predictions made by the LOT and OAC models respectively. When looking at tan α vs. time, as before, only trials that showed significant curvature of tan α vs. time up to correct movement in Y were used. The OAC model predicts that upward curvature of tan α vs. time will

cue the fielder to move backwards, whilst downward curvature of tan α vs. time will cue the fielder to move forwards.

To ensure that this comparison was as fair as possible, a random sample of trials of equal size was taken from each of the four subsets of trials (tan α vs. tan β: running forward, running back; tan α vs. time; running forward, running back). Table 3.4 shows the curvature of tan α vs. tan β for the sample of trials.

		tan α vs. tan β curvature		Total
		Down	Up	
Fielder ran	Forward	44	0	44
	Backward	37	7	44
	Total	81	7	88

Table 3.4.

The curvature of tan α vs. tan β correctly cues the fielder to run forward in all of the sample 44 trials where that was the correct course of action. However, in the sample of 44 trials where the fielder was required to run backwards, the curvature of tan α vs. tan β only acts as a valid cue in 7 trials. Overall, tan α vs. tan β accurately cues the correct motion of the fielder 51 times out of 88 trials. This is not significantly better than chance ($\chi^2(1) = 2.23$, $p > 0.1$). Table 3.5 shows the curvature of tan α vs. time for a similar sample of trials.

		tan α vs. time curvature		Total
		Down	Up	
Fielder ran	Forwards	40	4	44
	Backwards	3	41	44
	Total	43	45	88

Table 3.5.

Tan α vs. time accurately predicts fielder motion in 81 of the 88 trials. This is significantly better than chance ($\chi^2(1) = 62.2$, $p < 0.001$).

Tan α vs. tan β tends to curve downwards regardless of the trajectory of the ball. It is not predictive of the fielder's movement. Tan α vs. time is more consistent in predicting which way the fielder should move and for this reason should be considered a more valid cue to motion in depth. Examining tan α vs. time in all trials with significant curvature, it was found to be an invalid cue in 9 trials out of 127. One of these trials was for a ball landing short of the fielder's start position. Tan α vs. time should cue the fielder to run forwards but the relation was in fact cueing the fielder to run backwards. However, this was the correct course of action because the fielder had made an initial movement that took him beyond the interception point of the ball. Therefore, moving backwards (as cued to do by tan α vs. time) was the correct strategy. In the other eight trials where tan α vs. time was an invalid cue as to the direction of motion in depth, the fielder did not make a movement reversal.

3.3.5. Movement reversals

A movement reversal is when the fielder changes velocity in the opposite direction to that which would be expected. Two types of reversal are defined using the following criteria:

A reversal:

The fielder reaches >50cm/s in the wrong direction. For example, in a trial where the fielder had to move left, the fielder reached >50cm/s moving to the right in the X-axis.

A hesitation:

The fielder begins moving in the right direction but loses velocity by >50cm/s before continuing to run in the correct direction.

Graphs showing the fielders' velocity in the X-axis and velocity in the Y-axis were used to assess whether reversals or hesitations had been made in each of the trials. Table 3.6 shows the distribution of these events.

	Movement in X-axis	Movement in Y-axis	Total
Reversals	6	66	72
Hesitations	1	69	70
Non-reversals	158	30	188
Total	165	165	330

Table 3.6.

Reversals and hesitations are rare for motion in the X-axis but frequent for motion in the Y-axis. Figure 3.5 depicts the mean velocity of fielders in the Y-axis revealing the tendency for fielders to make apparently erroneous movements in the Y-axis.

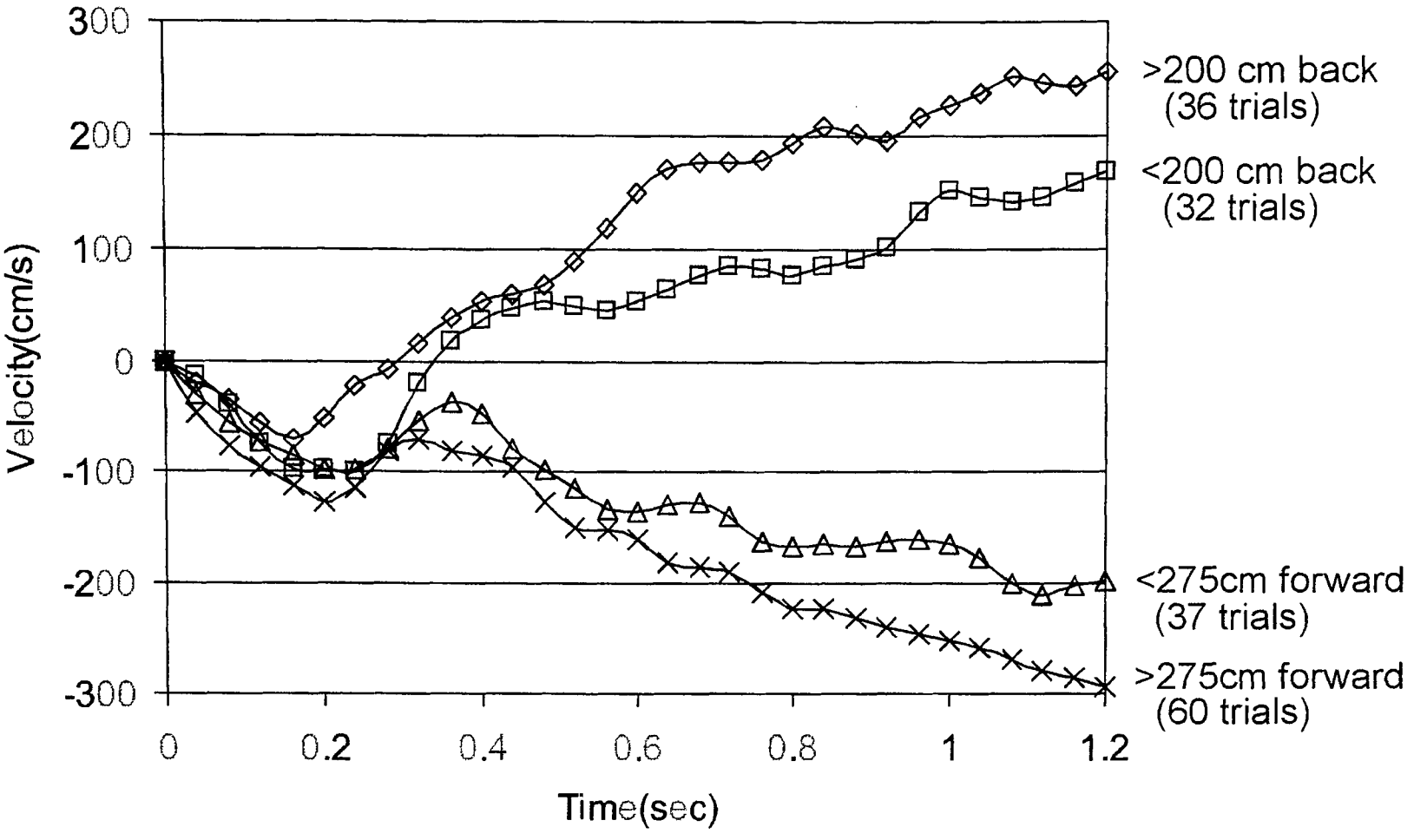


Fig. 3.5 Mean velocities of fielders over time separated by the distance they had to run in the Y-axis to reach the interception point.

The early portion of the fielder's movements illustrates the movement reversals. In each type of trial, the fielder begins by accelerating forwards to around 100cm/s. Trials where the fielder should run backwards require a reversal of motion. For trials where the fielder should run forwards, there is a period of deceleration before the fielder continues accelerating forward. It seems counter-intuitive that a fielder moving in the apparently correct direction should make a hesitation, decreasing their correct forward velocity.

Earlier it was stated that the fielder did not make either type of reversal in the 8 trials in which tan α vs. time presented an invalid cue. It therefore seems feasible that the initial movements made by the fielder, causing hesitations and reversals, are somehow vital in modifying the way tan α changes over time and that this modification leads to tan α vs. time providing a valid cue to interception. That there

are considerably more reversals in Y than in X fits with the hypothesis that the decision a fielder makes about the direction of depth movement is more complex than the lateral movement decision. Figure 3.6 also contradicts the assertion made by McBeath, Shaffer & Kaiser (1995) that fielders follow ∩-shaped running paths. Whilst, it is true that in some trials fielders decelerated as they neared the interception point, it was not a consistent characteristic of their movement.

3.3.6. Using tan α vs. tan β as a cue to lateral movement

Once again, a multiple regression method was used to examine the extent and type of curvature of tan α vs. tan β. All trials that showed significant curvature of the regression models of tan α vs. tan β up to the time at which the fielder reached criterion velocity in the X-axis were examined to see whether curvature of the optic trajectory changed depending on the correct lateral movement.

		tan α vs. tan β curvature		Total
		Down	Up	
Fielder ran	left	16	2	18
	right	21	1	22
	Total	37	3	40

Table 3.7.

Once again, tan α vs. tan β is always tending to curve down and is not predicting which way the fielder should move. There appears to be a consistent trend for the ratio of the visual angle tangents to show downward curvature.

3.4. An alternative strategy

A major difference between the experiments conducted by McBeath, Shaffer, & Kaiser (1995) and that presented here is the distance of the ball launch site from the start position of the fielder. McBeath et al.'s fielders began 50m from the launch site whereas fielders in this experiment were only about 15m from the launch position. This offers a possible explanation of why tan β has failed to change in proportion to tan α for fielders' movements in the present experiment. Fielders' lateral movements in McBeath's experiments (typically less than 10m) will have little impact on tan β because of the distance between the fielder and the 'home plate'. Lateral movements by fielders in the present experiment will have a greater effect on tan β and this is possibly why it fails to vary in proportion to tan α. Given this reasoning and the failure of the LOT model to satisfactorily predict interceptive behaviour, there appears scope for the proposal of an alternative model that isolates the lateral visual angle from reference to the launch site of the ball.

3.4.1. Constant lateral angle strategy

Chapman (1968) first suggested this strategy, proposing that a fielder wanting to intercept a projectile launched in an unaligned plane might move laterally so that the ball is kept at a constant bearing whilst also moving to cancel $d^2(\tan \alpha)/dt^2$. Dienes & McLeod (1993) also hypothesised that the fielder might control lateral motion in this way, but neither study conducted any analyses of this model of interception. Tresilian (1995) suggested the addition of a second control variable working in conjunction with cancellation of $d^2(\tan \alpha)/dt^2$ but failed to find an appropriate model. The constant lateral angle strategy is an attempt at finding a

suitable control variable. A feature it shares with Tresilian's model is control of a horizontal visual angle relative to an arbitrary reference direction.

Figure 3.6 shows β comprised of two components. Firstly, β_1, which represents the angle through which the fielder has moved away from their initial alignment with the 'home plate' (the launch site). Secondly, β_2, which represents the angle through which the fielder has had to turn in order to maintain fixation of the ball. LOT theory suggests that the fielder will run so that tan β changes in proportion to tan α, where $\beta = \beta_1 + \beta_2$. However, following from Chapman (1968) and Dienes & McLeod (1993), a valid interception strategy could entail the fielder running laterally to preserve a constant value of β_2 whilst controlling forwards or backwards motion to maintain $d(\tan \alpha)/dt$.

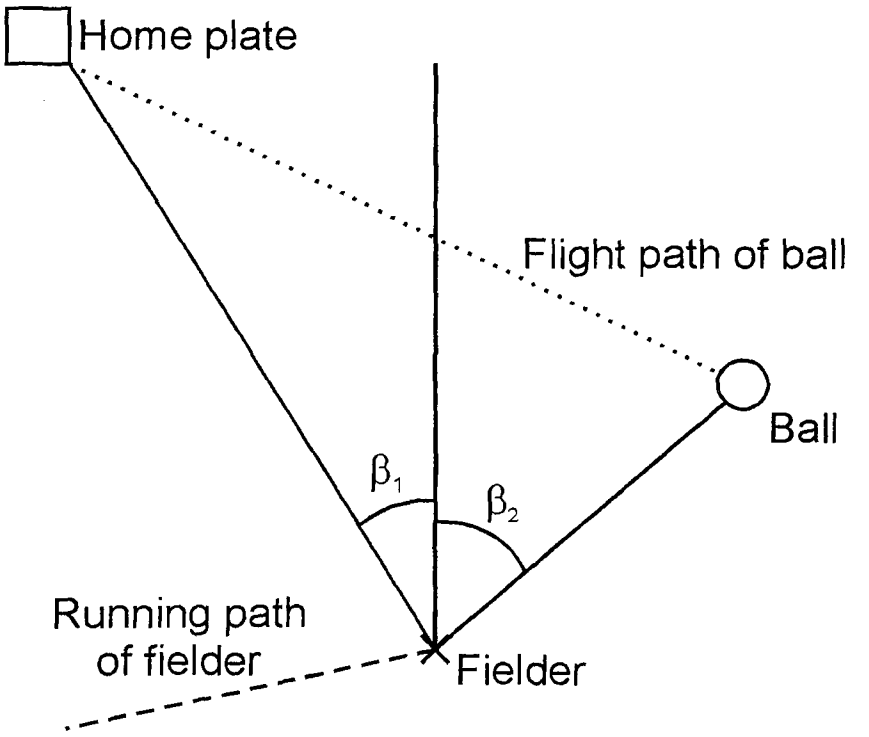


Fig. 3.6 Vertical projection onto the ground of the components of β for a fielder.

In this strategy, after a set period of time, the deviation in trajectory of the ball away from alignment with the fielder would be detected. The fielder would then move to maintain the angle β_2, which henceforth shall be referred to as δ, whilst trying to

maintain a constant rate of change of tan α. Maintaining constant δ is not a sufficient strategy for interception (as maintaining constant $d(\tan \alpha)/dt$ is) but it takes the fielder on a running path that gives him a good opportunity to cancel $d^2(\tan \alpha)/dt^2$ and thereby guarantee interception. Also, if the cue provided by δ were acquired prior to that provided by $d^2(\tan \alpha)/dt^2$, the observed pattern of curvature of running paths would result. For example, a ball is launched that would land in front and to the right of a fielder. First, the ball's movement to the right would generate an angle δ. The fielder would detect this cue and would accelerate right attempting to hold δ constant. Once it had been ascertained that $d(\tan \alpha)/dt$ was decreasing, acceleration would begin forwards as the fielder attempts to halt this decrease. Acceleration forwards would impinge on the fielder's motion to the right and a concave running path would result. It therefore seems valid to examine a strategy that can utilise this result.

3.4.2. Assessment of the constant δ and LOT strategies

3.4.2.1. Simulation of the two models

In order to test whether the constant δ strategy was legitimate, a computer program was written that could use data already gathered on ball trajectory and implement such a strategy based on the relevant cues. For the constant δ strategy, these are δ and $\tan \alpha$. The simulated running paths generated by the hypothesised strategy could then be compared to the actual running paths used by real fielders to the same trajectories. Included in the program for comparison purposes, was the LOT model. It was therefore possible to investigate which strategy provided the most valid model of human interceptive behaviour.

3.4.2.2. Movement of the simulated fielder

The simulated 'fielder' is represented by an X-Y co-ordinate position calculated by the computer program. Various constraints needed to be applied to the movement of the simulated fielder to ensure that it modelled human behaviour with reasonable authenticity. There was a consistent tendency for fielders to make initial steps forward, almost immediately after release of the ball. This was modelled by making the simulated fielder move forward a short distance in each 0.04second time increment, until the interception strategies were engaged. Suitable maximum running speed and maximum acceleration levels were applied. These were found by examining graphs of speed against time for the real fielder. The maximum running speed permitted was $4ms^{-1}$, whilst the maximum acceleration was set at $1ms^{-2}$. Should the interception strategy attempt to send the simulated fielder to a position that exceeds either the speed or acceleration limit then motion is restricted so that the simulated fielder is sent to the nearest position within these limitations. The constraints on motion do not reflect the absolute maximum values that a human could attain. However, the performance of the real fielder was adequate within these limits so any strategy should perform equally well under the same conditions.

The program that was eventually developed underwent much revision to include factors such as movement reversals and limits to running speed and acceleration. It is mathematically true that both strategies should result in the fielder being at the right place at the right time. However, care was taken to ensure that the simulated strategies remained true to their original principles, avoiding the circular argument that if the simulated fielder gets to the right place at the right time then the implementation of the strategy must be correct. The graphs shown in figure 3.7 show examples of the true running paths of one fielder for trials in each quadrant. The simulated running

paths, as predicted by LOT theory and the constant δ strategy, are overlaid on the true running paths. The two strategies both produce running paths that are reasonably similar to the real paths.

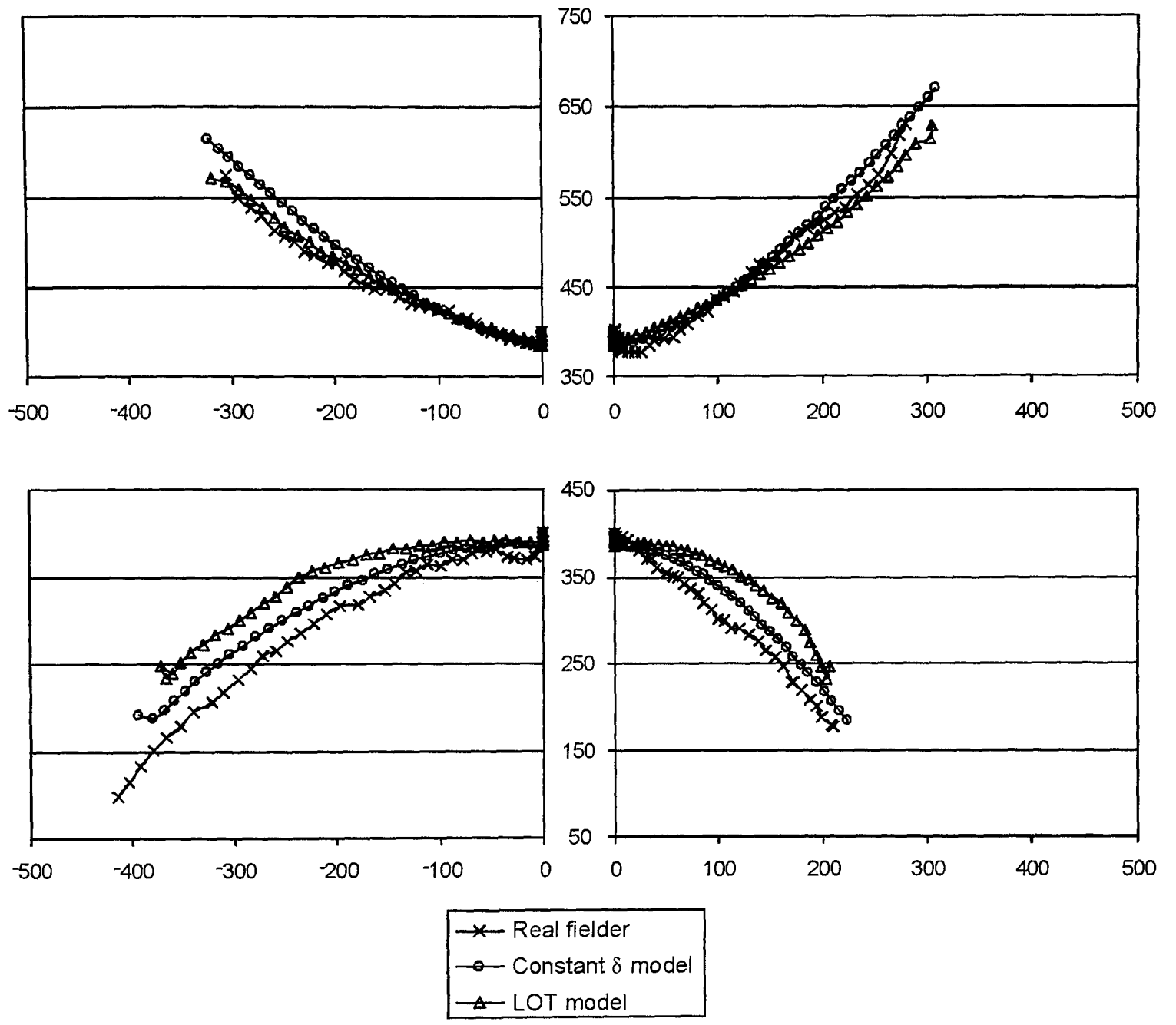


Fig. 3.7 Examples of strategy performance.

3.4.2.3. Strategy performance

The accuracy of the LOT and constant δ strategies for all trials was assessed. The computer program produces a predicted position of the fielder using the two strategies for each frame of film. The distance (in cm) of the simulated points away from the fielder's true position for the corresponding frame of film was calculated. A Wilcoxon signed ranks test was used to compare these deviations for each trial. In

104 of the 165 trials, the mean deviation was greater for the LOT strategy than the constant δ strategy. In all 104 trials, this deviation was significant. Of the remaining 51 trials, the difference between the deviations was insignificant in 10 trials and the LOT strategy produced significantly less deviation in 41 trials. The Wilcoxon tests suggest that the LOT model of interception can be improved upon.

Further insight into the performance and validity of the two models was obtained by investigating how various parameters for the simulated running paths change over time and how this compares with the real running paths. Perhaps the most important test was to see whether δ really does remain constant. The example graphs in appendix 3.4 demonstrate both strategies perform remarkably well in achieving an accurate change in tan α. Maintaining a constant increase in tan α is an efficient method for achieving interception so this was expected. Less impressive was the performance of the models in modelling δ. In some cases, the fielder allows δ to increase. These are where the fielder has by choice or by necessity taken the catch to further to their side. There are also cases in which δ at first increases then decreases to 0. These are where fielder has moved to achieve alignment with the ball and then maintained alignment until the catch was taken. Although there are some trials in which the LOT and constant δ strategies appear suitable, it is clear that neither represents the true strategy applied by fielders to achieve the correct lateral position when intercepting a projectile. Although the constant δ strategy surpasses the performance of the LOT model in terms of its discrepancy from the true position of the fielder, when it is assessed by other measures it appears no closer to the true strategy.

3.4.3. Further ideas for interception strategies

The fact that there is a steady increase in tan α seems without question. LOT theory suggested this is an indirect result of maintaining the LOT, whereas it is computed directly in the constant δ strategy. To maintain a constant increase in α throughout the flight of the ball, the fielder must get closer to the ball in X as well as Y. If $d(\tan \alpha)/dt$ is to be held constant then for each successive time increment of dt the fielder is required to move to a point at which tan α has increased by $d(\tan \alpha)$. The result is that a ring of points exists around the X-Y position of the ball for which the correct tan α will be true. The correct tan α is obtained from the ratio of the relative height of the ball above the fielder's eye to a specific radius of this ring. To discover how fielders truly achieve interception it is vital to know on which point of the ring the fielder moves to at each time point. This is investigated in chapter 6.

3.5. Discussion

3.5.1. Running paths

The results of this experiment confirm McBeath et al.'s observation of curved running paths. Fielders tended to follow running paths which (relative to the origin of the ball) were convex if moving backward to catch, concave if moving forward. This was validated using a t-test that compared fielders' times to criterion velocity in the each axis. However, curved running paths do not provide evidence in favour of a LOT strategy of interception. Any strategy that instigates motion in X before that in Y will produce running paths that curve in the manner observed. McBeath et al. cited curved running paths as support for the LOT model over those based on OAC (e.g. Chapman (1968), McLeod & Dienes (1996)), which they believe predict straight running paths. However, straight running paths are only predicted if one presumes that cues for

motion in X and Y are utilised at precisely the same time. This has never been a claim of such models. In fact, it follows quite naturally in OAC models that lateral motion cues should be exploited earlier than those to depth motion. Computation of tan α acceleration must occur before a decision about Y-axis motion can begin. The lateral motion decision is based simply on the direction (left/right) that the fielder has had to rotate their gaze in order to fixate the ball. It follows that the LOT strategy makes a similar prediction about the utility of lateral and depth cues (although this was not specified in the McBeath et al. paper). For a ball launched in a non-aligned vertical plane relative to the fielder, the optic trajectory of the ball will set off either left or right. It is highly probable that this cue can be detected and utilised before the appropriate Y-axis motion can be determined using curvature of the optic trajectory. Control of optic trajectory would proceed once the appropriate depth motion decision had been made. Figure 3.6 showed that fielders do not always run with $\cap$-shaped speed functions. McBeath, Shaffer, & Kaiser (1995) suggested that fielders typically run in such a manner when running to intercept a projectile and that the LOT strategy predicts this behaviour. However, fielders in this experiment did not exhibit such behaviour.

3.5.2. Variation in angles over time

The LOT model relies on fielders controlling Ψ such that tan α and tan β remain proportionate. Analyses of the variation in tan α and tan β over time suggest that if these parameters are being controlled, it is not in the way proposed by McBeath et al. Tan α increased in every trial but tan β changes in different ways for different catches. Firstly, regressions of tan α vs. time and tan β vs. time showed that the regression on tan β tended to have a positive component. This tendency was not

observed for regressions of tan α on time. In fact, the curvature of the tangents only matched in around half of the trials. Secondly, the efficacy of tan α vs. tan β and tan α vs. time in signalling the appropriate depth motion cue was investigated by examining the curvature of their regressions up to the point where the fielder had reached the criterion velocity in the Y-axis. In a matched sample of trials, the accuracy of curvature of tan α vs. tan β as a cue to depth movement was not significantly better than chance. However, tan α vs. time was a highly accurate cue to the correct depth movement. Use of tan α vs. tan β appears an inefficient method of signalling the appropriate depth motion. Given the significance of the outcome – achieving (or avoiding) collision with a projectile, it seems unlikely that such an aberrant cue would be exploited. By the same token, tan α vs. time was not a perfect cue to motion in depth. There were nine trials in which curvature of tan α vs. time provided an invalid cue to depth movement. What was special about the nine trials where tan α vs. time signalled the incorrect action? In one of the nine, the trajectory of the ball was such that it would land in front of the fielder's start position yet tan α vs. time curved upwards, signalling that the fielder should move backwards. In this particular case, the fielder made an initial movement forwards which took him beyond his final ball intercept point. Therefore, the correct course of action from then on was to move backwards. Although this was a trial where the fielder had to move forwards from the start position to intercept the ball, tan α vs. time cued the correct action given the special circumstances involved. In the remaining eight trials where tan α vs. time was an invalid cue the fielders did not make a movement reversal (defined in section 3.3.5.). Although not always necessary, it appears that a small

initial movement (not necessarily in the appropriate direction to achieve interception) can validate tan α vs. time as a cue to depth motion.

The power of tan α vs. tan β as a cue to lateral motion was investigated by examining trials that showed significant curvature in the regression on tan α vs. tan β up to movement in X. Of the 165 trials there were 40 trials where this was true. It was found that the significant curvature tended to be downwards, irrespective of whether the fielder had to move left or right. This suggests that the curvature of the optic trajectory itself does not act as the initial cue to lateral motion. The cue to lateral motion must first come from the quadrant in which the optic trajectory sets off. Presumably this can be utilised prior to curvature of the optic trajectory as a cue to motion and lateral motion can begin prior to depth motion. The consequence of this is running paths that curve in the manner observed, not due to the fielder controlling the optic trajectory of the ball but merely because the lateral motion cue is available prior to that for motion in depth.

3.5.3. Rival strategies

The constant δ strategy was proposed. It was found to fit the true running paths of the fielders better than the LOT strategy. However, neither strategy suitably modelled how the vertical and lateral optical angles changed over time. Whilst this suggests that the LOT model is an insufficient account of human interceptive performance, the rather negative conclusion to this chapter is that a full description of how human fielders achieve interception in two dimensions remains elusive. It seems without question that whatever strategy is being used, the fielder moves such that $d(\tan \alpha)/dt$ is constant and any proposed strategy must incorporate this fact. As was suggested in 3.4.3, to find the true strategy that fielders obey, it is critical to find the

position on the loci of points that give the appropriate tan α that a real fielder moves to in when running to catch a ball.

4. Further investigation into interception in two dimensions

This experiment used a similar protocol to that in chapter 3 with some important differences. Balls were no longer launched by hand from a position adjacent to the camera on top of the building (see figure 3.2). A ball-firing machine (normally used for tennis practice) was used to launch tennis balls on a consistent trajectory. This was positioned at ground level so trajectories were more familiar to subjects. However, a steep launch angle was used so that large values of α were obtained. These conditions, like in chapter 3, allowed investigation of interception strategy in an area of α/β space not usually covered by studies of interception (e.g. McLeod & Dienes (1996), McBeath, Shaffer & Kaiser (1995)). Secondly, in chapter 3, the fielder started each trial from the same central position and the balls were launched to the extremes of the catching area. This required accuracy from the thrower – throw the ball in the wrong place and the fielder would either take the catch beyond the view of the camera or would have to move so little that movement analysis was trivial. In this experiment, the fielder began each trial from one of four different start positions, situated at the edges of the catching area. The ball was then launched to the same central position in every trial. Thirdly, an extra information source was exploited. The frame in which subjects made a symmetrical hand movement upwards in preparation to catch was recorded. It has been suggested that as a fielder nears interception with their target projectile, there is a change in their interception strategy (e.g. Babler & Dannemiller (1993), Peper, Bootsma, Mestre, & Bakker (1994)). In proceeding from their start position toward the eventual interception point, the consensus of opinion is that a fielder will follow a strategy that, if followed exhaustively, would cause their eye to intercept the ball. Clearly, fielders do not use this strategy in the final moments before catching. The emphasis of interception shifts from causing the eyes to meet the ball to causing the hand(s) to meet the ball. It was noticed in the video footage

of the fielders running to catch in chapter 3 that there was a consistent change in the motion of the arm-hand systems, approximately 500msec before the ball was caught. The usual 'pumping' action of the arms that is associated with running diminished and both hands were lifted together with palms facing upward in readiness to catch the ball[1]. This change in behaviour makes it prudent to discount the X-Y positional information collected after this point since this component of interception is not currently accounted for by any proposed strategies modelling locomotion to the interception point. Henceforth, this final period of catching shall be referred to as the fielder's *prehensive* behaviour (behaviour that results in their grasping of the ball).

4.1. Aims of the experiment

This experiment is concerned with how fielders run in two dimensions to catch projectiles launched in a non-aligned plane. McBeath, Shaffer, & Kaiser (1995) and chapter 3 of this thesis reported curvature of running paths in achieving this task. The evidence suggests that fielders utilise an interception strategy in which lateral movement begins prior to movement in depth. The result is running paths that (relative to the launch point of the ball) are concave when the fielder has to run forward and convex when the fielder has to run backward. After a few visits to each of the four start positions used in this experiment, it is possible that the fielder will acquire some sense of where the consistent interception point is located. If this happens the fielder may make the logical decision to follow the most direct and efficient route from their start position to the interception point. Consequently, the fielder may be observed running on a straight rather than curved path.

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[1] Fielders schooled in baseball may be more used to catching using a single glove or 'mitt'. They may therefore make a slightly different movement as they prepare to catch the ball. This unlikely to affect how they move from their start position to the interception point.

The change in interception strategy that occurs when fielders alter from a strategy to cause interception of their eye with the ball to a strategy that will cause interception of their hand(s) with the ball (the switch to prehensive behaviour) can be investigated. By looking at how fielders motion changes and the visual information they receive before and after this critical point it should be possible to further develop theories about interception strategy. The data collected in this experiment can also be used to confirm or reject the evidence reported in chapter 3 against LOT theory. If it is shown that, in these more familiar circumstances, fielders run to intercept the ball by maintaining a linear optic trajectory then the previous data could be regarded as a peculiarity of the conditions used. Furthermore, it is possible that in the previous experiment, subjects appeared not to obey the constraints of the LOT model because the data was contaminated by the actions of the fielder during prehensive behaviour. Consequently, fielders may show a linear optical trajectory when their motion prior to prehensive behaviour is examined. However, if the data shows that, again, subjects are not moving so that the tangents of α and β change in constant ratio then the LOT model will have to be rejected as a valid account of human interceptive performance.

4.2. Method

4.2.1. Experimental apparatus

VHS video camera, tripod, tennis balls, tape measure, 'Tennis Tutor Jr.' ball firing machine, infrared launch detector and indicator light.

4.2.2. Subjects

5 male university graduates, all experienced at ball sports.

4.2.3 Interception

4.2.3.1. Experimental set-up

The experiment was set up as shown in figure 4.1. The VHS-C video camera was situated atop a three-storey building at a height of 14.75m and angled down to view the area in which trials were run. The ball launch apparatus was sited 5.90m in front of the building in line with the camera at ground level.

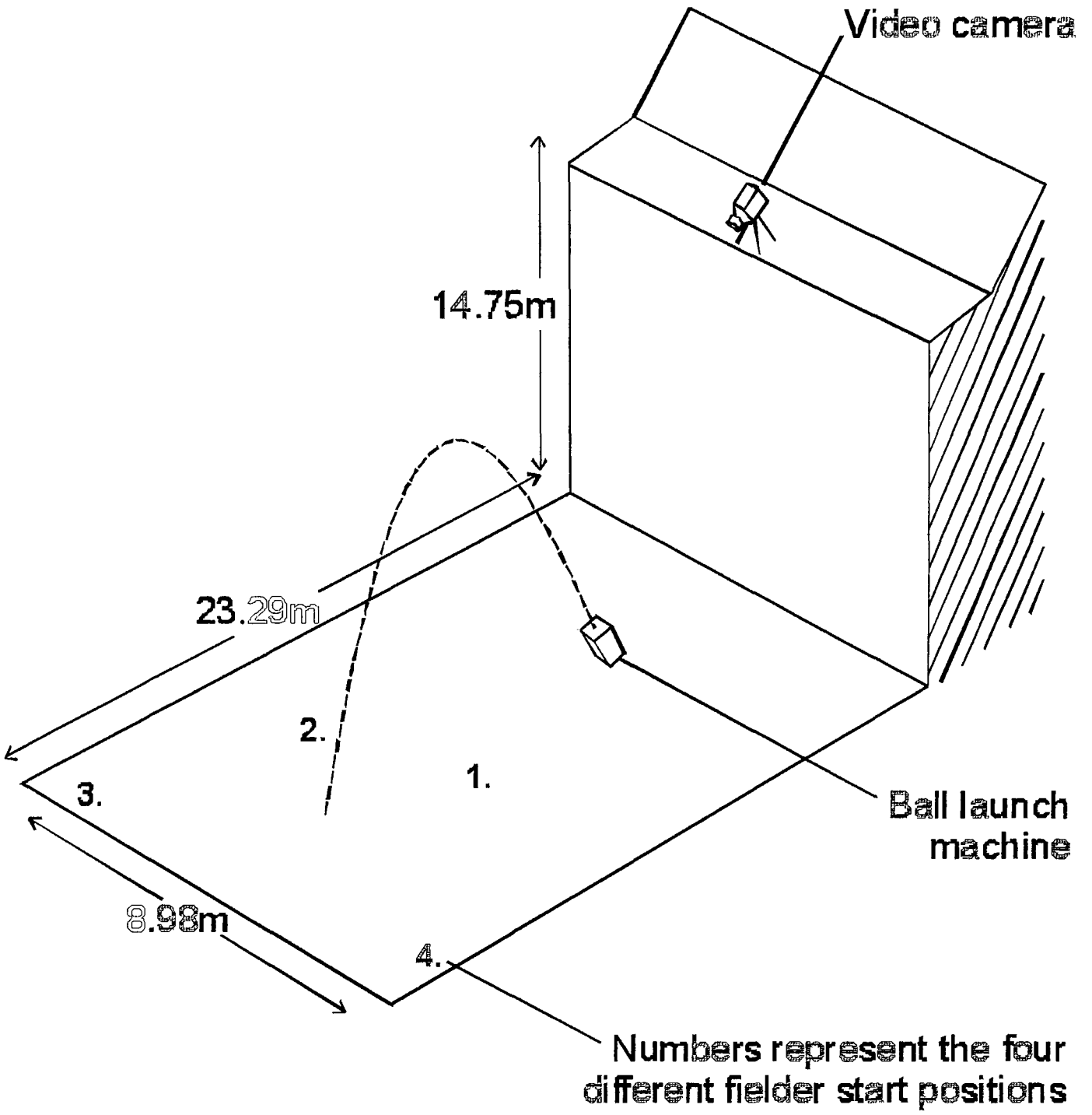


Fig. 4.1 Experimental set-up (not to scale).

Fielders started their set of trials by beginning from position 1, visiting positions sequentially so that they began their second trial from position 2, their third from position 3, and their fourth from position 4. For their fifth trial, subjects returned to position 1, restarting the sequence. Subjects 1 and 3 each completed 40 trials, ten from each position. Subject 2 completed 39 trials, ten from positions 1 to 3 and nine from position 4. Subjects 4 and 5 each completed 28 trials, seven from each position. Each start position constitutes a different combination of distances in the X and Y-axes through which the fielder has to

move to get to the catch position. Table 4.1 shows the direction and magnitude of the movement that the fielder must perform to get to the interception point. The directions given are from the perspective of the fielder.

	X-axis		Y-axis	
Position	Direction	Magnitude	Direction	Magnitude
1.	Left	3m	Backward	4m
2.	Right	3m	Backward	2m
3.	Right	4m	Forward	4m
4.	Left	5m	Forward	2m

Table 4.1.

The beginning of a trial was marked by the release of the ball from the launching machine. Tennis balls emerged from the launch machine at a height of 1.35m. However, this was not visible in the field of view of the camera. For analysis, it was vital to know when the ball was launched. A mechanism was used to indicate on the video footage the precise moment that the ball had been released and is shown in figure 4.2.

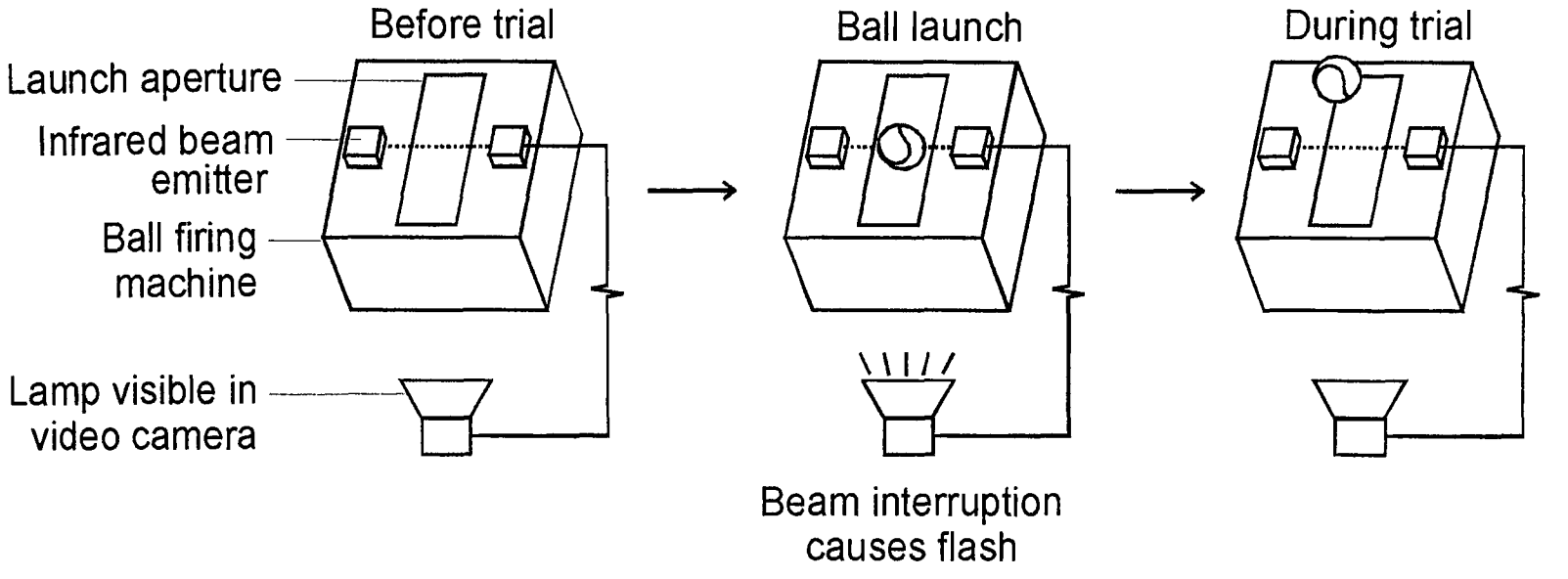


Fig. 4.2 Indication of the beginning of a trial.

As the ball emerged from the launch machine, it momentarily interrupted an infrared beam situated across the launch aperture. The break of the infrared beam caused a red light, visible to the video camera, to flash. This marked the point of release of the ball on the video footage and signalled the start of each trial. Balls were projected at an approximate angle of 69° and were airborne for around three seconds. Launch characteristics were uniform and balls followed consistent trajectories[2]. The fielder making contact with the ball signified the end of a trial. The same constraints for trial validity as used in chapter 3 were applied here; i.e. a trial was valid if the fielder managed to get their hand to the ball before it landed. However, due to the steep launch angle and large launch velocities used, fielders always had sufficient time to reach the interception point. Consequently, there were no invalid trials. The camera shutter was set to its fastest mode, running at 1/500th of second, to minimise of the video images blurring of the fielder and the ball[3].

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[2] Slight inconsistency of trajectory was encountered due to imperceptible variation in the physical properties of the tennis balls, such as weight, internal pressure, and tension in the rubber wall. However, balls were found to land within a 0.5m radius. See 4.3.2. for full details of trajectory consistency.

[3] The camera was actually set to its 'Sport' mode, which operates the shutter at the fastest possible speed for the prevailing light conditions, up to 1/500th of a second. The experiments took place outdoors in bright sunshine so the likelihood is that the shutter operated at maximum speed.

4.2.3.2. Recording of fielder movement

Fielder movements were estimated using a similar technique as that described in chapter 3. Differences are outlined here.

The grid of tennis balls for calibration were arranged in a 5×5 grid with 2 extra balls positioned outside the grid to mark the third and fourth start positions (see figure 4.3). The reference points used are marked with asterisks in the figure.

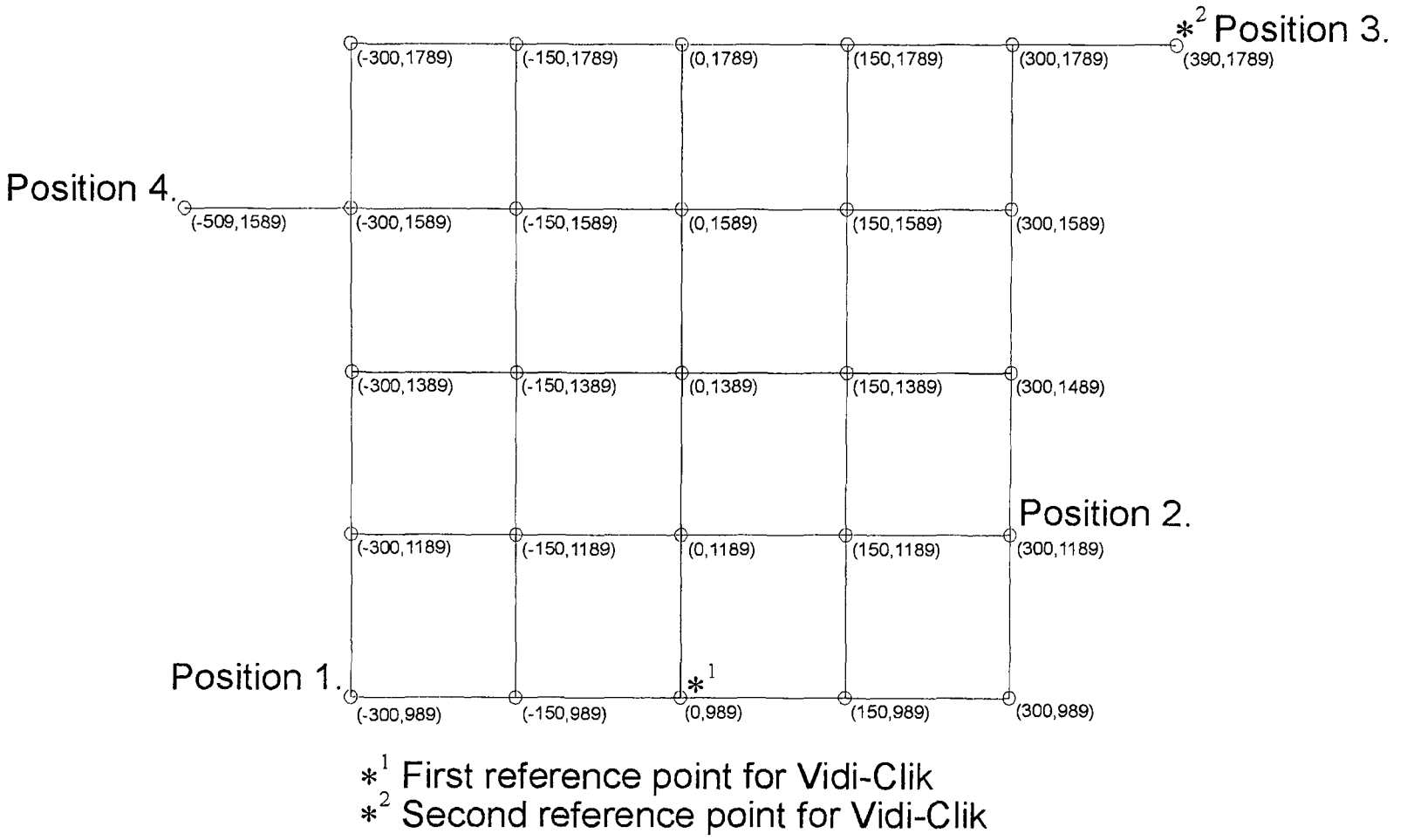


Fig. 4.3 The calibrated area used for trials. The grid shows the measured, true positions of the positions used for calculating the parameters of the conversion equations (co-ordinates are true distances in centimetres relative to the position of the ball-firing machine).

Appendix A1 gives full details of the equations used to convert Vidi-Clik co-ordinates to true positions.

For each trial, the frame number in which fielders began the symmetrical movement of their hands upward in preparation to catch was noted.

4.3. Results

The 5 subjects received a total of 175 trials of which all were valid.

4.3.1. Performance of trajectory calculation program

The error data, summarised in table 4.2, is the difference between the actual final position of the ball as converted from the Vidi-Clik co-ordinates and the predicted final position of the ball as calculated by the trajectory estimation programs.

	N	Mean	Minimum	Maximum	SD
Error (cm)	175	0.68	0.08	2.05	0.32

Table 4.2.

4.3.2. Trajectory statistics

Table 4.3 summarises the best-fit parameters calculated by the trajectory estimation programs.

	N	Mean	Minimum	Maximum	SD
Launch velocity (ms^{-1})	175	16.2	15.3	17.1	0.27
Launch angle (deg)	175	69.3	67.0	71.6	0.79

Table 4.3.

4.3.3. Visual angles

The maximum visual angles experienced by fielders during trials were 79° for α and 47° for $|\beta|$ (the modulus maximum was required because β could be positive or negative, depending on the direction of a fielder's lateral movement).

4.3.4. Running patterns

The running paths followed by subjects were approximately similar across subjects. Figure 4.4 on the following page shows the running paths of 28 trials completed by subject 2. These are the first 7 trials completed from each position. Each circle represents the position of the fielder's head at 120msec intervals. For the sake of the clarity of the figure, the positional data for successive trials from each position has been displaced upwards by 100cm in the Y-axis. Consequently, trials from positions 3 and 4 are not located correctly in the Y-axis relative to those from positions 1 and 2.

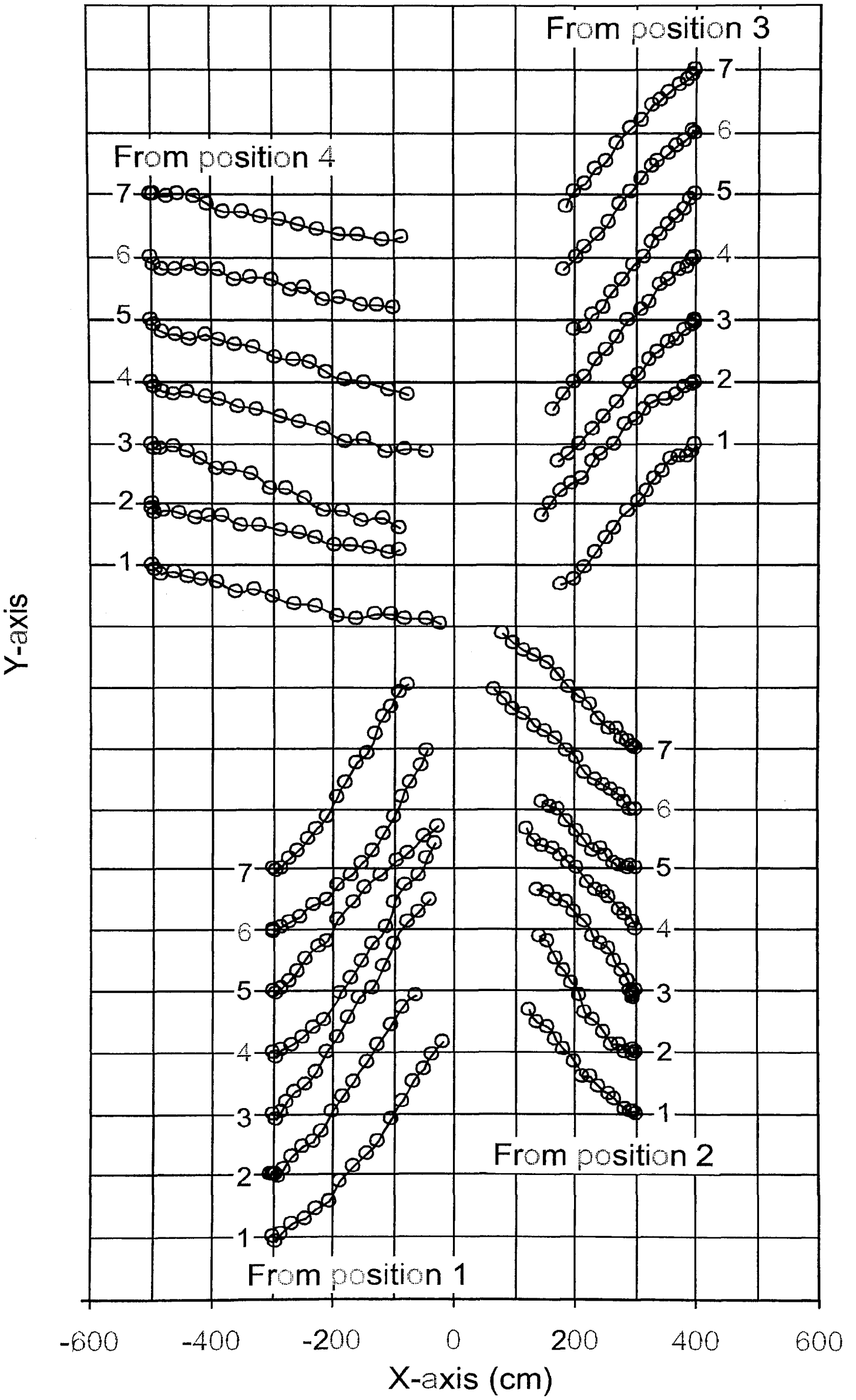


Fig.4.4. Running paths of a typical subject (each square represents 100cm × 100cm).

In comparison to the running paths produced by subjects in chapter 3 (see figure 3.5), the routes taken by subjects to the interception point appear straighter. However, this is perhaps not surprising because, unlike the experiment in chapter 3, the location of the starting position provided cues to the interception point. When subjects were waiting for the launch of the ball at each start position, they would have been immediately aware of the approximate direction in which they would have to run to catch the ball. As a result, their initial movements were (perhaps) toward where they believed the approximate interception point was rather than as the consequence of following an error-nulling interception strategy. Recall the finding of section 3.3.2, that the curvature of running paths is due to fielders following an interception strategy that invokes lateral motion prior to motion in depth. If the fielder begins moving with a preconception of where the interception point is, presumably motion will begin toward that. The curvature of the running path would then depend on how accurate the fielder's prediction of where the ball would land was – not the timing of lateral and depth motion. This hypothesis was tested in the following analyses.

4.3.4.1. Curvature of running paths

See appendix A3.2 for an example of the statistics used in this section. Linear and quadratic models were fitted to the X-Y positional data to assess quantitatively the curvature of running paths. This technique was used for the same purpose in section 3.3.2 and, in common with the protocol used in that chapter, the data was cropped before being analysed. Positional data from the first ten frames was removed to prevent any initial movements (movement reversals – see section 3.3.5) interfering with the regression. The positional data obtained after the fielder had begun prehensive behaviour was also discounted. Since subjects 4 and 5 only completed 7 trials from each position, only the

first 7 trials from each position were analysed for fielders 1-3, to equalise the number of trials analysed for each subject (28 trials).

An F-test determines whether the quadratic fit is significantly better than the linear fit. If the F-test finds that the quadratic fit is not significantly better than the linear fit, then the linear model can be considered most appropriate and the running path is considered straight. If running paths were to be curved in a manner similar to those in chapter 3, there should be a significant positive quadratic component to the fitted model for trials when the fielder runs backward. A positive quadratic component represents a convex running path relative to the origin of the ball and was expected from positions 1 and 2. Accordingly, when the fielder runs forward, i.e. from positions 3 and 4, there should be a significant negative quadratic component to the fitted model. This represents a concave running path relative to the origin of the ball. The results of this analysis are shown in table 4.4.

Position	Fielder runs	Concave	Straight	Convex	Total
1.	Backward	3	3	29	35
2.	Backward	15	6	14	35
3.	Forward	24	6	5	35
4.	Forward	26	6	3	35
	Total	68	21	51	140

Table 4.4.

For positions 1, 3 and 4, the data appears to approximate the pattern established in chapter 3 – when the subject runs forward the running path tends to be concave relative to the origin of the ball and when the subject runs backward the running path tends to be convex. From those 3 positions, 90 trials have a significant quadratic component to the fitted model, of which 79 (88%) conform to this pattern. From position 2, a fielder must

move backward and to their right in order to reach the interception point. It might be expected that running paths from this position would tend to be convex. However, the analysis of trials from position 2 shows approximately equal numbers of concave and convex running paths. The example trials in figure 4.4 also show that running paths seem to be less consistent from position 2. To get to the interception point from position 2, the fielder has to move the least distance. Consequently, there is less time pressure on the fielder to adhere strictly to a particular interception strategy. With this pressure removed, it seems that variation emerges in the path they choose to take, accompanied by no loss in performance.

4.3.4.2. Effect of experience on running paths

The r^2 value for a regression model is the proportion of the variation in the dependent variable (the fielder's position in the Y-axis) explained by the regression model. By looking at how r^2 changes for the linear regression model as the trials proceed, it should be possible to see whether running paths become straighter through experience. The r^2 value for the linear fit is relatively high but unsurprising given the gentle curvature of running paths. Table 4.5 summarises the r^2 data for the linear and quadratic fits to the X-Y positional data in the 140 trials analysed earlier.

	N	Mean	Minimum	Maximum	SD
r^2 for linear fit	140	0.89	0.05	1.00	0.16
r^2 for quadratic fit	140	0.96	0.23	1.00	0.09

Table 4.5.

The range of r^2 for the linear fit is large – going from a hopeless fit to near perfect. It is, therefore, possible that the early trials completed by the fielders are responsible for the most curved running paths whereas paths straighten in the later trials. These later

trials would have a large value of r^2, thereby increasing the mean value. Figure 4.5 shows the mean value for the linear fit r^2 across all subjects and all trials.

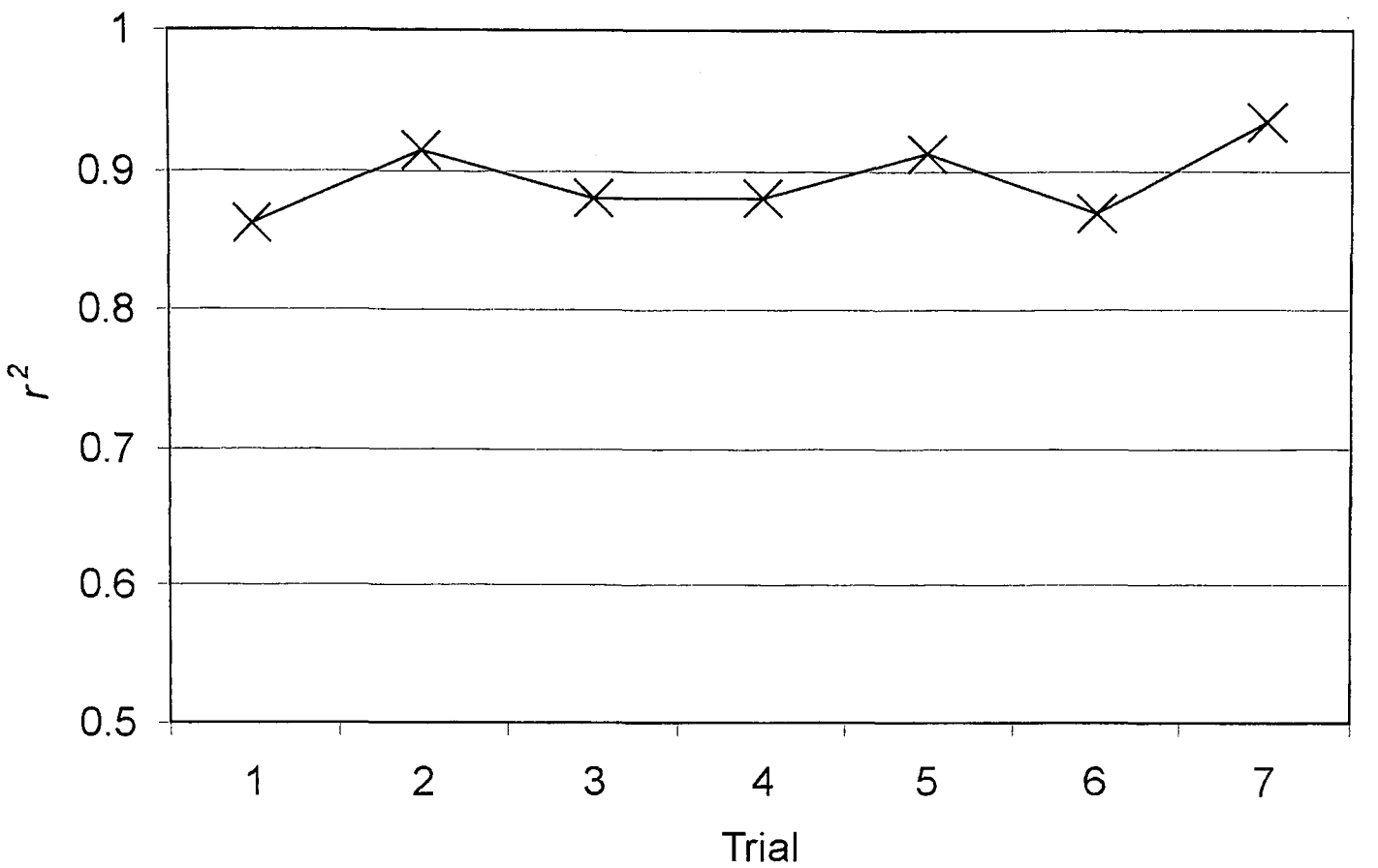


Fig. 4.5 Mean r^2 for the linear fit to X-Y positional data against trial number.

There does not appear to be any appreciable increase in r^2 to correlate with fielders' experience at catching from each position. A Kendall's τ test was performed to check that the apparent lack of correlation between r^2 and trial number was true and confirmed this assertion ($N = 140$, Kendall's $\tau = -0.001$, $p > .95$). Recall the earlier result that the running paths of trials beginning from positions 1, 3, and 4 show the expected pattern of curvature, whereas those from position 2 do not. There is the possibility that any effect of experience will not manifest itself in trials from all positions. To investigate this hypothesis, the above analysis was repeated on the data, this time grouped by position. Figure 4.6 represents this data.

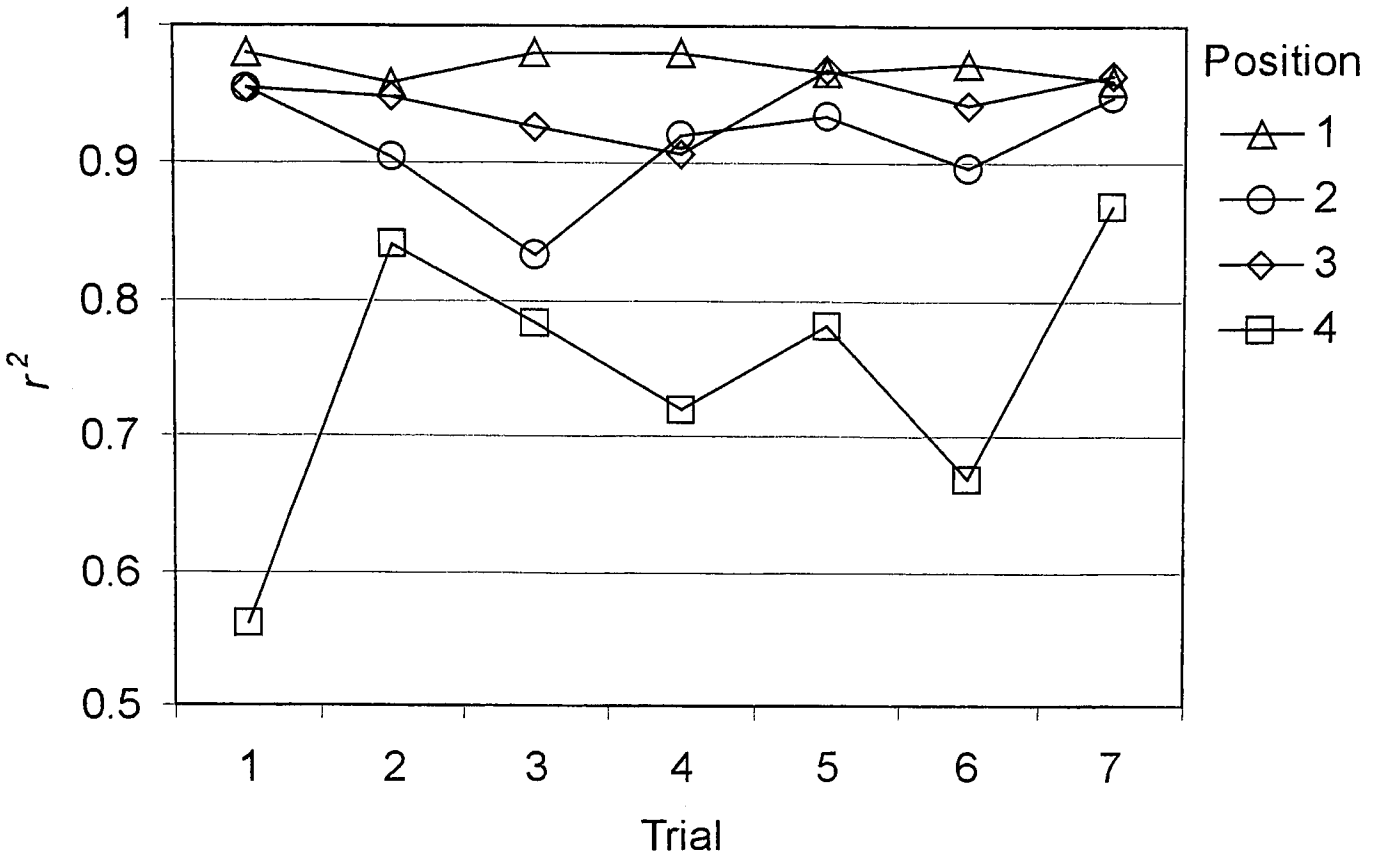


Fig. 4.6 Mean r^2 for the linear fit to X-Y positional data for each starting position.

Again, there is no clear effect of experience on the linearity of running paths. The results of Kendall's τ correlation tests (shown in table 4.6) support this claim. In fact, the correlation coefficients produced here and on the previous test are surprisingly small, suggesting that the curvature of running paths remains robust to the effect of experience.

Position	*1*	*2*	*3*	*4*
Correlation Coeff. (N=35)	-0.13	0.00	0.10	0.04
Sig. (2-tailed)	0.28	0.99	0.41	0.76

Table 4.6.

4.4. Discussion

The first point to note is that fielders, once again, tended to follow curved running paths when running to catch. The direction of curvature was revealed by the multiple regression analysis. If required to move forward, their path was usually observed as being concave relative to the origin of the ball. If the fielder had to move backwards to catch, their path was usually convex. This corresponds with the findings of chapter 3 and to those of McBeath, Shaffer, & Kaiser (1995) and seems to confirm that fielders' use an interception strategy that engages lateral motion prior to depth motion. Contradicting this hypothesis is the curvature of fielders running paths when beginning trials from position 2. Catching the ball from position 2 required the fielder to move backward and to his right. Given previous results, one might predict that fielders would follow convex running paths. However, the regression analysis for trials from position 2 showed that the subjects ran paths that were concave and convex in almost equal proportion. The most obvious reason why this might be the case is that position 2 was situated closest to the interception point. Consequently, fielders had ample time to reach the interception point. It would have rapidly become apparent to the fielder that engaging the usual interceptive behaviour (controlling running using an error-nulling formula ensuring that they reached the right place at the right time) was not critical. They may have then focussed on prehensive behaviour. The resultant interception path would have a shape that depended partially on the catching technique chosen by the fielder for that trial. For example, for one trial the fielder may choose to catch the ball directly in front of them (the fielder's midline is aligned with the plane of trajectory of the ball) with both hands raised in front of the face. However, for another trial they might choose to catch the ball at chest level and to one side (the fielder does not attain alignment with the trajectory of the ball). If one assumes that fielders do not necessarily always choose the same technique to catch a

ball on every occasion, this adequately explains a result where there are approximately equal numbers of concave and convex running paths for catches made from position 2.

The r^2 values of the regression analysis were used to investigate the effect of experience on fielders' chosen paths to the interception point. The hypothesis was as follows. Running paths for early trials would be concave or convex in the expected direction. In later trials, fielders would be more familiar with catching from each position and the location of the interception point. They would then choose to run to the interception point by the most efficient route – a straight line. Using the r^2 value for a linear fit to the X-Y positional data for each trial allowed quantitative assessment of the curvature of each running path. As expected, the linear fit was reasonably good for most trials. However, as fielders became more experienced at catching from each position, there was no commensurate change in the mean value of r^2 (see figure 4.5), confirmed by a Kendall's τ correlation test. The use of r^2 values in this analysis can be misleading. The running paths shown in figure 4.4 from position 4 appear quite straight but in fact show lower r^2 values for the linear fit than from other positions. This is likely to be due to slight differences in the consistency of fielders' movements in different trials. However, the critical point is that there is no trend for r^2 to increase as subjects complete more trials. Therefore, it is fairly safe to reject the hypothesis that running paths would straighten in later trials.

Fielders do not choose to run to the interception point by the most efficient route, even when (presumably) they have some sense of where that point is. This is an interesting result that seems to confirm that fielders' interceptive behaviour remains true to an error-nulling strategy that gets them to the right place at the right time to intercept a projectile, even when they could use supplementary information to improve the efficiency of interception. This validates the data collected in this experiment for investigation into

the form of the strategy that fielders use. It also confirms the assertion made by McLeod & Dienes (1996), that interception strategy cannot be based on a mechanism of learned trajectories. The following analyses assess how well the fielders' interceptive behaviour fits with the LOT model and the predictions made by the OAC model.

4.5. Performance of LOT and OAC models in explaining interceptive behaviour

When a fielder runs to intercept a projectile, the variables controlling his actions should behave in a consistent manner. In contrast, there is no reason to expect consistency in a variable that is not controlling behaviour. This logic is exploited here to investigate whether the horizontal optical angle, β, is controlled in the way predicted by the LOT model. The model states that a fielder runs to keep the optic trajectory linear. In order for this to be true, the ratio $\tan \alpha / \tan \beta$ must remain constant. Consequently, $\tan \beta$ must change in proportion to $\tan \alpha$. The OAC model predicts that a fielder runs so that $\tan \alpha$ increases at a constant rate. It does not require the fielder to observe proportional changes in $\tan \beta$.

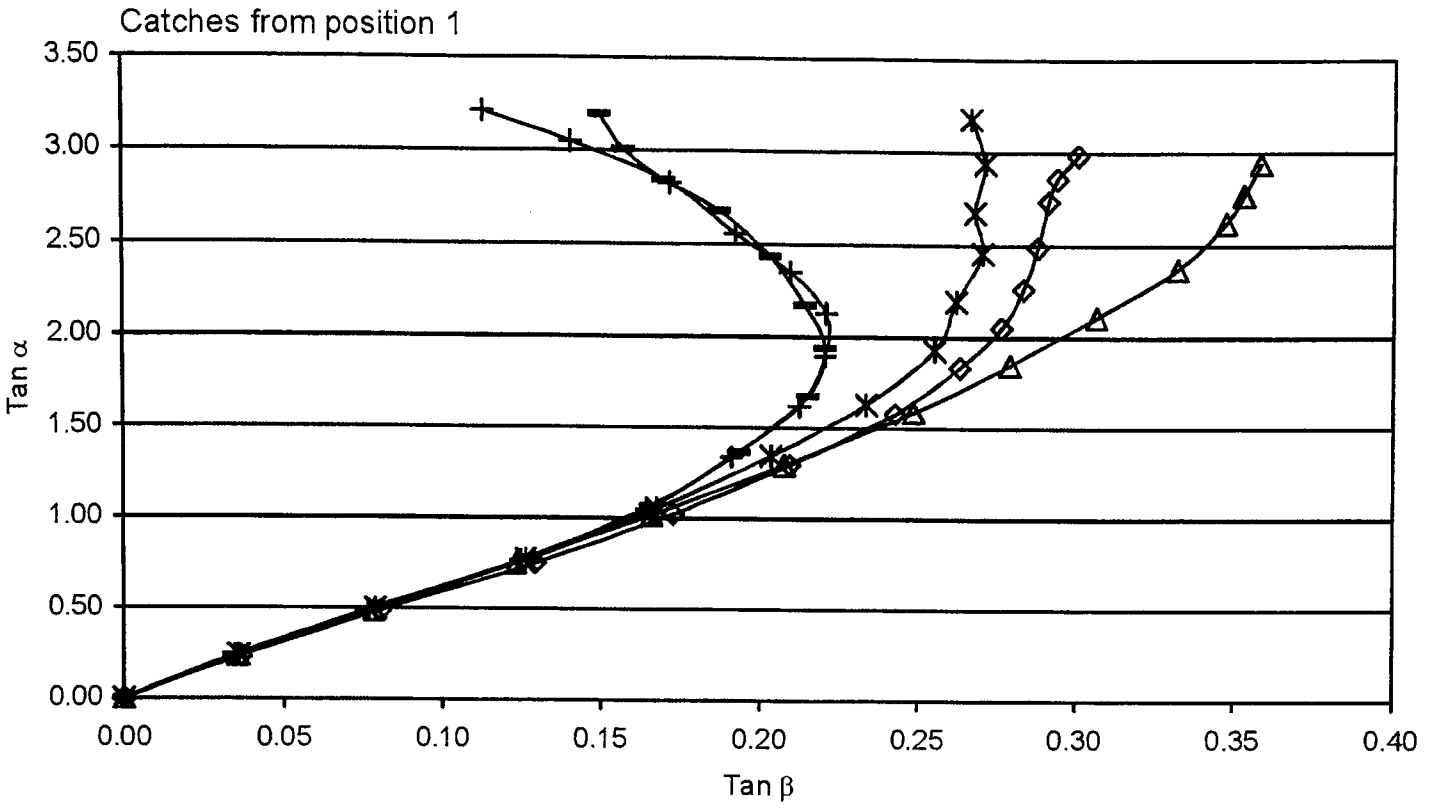
4.5.1. Results

4.5.1.1. Tan α vs. Tan β

Tan α and tan β were plotted against time for each catch. Variation in the curves was orderly until just before the ball was caught. Disorderly variation was observed during prehensive behaviour. Figure 4.7 illustrates how tan α changed relative to tan β for trials beginning from each of the four starting positions[4]. Each line represents the average value across all trials for one subject.

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[4] To ease comparison between trials where the subject ran left and those where he ran right, figure 4.7 shows tan α vs. $|\tan \beta|$.



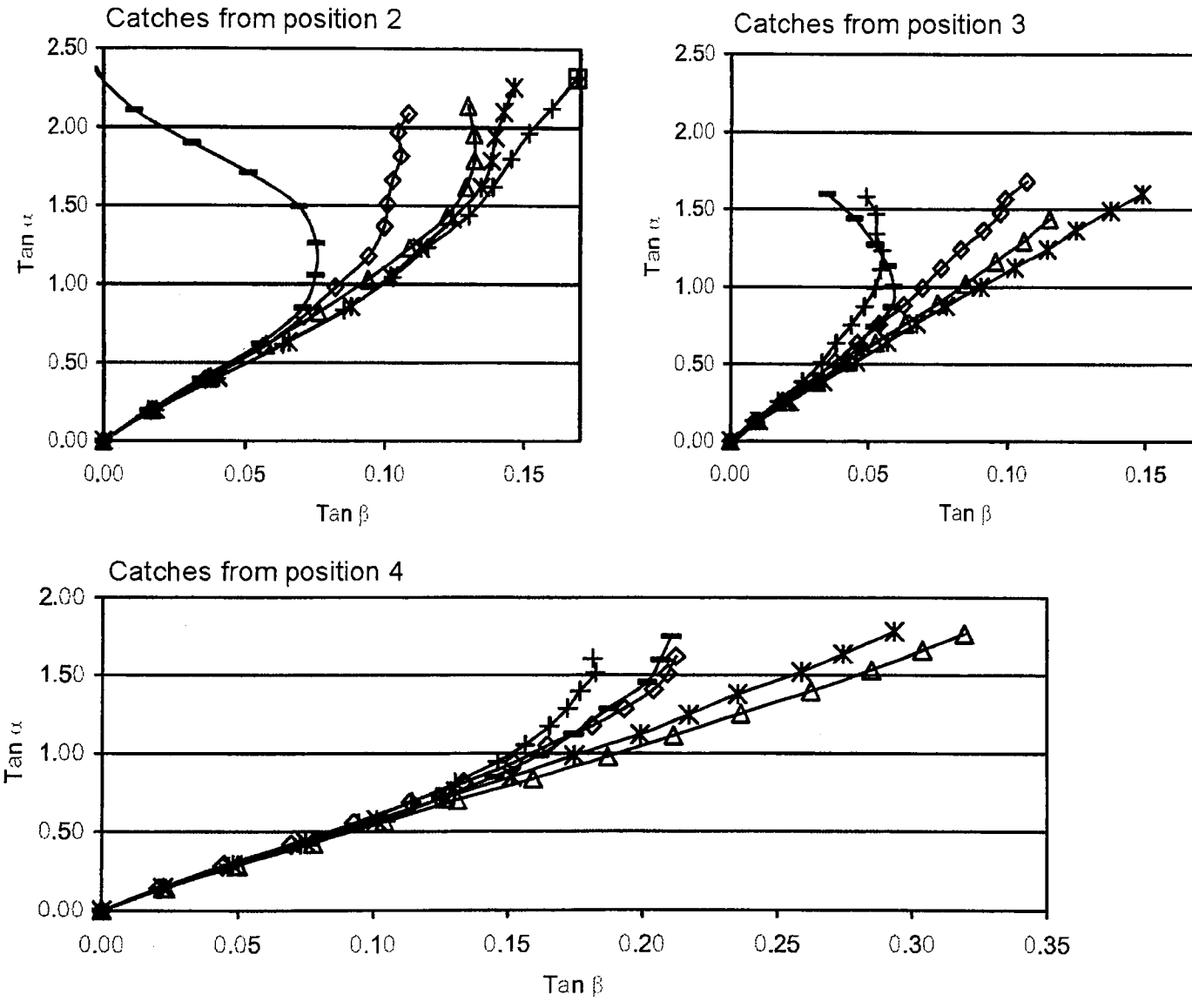


Fig. 4.7 Mean values for tan α vs. tan β for each subject at each position.

Tan α increases at close to constant velocity throughout the flight of the ball for every subject from all starting positions. Tan β starts increasing at constant velocity for all subjects, as predicted by LOT theory. However, about halfway through the flight, the

pattern changes. From positions 1 and 2, for some subjects, tan β reaches a steady value, whilst for others it starts to decrease. From position 3, for some subjects, tan β continues to increase, whilst for others it reaches a steady value.

To assess the linearity of variation in each of the visual angles, r^2 for the linear regression of both tan α and tan β on time was calculated for every catch. Table 4.7 shows the inter-subject medians of the minimum and maximum values.

	tan α		tan β	
Position	min	max	min	max
1.	0.98	1.0	0.02	0.96
2.	0.98	1.0	0.04	0.98
3.	0.99	1.0	0.97	0.99
4.	0.99	1.0	0.23	1.0

Table 4.7.

For every subject, independent of how far they had to run laterally and in depth, r^2 for tan α vs. time was effectively 1.0. This confirms the findings of McLeod & Dienes (1993, 1996), Dienes & McLeod (1993) and Michaels & Oudejans (1992) and is the cornerstone of the OAC theory – fielders run at a speed such that tan α increases at constant velocity. Consequently, α is greater than 0° but less than 90° for the duration of the flight of the ball and the fielder is in a position to catch it as the ball falls to ground. For tan β, the maximum value is also close to 1.0 from every start position (as predicted by the LOT model). This is a consequence of the fielder approaching the descending ball from the side such that β increases throughout the flight. However, the minimum values depend on the starting position. For positions 1 and 2 the median minimum value is close to 0.0. To get to the interception point from these positions, the fielders had to move the

shortest distances laterally. As a result, they had enough time to move into line with the arc of the ball if they chose to do so. If this happened, β would decrease back towards 0 as fielder, ball, and the origin of the ball approached alignment. The resultant linear regression model of tan β on time would fit poorly, giving a low r^2. Most subjects made at least one catch by approaching the ball from the side and at least one where they got into line, despite the fact that they were running from the same start position to catch a ball on the same trajectory. This led to the median maximum value of r^2 being close to 1.0 whilst the median minimum value was close to 0.0. The maximum median value of r^2 for β from each start position is close to 1.0. This shows that most subjects were making at least one catch where tan β increased linearly with time. So data that supports the LOT model can be obtained from the short runs undertaken by fielders in this experiment as well as the longer runs performed by fielders in the McBeath, Shaffer, & Kaiser (1995) experiment. However, it is clear that fielders do not always run to maintain a linear optic trajectory.

A supporter of the LOT model might argue that in this experiment, fielders could learn where the ball would fall and thereafter engage a different running strategy to get to that point. Hence, early on they used one strategy based on watching the ball and later they use another based on their knowledge of the ball flight. It might then be claimed that this explains why the regression of tan β against time was not always close to 1.0 as the theory predicts. Although the analysis of running paths suggests that fielders do not learn where to go to catch the ball, this possibility was investigated by seeing whether there was trend in r^2 for the linear regression of tan β on time across the trials for each subject. If subjects were maintaining a linear optic trajectory in early trials, r^2 would be close to 1.0 and would fall as a consequence of their interception strategy changing when they had learnt where the ball would land. There would therefore be a negative correlation between

r^2 and how many trials had been completed. The full statistics for the Kendall's τ test are shown in appendix A4.1. In fact, the correlation for each subject was positive, although none reached significance. The evidence therefore suggests that the strategy for control of β did not begin conforming to the LOT model and deteriorate as they learned the trajectories and intercept point.

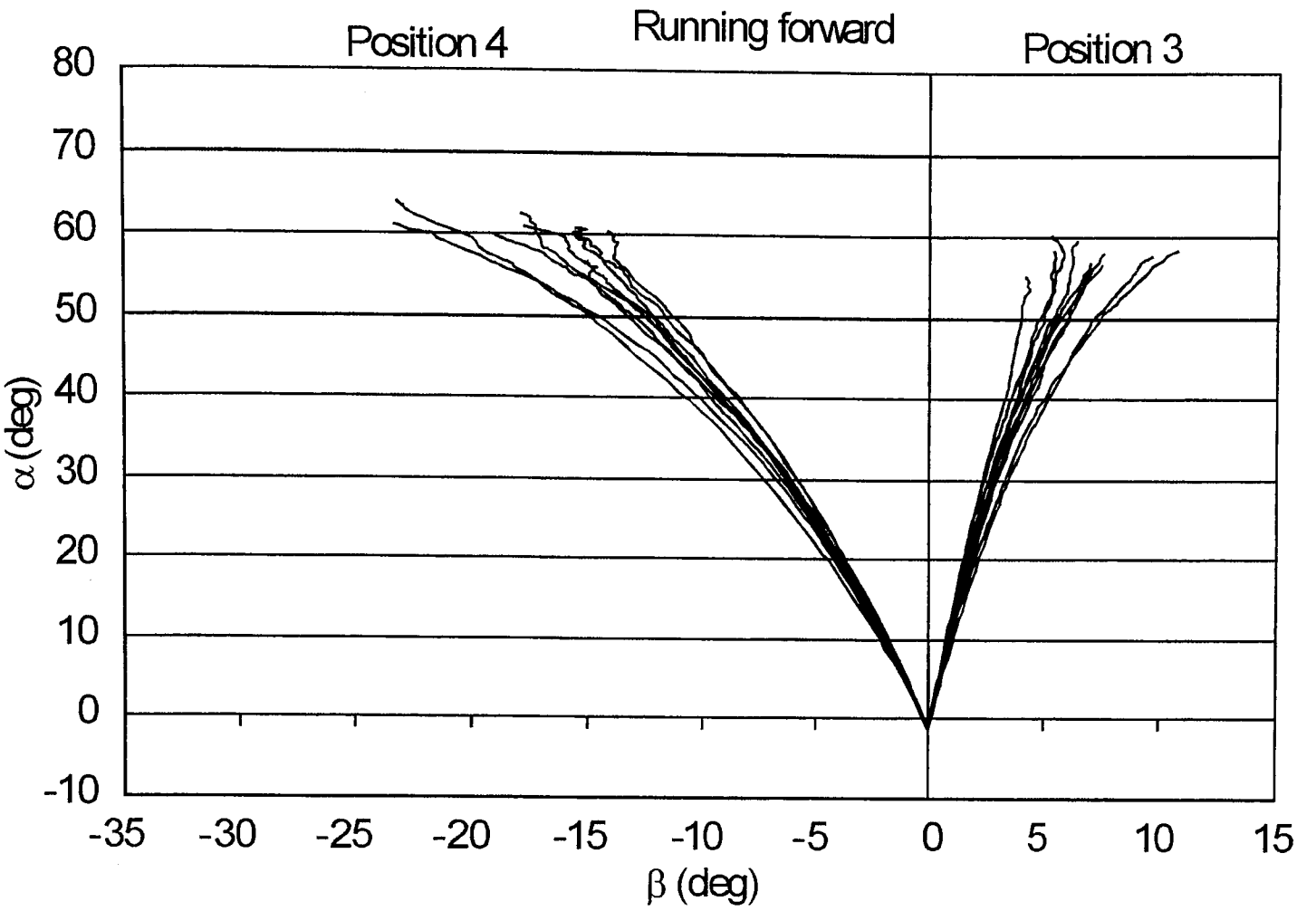
This analysis is similar to the appraisal of whether experience has any effect on the curvature of running paths (see 4.3.3.2.). However, in this instance it is the visual angle tangents experienced by the fielder that are being assessed. These are not independent of the running path taken by the subject. However, it is conceivable that after a few trials subjects may have learnt where the interception point would be and then run on interception paths that do not exhibit a linear change in tan β against time (resulting in a non-linear optic trajectory) but do show the usual curvature. However, the result of the Kendall's τ correlation test suggests that this is not the case.

4.5.1.2. α vs. β

In work since their 1995 paper, in which the LOT model was defined (McBeath, Shaffer, & Kaiser (1996); Shaffer & McBeath (2002); Shaffer, personal communication), McBeath and colleagues have suggested that the optic trajectory can be defined by the ratio α/β rather than $(\tan \alpha)/(\tan \beta)^5$. To check this possibility, the data was analysed in terms of α and β. Figure 4.8 shows the α vs. β data for all trials completed by subject 2 from each start position. The α vs. β data for all other subjects is shown in appendix A4.2.

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[5] There are some theoretical issues with this supposition. These are examined in chapter 5.



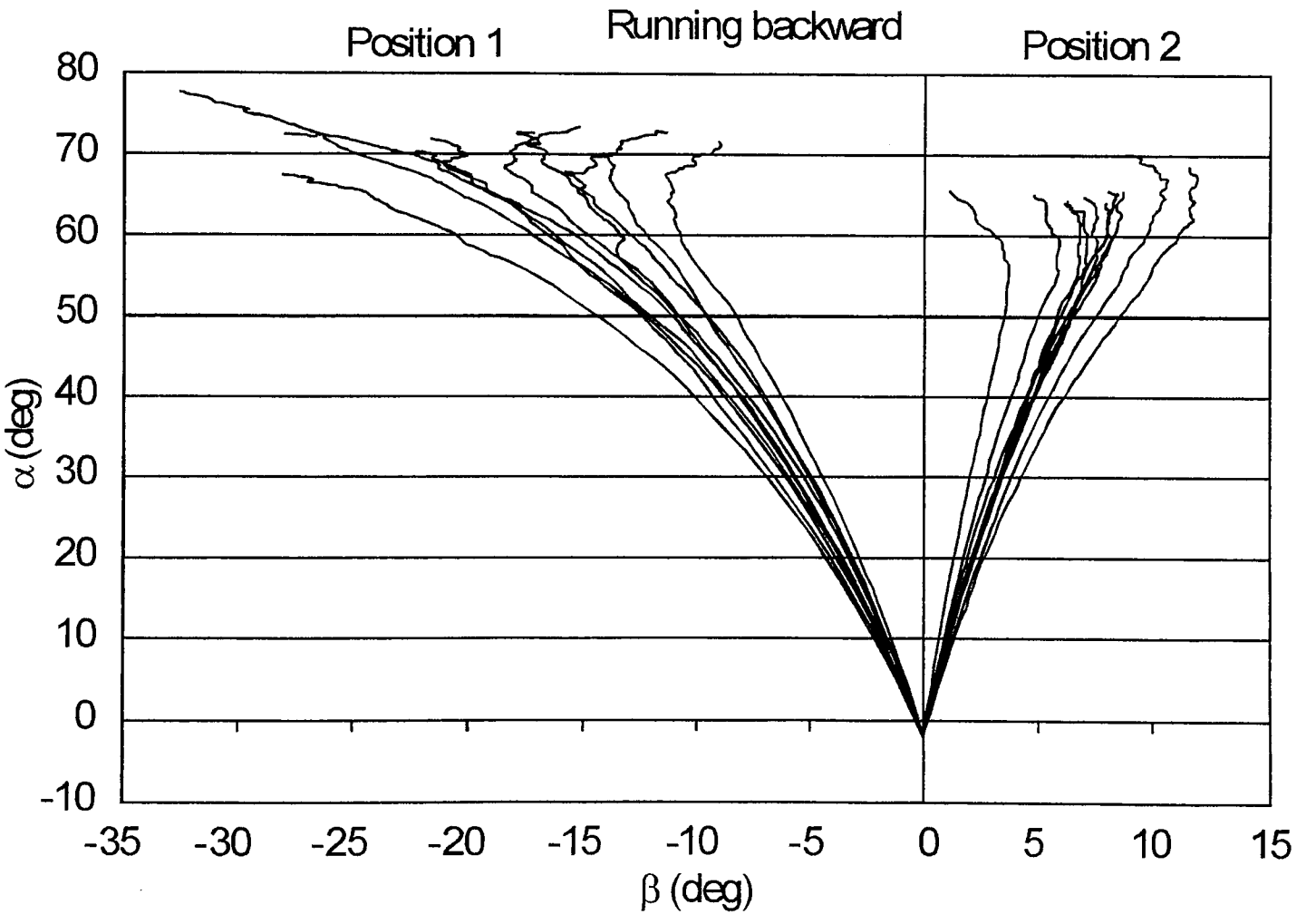


Fig. 4.8 α vs. β for all trials completed by subject 2.

The individual subject data seems to offer no more support for this alternative version of the LOT model than the group data did for the standard version of the theory.

From starting positions 3 and 4, α and β both increased throughout the trial but the ratio α/β did not remain constant. A multiple regression technique revealed that the regression of α on β was significantly improved by the addition of a quadratic component for all but one of the trials from these positions. The sign of the quadratic component is negative in each case, confirming what is apparent from figure 4.8 – the rate of increase of α decreases, compared to the rate of increase of β. This means that the ratio α/β is not constant because the denominator (β) is getting progressively larger, relative to the numerator (α). The LOT model predicts that the fielder would have maintained this ratio at a constant value.

A multiple regression of α on β was also performed on trials from positions 1 and 2. The result mirrored that of the multiple regression performed on trials from positions 3 and 4. In the majority of trials (17 out of 20), the regression model was significantly improved by the addition of a quadratic component. In all cases the sign of the quadratic component was negative. Therefore, the relative rate of increase of α decreases compared to the rate of increase of β, giving a non-constant value of the ratio α/β.

4.5.2. Conclusion

The LOT model predicts that fielders intercept the ball by moving to maintain a linear optic trajectory. A linear optic trajectory will result in tan α and tan β changing proportionally as the fielder runs. Although tan α always changes in the same way, increasing linearly with time, tan β changes in a different way for different catchers, for different fielders, and even for repeated catches of balls on the same trajectory by a single fielder. If one considers the LOT model in terms of the ratio α/β rather than tan α/tan β, the analysis is no more favourable. The inevitable conclusion is that control of α is involved in the strategy used to achieve interception but β is not maintained in the manner proposed in the LOT model.

4.6. Discussion

The analysis of fielders' running paths suggested that fielders treated each trial as a novel experience and previous trials did not affect how they ran to the interception point. Consequently, the likelihood is that they are using the same technique to get to the interception point each time. This validates the data acquired from this experiment for use in analysing proposed interception models that rely on an error-nulling strategy to guide behaviour. One aspect of catching behaviour is now beyond doubt: when people run to catch a ball, they do so in way that results in α increasing at a decreasing rate. This has been shown for balls being launched over a short distance to fielders aligned with the projection plane of the ball (Michaels & Oudejans (1992)) and for fielders out of alignment with the projection plane of balls launched from the top of a building (chapter 3). It has also been shown for balls launched over longer distances both to fielders in the aligned (McLeod & Dienes (1996)) and unaligned (McBeath, Shaffer, & Kaiser (1995)) planes. This facet of

interception strategy was confirmed in the experiment described in this chapter. In this experiment, fielders were catching balls launched on high trajectories over a relatively short distance. The multiple regression analysis found that for all trials, tan α increased almost precisely linearly over time in every trial.

In previous work (Dienes & McLeod (1993); McLeod & Dienes (1996); Tresilian (1995)), it has been assumed that α forms the input to a servo-mechanism that produces a running speed for the fielder that ensures α increases at a decreasing rate. However, this work had focussed on fielders aligned with the plane of trajectory of the ball. McBeath, Shaffer, & Kaiser (1995) proposed the LOT model that accounted for fielders' motion in two dimensions (catching balls in an unaligned plane). In the LOT model, fielders would still experience a constant rate of change of tan α but this was a by-product of the strategy rather than the driving force behind it. The input to the system that controls running in the LOT model is the optic trajectory. If a fielder can move so that the optic trajectory is linear, tan α and tan β will increase proportionally. The consistent finding has been that fielders move so that tan α increases at a constant rate. Therefore, if the LOT model is correct, tan β should be found to increase at a constant rate. However, although tan β was found to increase linearly on a couple of occasions, this was exceptional rather than consistent. In general, the manner of its increase varied between fielders and even between equivalent trials by a single fielder. The LOT model is not consistently supported by the present data.

In this experiment, fielders repeatedly caught balls on an invariant trajectory from four different start positions over relatively short distances. This made for simpler catches than those completed by the subjects in McBeath, Shaffer, & Kaiser's task. It is assumed that whether making a simple or difficult catch, subjects employ

the same strategy for guiding their movement to the interception point. The repetitive nature of the trials means it is feasible that fielders learnt where the interception point was and used that knowledge to catch balls rather than following the LOT model. If this were true, then one would expect tan β to be linear in early trials whilst the fielder is learning where the interception point is and gradually to become more variable. As the fielder became more experienced they could rely on the optic trajectory less and on their knowledge of the interception point location more. The result of a correlation test revealed that there was no decrease in linearity of tan β vs. time to correspond with the accumulation of experience by fielders as they complete further trials. Although, it is possible for fielders to use information they gain by experience to reach the interception point, there is no suggestion that this is disrupting their usage of a LOT-based strategy.

McBeath and colleagues have also defined the optic trajectory in terms of the ratio α/β. However, when the visual angles (rather than their associated tangents) of a single fielder were examined, the evidence suggested that the fielder did not keep this ratio constant either. Plots and regression models showed that α/β tended to decrease. Furthermore, in the latter stages of trials where the fielder ran backwards, variation in β was highly inconsistent. The evidence from this experiment is clear: fielders do not use ratios of visual angles (or their tangents) to get to the right place at the right time to catch a ball. There are also methodological problems with the implementation of the LOT model. These are explored in the following chapter.

5. Problems with the LOT model and exploitation of the optic trajectory

McBeath, Shaffer, & Kaiser (1995) proposed the LOT model as a solution to the 'outfielder problem' – how a fielder moves to the right place at the right time in order to intercept a projectile. They suggested that a fielder moves so that he observes linearity of the optic trajectory of the ball, where the optic trajectory represents its movement relative to the background scenery. In doing so, he causes the tangent of vertical optical angle (α) and the tangent of the horizontal angle (β) to increase at a constant rate, such that the optical trajectory ascends at a constant angle Ψ, where $\tan \Psi = (\tan \alpha)/(\tan \beta)$. Figure 5.1 illustrates this configuration of angles.

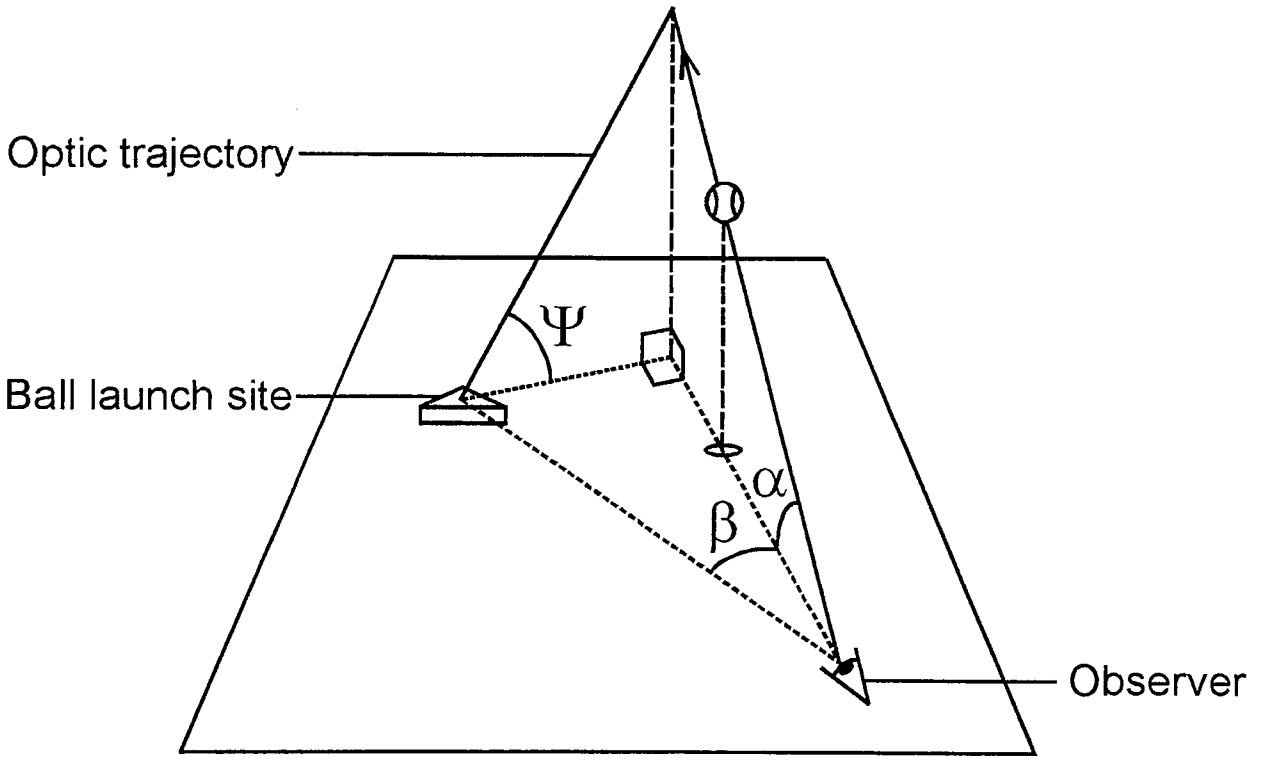


Fig. 5.1 The angles involved in the LOT model (reproduced from McBeath, Shaffer, & Kaiser (1995))

Ensuring linearity of the optic trajectory is a mathematical solution to the outfielder problem. McBeath, Shaffer, & Kaiser (1995) examined the movements of human fielders running to catch balls and reported empirical evidence that the fielders moved experiencing linearity of their optic trajectory. They found that a linear model explained a large proportion of the variation of the regressions of tan α and tan β over time (r^2 typically >0.9), supporting their claim that the optic trajectory follows a linear path. However, in a figure they presented to illustrate this point, they plotted α against β, rather than their tangents. In response to technical comments on their work, McBeath, Shaffer, & Kaiser (1996) revealed that their analyses were performed using α and β rather than their tangents and the authors appear to use the terms interchangeably. This chapter examines the validity of this assumption and investigates problems with implementation of the LOT strategy. It examines the findings of Shaffer & McBeath (2002) that claims fielders maintain linearity of their optic trajectory even for balls that they fail to catch. In their experiment, they gave fielders a mixture of catchable and uncatchable trajectories and found that even when fielders failed to reach the interception point, they seemed to hold linearity of their optic trajectory for longer than they maintained cancellation of optic acceleration. Also investigated is the cue provided by the curvature of the optic trajectory itself by looking at its curvature with different simulated configurations of ball trajectory and fielder movement. Dannemiller, Babler, & Babler (1996) used this technique in their contribution to the technical comments on McBeath, Shaffer, & Kaiser (1995), showing that a fielder moving to the wrong place to intercept a ball could achieve linearity of their optic trajectory. This chapter reinforces the evidence of Dannemiller, Babler, & Babler (1996), showing that the curvature of the optic trajectory is ambiguous as a cue to the appropriate interceptive behaviour.

5.1. Validity of exchanging Tan α/Tan β with α/β

The configuration of the right-angle triangles at the centre of figure 5.1 is such that tan Ψ = tan α/tan β. This is mathematically correct. If tan Ψ = tan α/tan β, then for small values of α and β (expressed in radians), Ψ≈α/β. However, for larger angles this relation breaks down. Figure 5.2 illustrates this point by comparing α to tan α up to 90°.

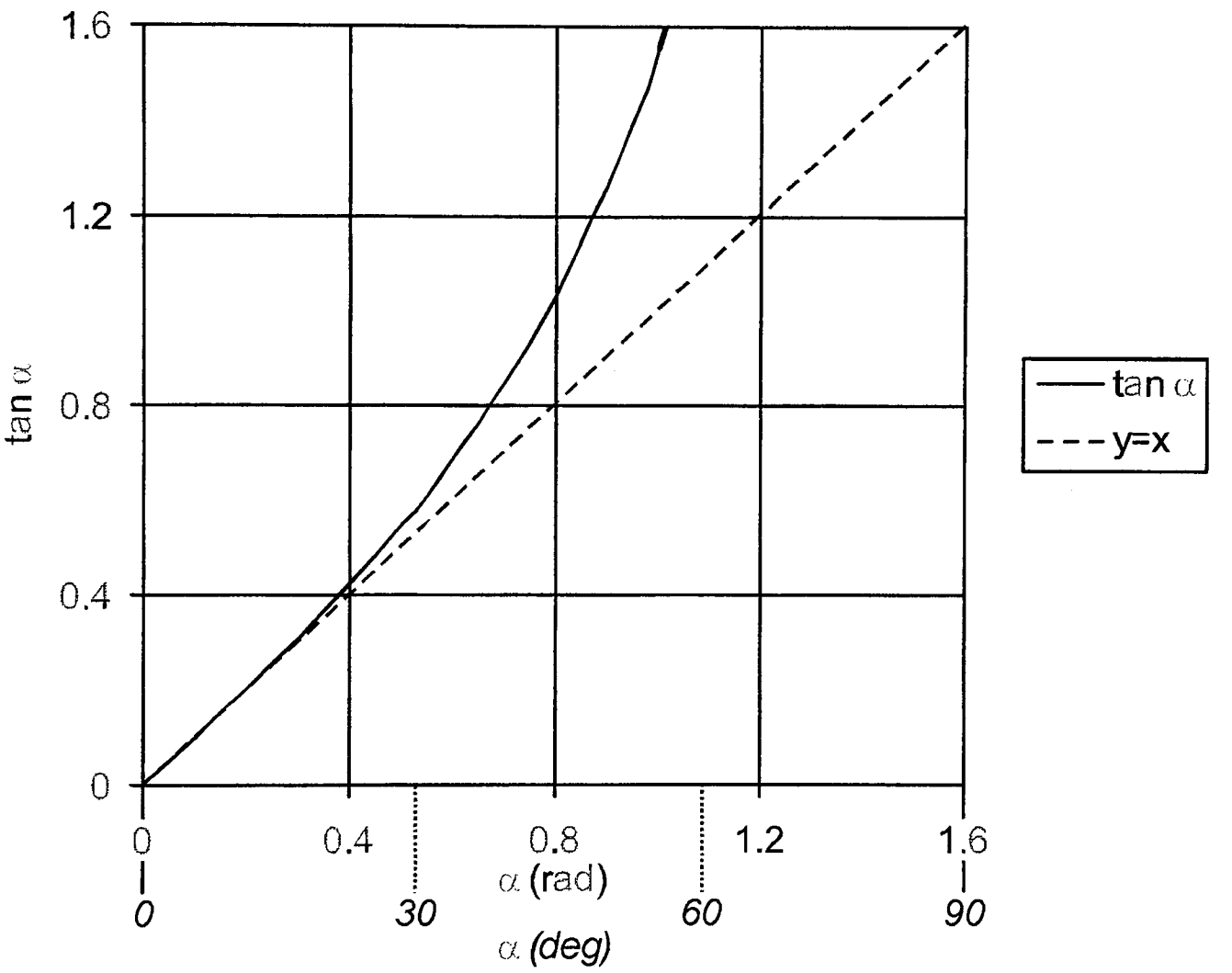


Fig. 5.2 The relation between α and tan α.

Up to 30 degrees (0.52 radians), the approximation is reasonably accurate (α is approximately equivalent to 90% of tan α). From there on it gets progressively worse and beyond 60 degrees (1.05 radians) the approximation is poor (α is approximately equivalent to 60% of tan α). The calculation of Ψ and tan Ψ must be affected when

either α or β reach these values when catching. How this effect relates to interception strategy is revealed in figure 5.3. It compares the changes in α vs. β and tan α vs. tan β for steady proportional increases in tan α and tan β as one might find if a fielder were following the LOT model.

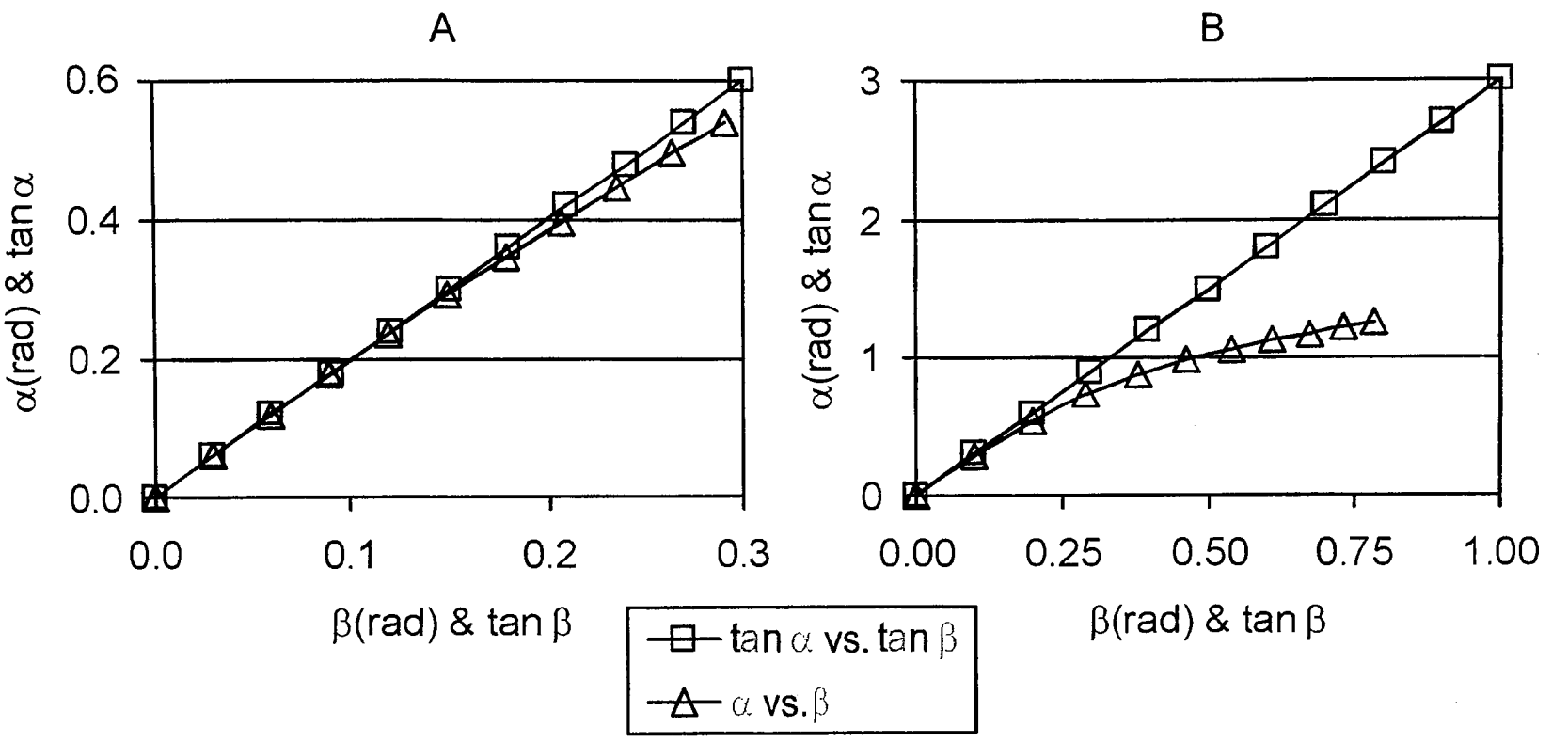


Fig. 5.3 α vs. β and tan α vs. tan β for steady increases in tan α and tan β.

Graph A in figure 5.3 shows the interrelation of α, β, and their tangents for a small, steady increase in the tangents of the angles. Graph B shows the same information for a larger increase, using the range of angles commonly experienced by subjects in the experiment described in chapter 4. Table 5.1 expresses the angles involved.

		Graph A	Graph B
α	Maximum tangent	0.6	3
	as radians	0.54	1.25
	as degrees	31.0°	71.6°
β	Maximum tangent	0.3	1
	as radians	0.29	0.79
	as degrees	16.7°	45.0°

Table 5.1.

Graph A shows that over the range of angles used, α vs. β approximates tan α vs. tan β reasonably well. However, Graph B is more pertinent to the experimental results of chapter 4. It shows how α vs. β becomes a progressively poorer approximation of tan α vs. tan β as the angles involved get larger. As a result, the ratio α/β can only be interchanged reliably with tan α/tan β for a limited range of angles. McBeath, Shaffer, & Kaiser conducted their experiments so that the fielder was a much further distance from the launch point than were fielders in either of the experiments in chapters 3 and 4. This meant that in the early stages of trials in their experiment, α and β would be very small and consequently exchanging tan α for α and tan β for β is reasonably accurate. However, chapter 4 showed that when catching, fielders can encounter visual angles in the range where the relation between α/β and (tan α)/(tan β) breaks down. Consequently, it is invalid to make the assumption that the LOT model can be defined equally using α/β and tan α/tan β.

5.2. The signal to move provided by the optic trajectory

The issue of how the LOT model conveys the signal to move to fielders was addressed in chapter 3. It was shown that the optic trajectory gave ambiguous information about the motion a fielder should make to intercept the ball, tending to show downward curvature no matter what the actual movement that was required of the fielder. Examining the results of the experiment described in chapter 4 revealed instances where the fielders' behaviour was similarly incompatible with the predictions of the LOT model. Figure 5.4 is a reproduction of figure 4.9 from the previous chapter, showing the change in α and β over time for a typical trial.

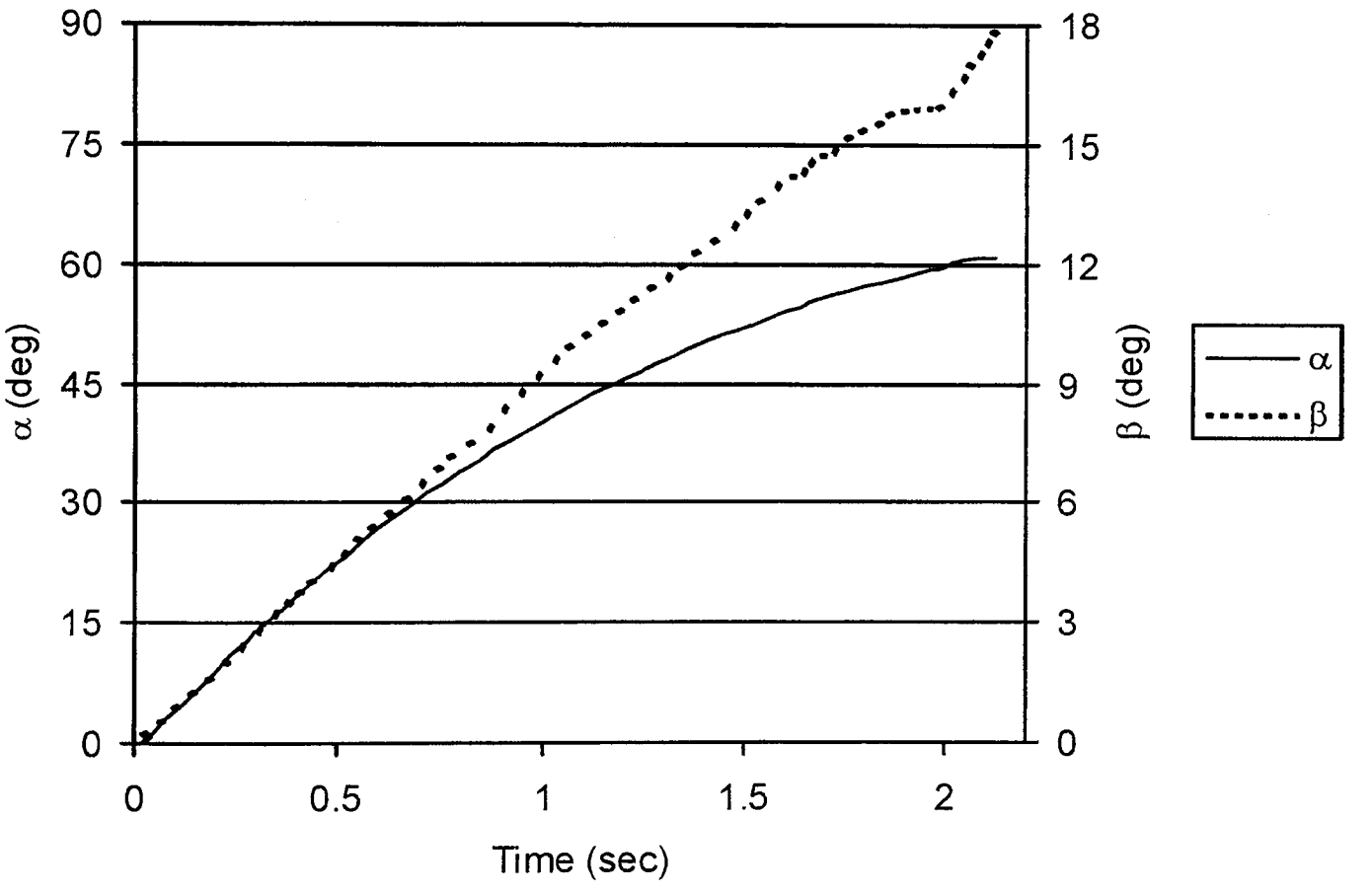


Fig. 5.4 α vs. time and β vs. time for a single trial (note separate axes for α and β).

In the first 0.5s, α and β increased in an approximately proportional manner. McBeath, Shaffer, & Kaiser would say that the fielder is experiencing a linear optic trajectory. This observation is somewhat surprising since the LOT model suggests

that a fielder trying to intercept a projectile should move in response to non-linearity of the optic trajectory in an attempt to restore (or achieve) linearity. Consequently, for the fielder in this trial, the LOT model would give him no signal to move. Yet the data from the experiment shows that it is during this first 0.5s that the fielder began motion toward the interception point. Furthermore, the LOT model states that the fielder should move to eradicate non-linearity of the optic trajectory. However, in the later stages of the trial the optic trajectory continued to deviate further from its original linearity and still the fielder reached the interception point comfortably. The strategy that was used by the fielder in this instance is incompatible with the LOT model.

5.3. Regression of data used to claim linearity of the optic trajectory

McBeath, Shaffer, & Kaiser (1995) used linear regression to support their claims for linearity of the optic trajectory. They found that, on median, a linear model accounted for 99% of the variance in the regression of tan α on time and 97% of the variation in the regression of tan β over time for trials in their experiment. To demonstrate linearity of the optic trajectory, the authors used plots of α against β for example trials of fielders running to catch balls in their experiment. In Shaffer & McBeath (2002), plots of α against β were used to show that fielders maintain linearity of their optic trajectory even for balls that they are unable to catch. A troubling point is that in each α vs. β plot presented by McBeath & Shaffer in the two publications, there appears to be consistent curvature of the data. The validity of the claims to linearity of the optic trajectory made by these advocates of the LOT model were tested by examining of the figures published in their articles.

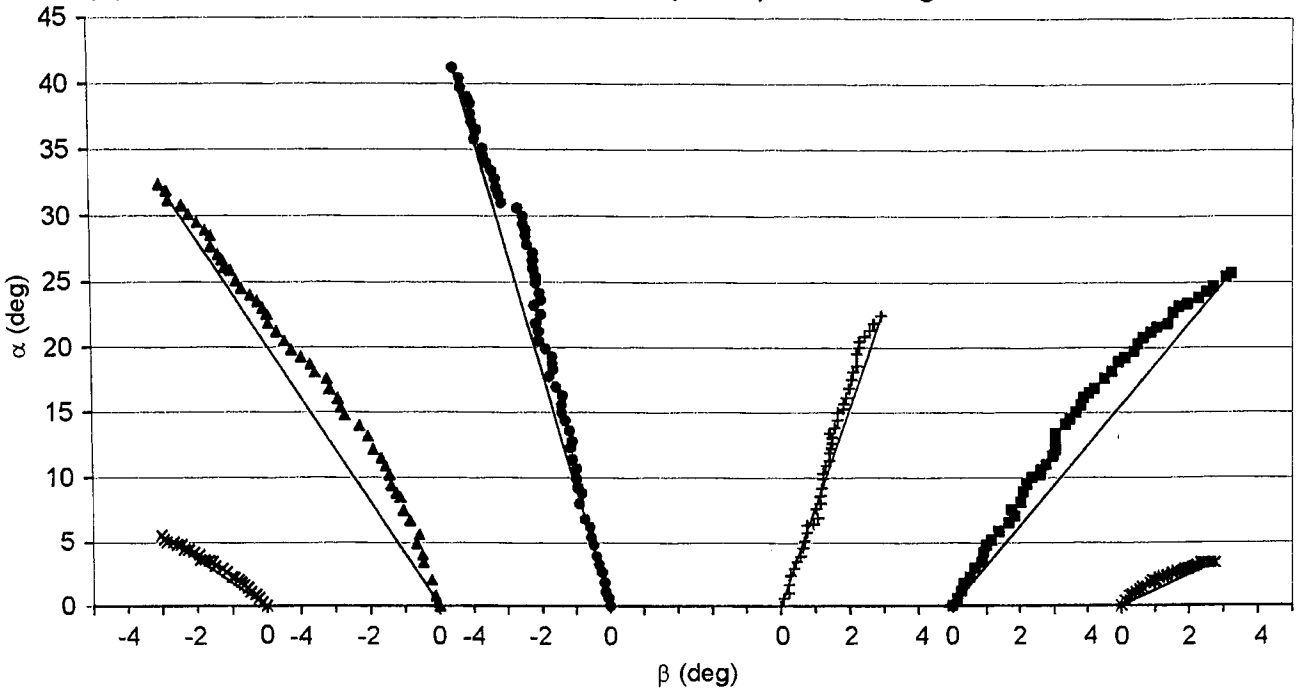
5.3.1. Method

Three figures presented by McBeath & Shaffer were studied. Firstly, the plot of α vs. β for six example trials in which balls were caught by fielders, corresponding to figure 4 in McBeath, Shaffer, & Kaiser (1995). Secondly, two figures from Shaffer & McBeath (2002) showing plots of α vs. β for trajectories where the fielder failed to reach the interception point. One that shows four trials where the ball goes over the fielder's head and one showing five trials where he could not run fast enough forwards to catch the ball. Each figure was analysed separately. Data capture from a figure was achieved by placing it in front of a VHS video camera that had a direct feed into a computer running the program Vidi-Clik. The position of the figure was adjusted so that it filled the field of view of the camera and therefore filled the Vidi-Clik window on the computer screen. Vidi-Clik allows the user to enter the X-Y position of two reference points on the screen. The program then maps the entire screen relative to the two reference positions. Entering these reference points as the maximum points of the X and Y-axes of a figure meant the screen was calibrated such that the X-Y co-ordinates of any point on the screen were equivalent to the values of β(X-axis) and α(Y-axis) on the figure. This allowed the values of α and β for each data point in each series on each figure to be recorded.

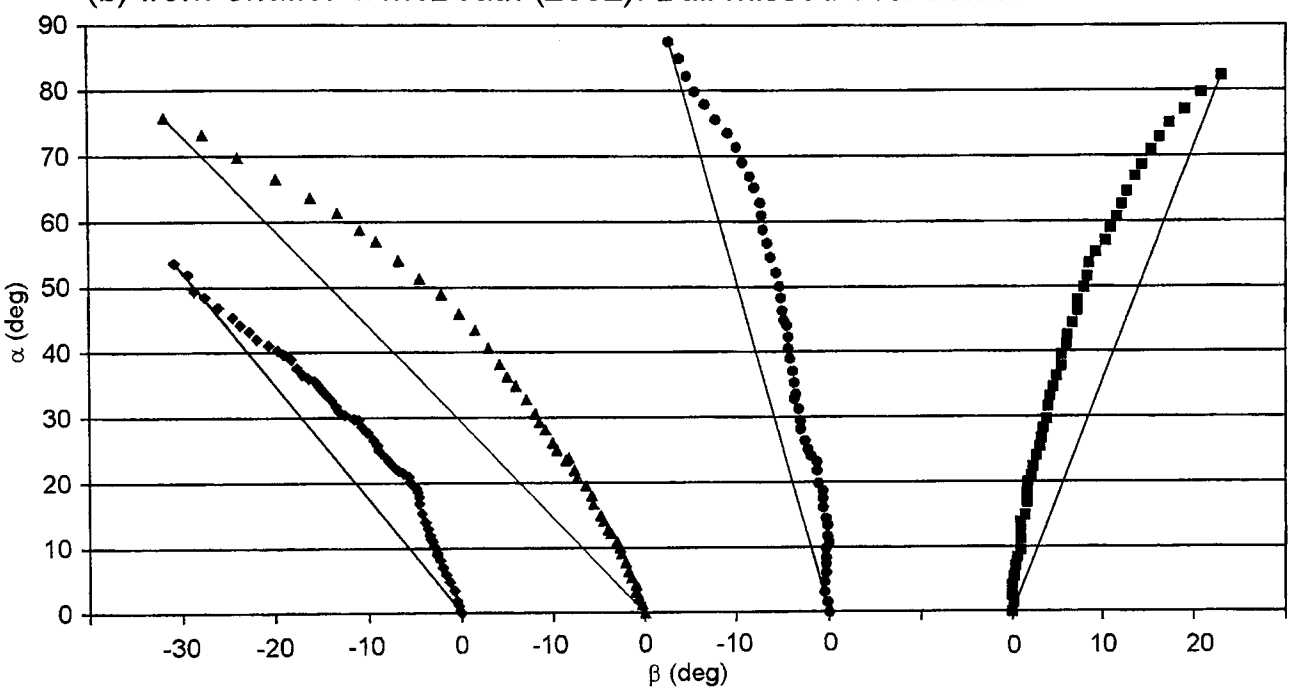
5.3.2. Results

Figure 5.5(a), (b), and (c) on the following page show the recorded variation in α and β for the data presented in McBeath, Shaffer, & Kaiser (1995) and Shaffer & McBeath (2002). Lines have been added to the first and last data point of each series to emphasise the curvature of the optic trajectory.

(a) from McBeath, Shaffer, & Kaiser (1995). Ball caught in front of fielder



(b) from Shaffer & McBeath (2002). Ball missed over fielder's head



(c) from Shaffer & McBeath (2002). Ball missed in front of fielder

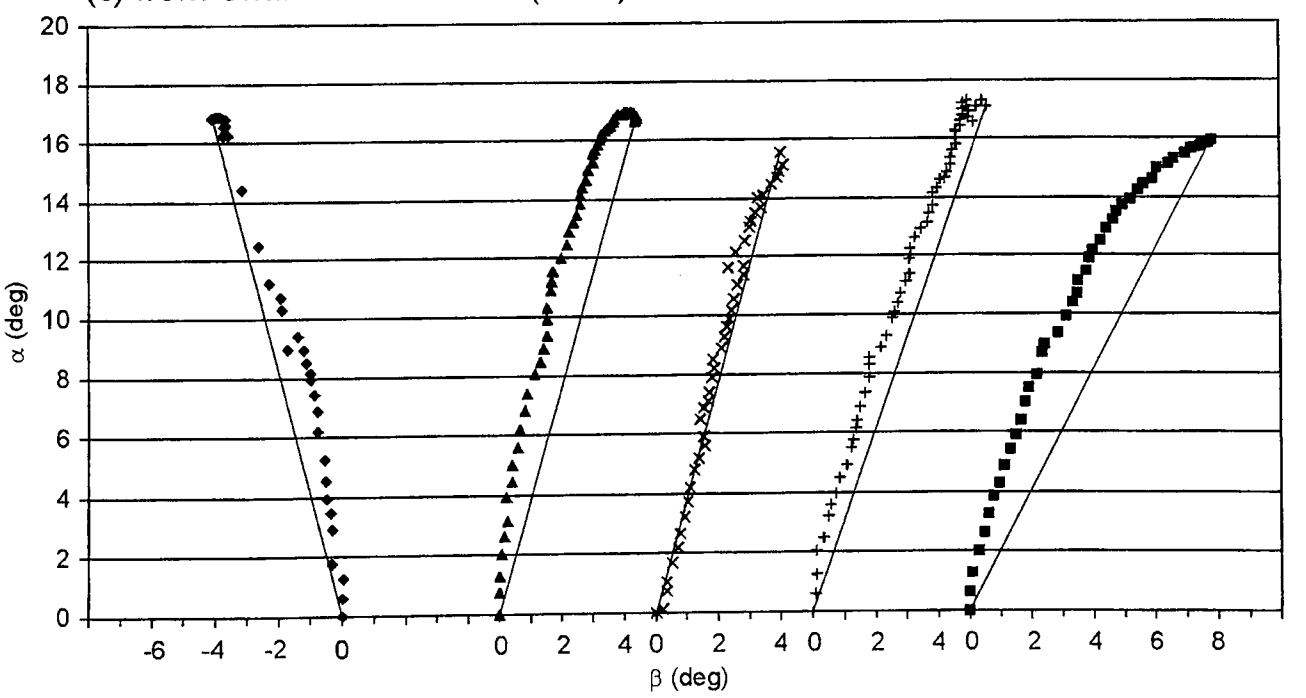


Fig. 5.5 The α vs. β data presented by McBeath & Shaffer.

There is consistent downward curvature of the optic trajectory in figure 5.5(a), which depicts trials where the fielder caught the ball. Regression analysis of the data revealed that, as reported by McBeath, Shaffer, & Kaiser (1995), a linear model provides a good fit to the data ($r^2 > 0.94$ in each case). However, fitting a quadratic model to the data significantly improved the fit in 5 of the 6 trials ($p < 0.001$ in each case), the exception being the fourth series from the left. The presence of significant downward curvature in the optic trajectory replicates the findings reported in chapter 3, where the optic trajectory of fielders running to catch balls tended to curve downwards regardless of whether the fielder had to run forwards or backwards to catch the ball. According to the LOT model, downward curvature of the optic trajectory would inform the fielder that he must modify his interceptive behaviour in some way to reach the interception point. Yet for these examples, the fielder actually reached the interception point.

The downward curvature of the optic trajectory is even more pronounced for the four trials in which the fielder fails to move backwards fast enough to reach the interception point, depicted in figure 5.5(b). Although Shaffer & McBeath (2002) claim linearity, regression analysis showed that although linear models provide a good fit to the data ($r^2 > 0.91$ in each case), the fit using quadratic models is significantly better ($p < 0.001$ in each case). Finding significant downward curvature of the optic trajectory in trials where the fielder fails to run fast enough backwards is surprising as the LOT model predicts that the optic trajectory should curve upwards if the fielder needs to run farther backwards to make the catch. Again, the findings of chapter 3 are replicated – the optic trajectory has a tendency to curve downwards irrespective of the interceptive behaviour required of the fielder.

Predictably, all the plots shown in figure 5.5(c) show significant downward curvature ($p < 0.001$ in each case). This fits with the predictions of the LOT model – the downward curvature of the optic trajectory reflects the fact that the fielder needed to run further forwards in each case. It is unclear why Shaffer & McBeath (2002) claim that the fielder maintains linearity of the optic trajectory in these examples since this policy has failed to get the fielder to the interception point. It is interesting to note the similarity in the curvature of the optic trajectory across the three figures. In (a), the fielder makes the catch whereas in (b) and (c), he fails to do so. Yet the optic trajectories display the same curvature in each case. There is apparently no information in the curvature of the optic trajectory to tell the fielder whether he needs to run forwards or backwards or whether his current running speed is appropriate or not. Given these findings, the following section uses simulated trajectories in an attempt to discover how the optic trajectory varies when the movement requirement of the fielder changes.

5.4. Variation in the optic trajectory using simulated trajectories

5.4.1. The stationary fielder

The information provided by the optic trajectory was first examined by looking at the optic trajectory observed by a stationary fielder watching a ball following simulated trajectories and would land in different positions relative to his. This was achieved using a modified version program used in chapters 3 and 4 to calculate the position of the ball at 0.04s intervals in its flight between two known positions. In this first example, a simulated fielder stands stationary at a point 50m away from the launch position. Balls were launched at an elevation angle of 45° and land at different

distances from his position laterally and in depth. The landing positions form a grid to the right of the fielder. This is illustrated in figure 5.6.

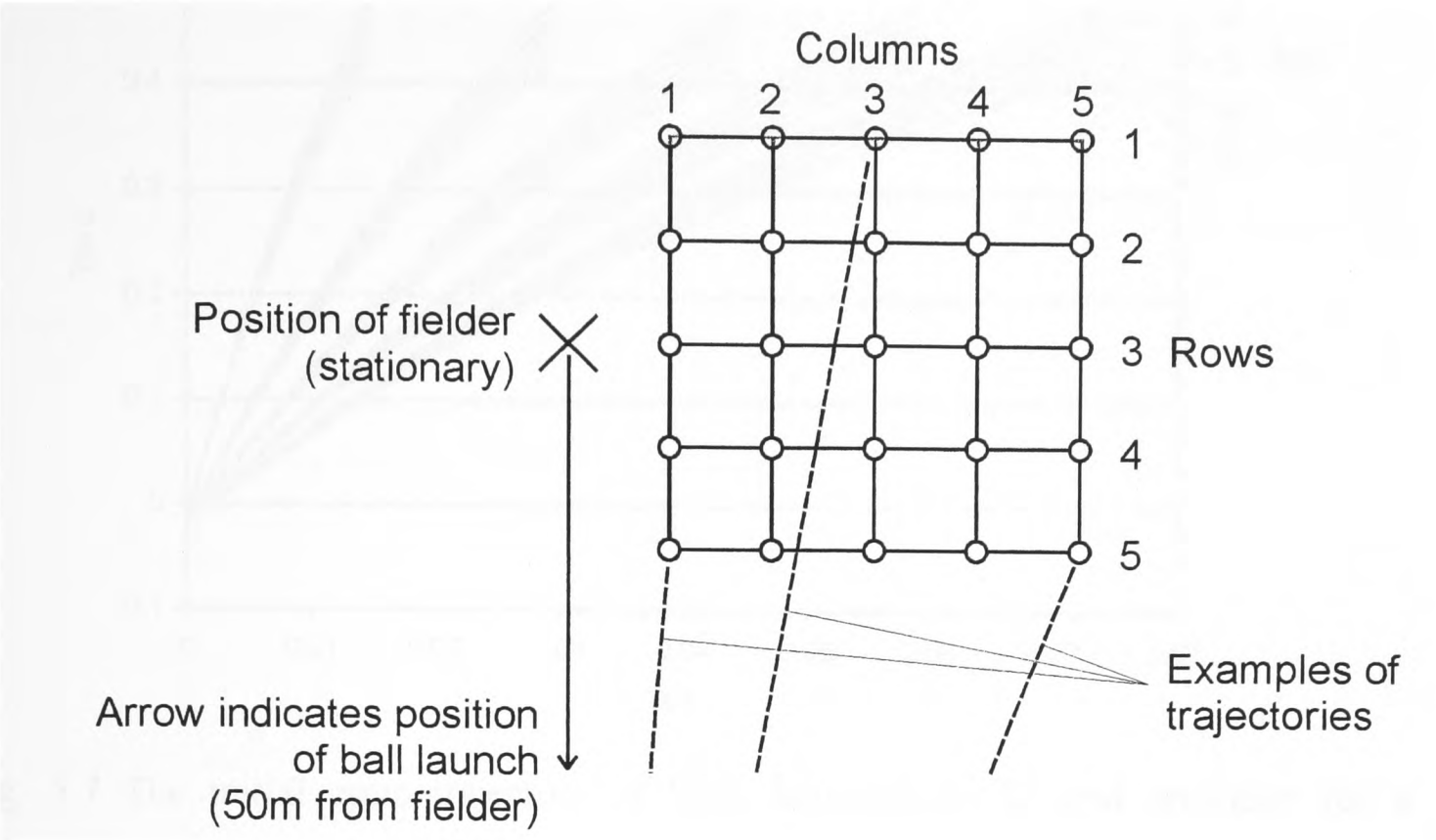


Fig. 5.6 Vertical projection of the grid of positions to which the simulated trajectories were launched.

Column 1 is 1m right of the fielder and each subsequent column is 1m further right. Balls launched to row 3 would require the fielder to move only laterally. The other rows are separated by gaps of 1m. Rows 1 and 2 being further from the ball-launch position and rows 4 and 5 being nearer to it. The values of tan α and tan β that the stationary fielder would experience watching the first 1.2seconds of ball flight for each landing position were calculated (the duration of the entire ball flight was typically around 3.5s). Figure 5.7 shows tan α vs. tan β for balls going to each grid position and therefore illustrates the optic trajectory that each would induce.

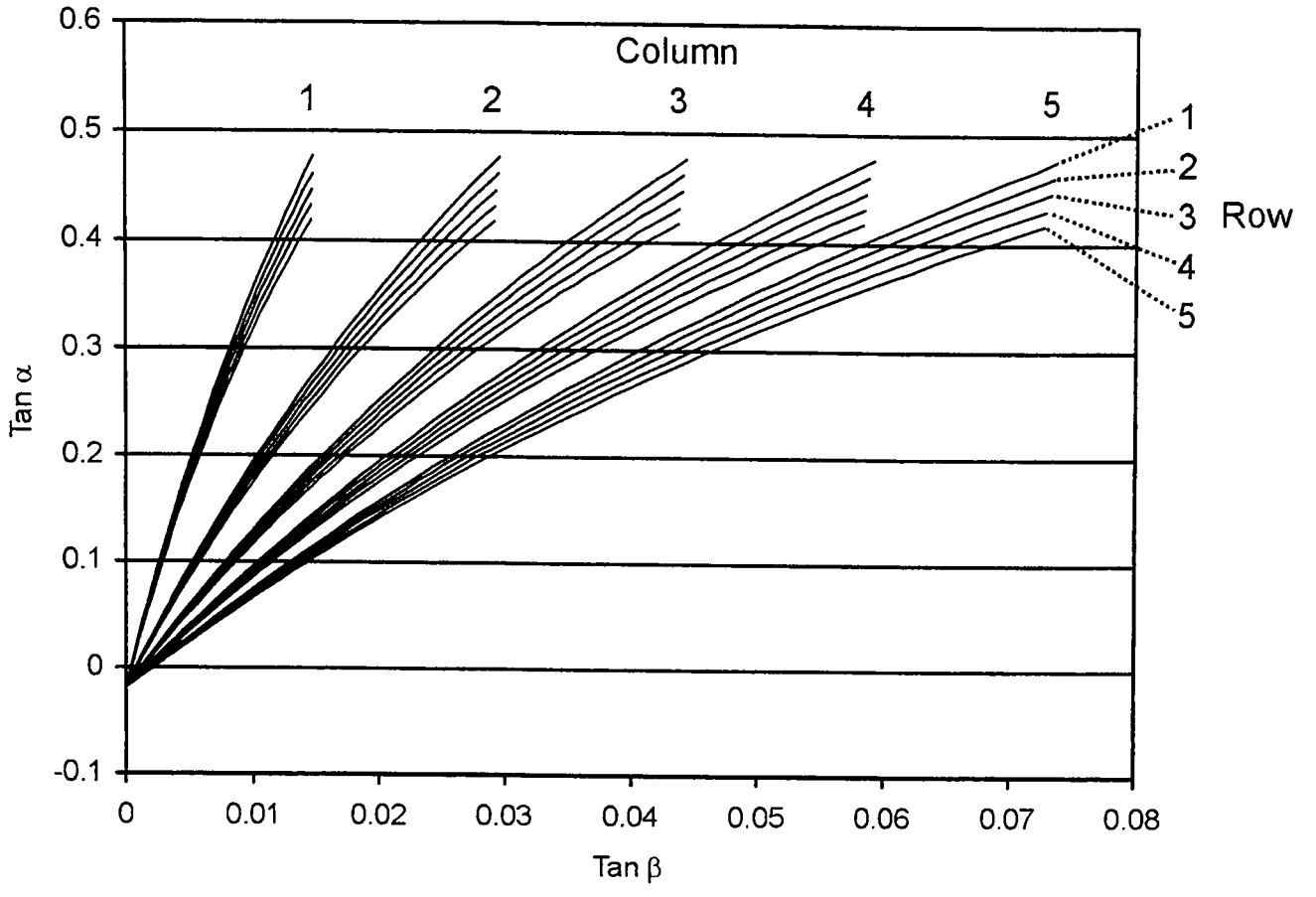


Fig. 5.7 The initial optic trajectory of balls launched to 25 grid positions for a stationary fielder.

Figure 5.7 shows that the optic trajectories are a translation of the grid of positions. The location of the optic trajectory in (tan α)/(tan β) space for each ball flight corresponds with its eventual landing position. Therefore the optic trajectory uniquely specifies the landing location of the ball. However, there is nothing distinct about the curvature of the optic trajectory that differentiates the trajectories. Each has a steady downward curvature and so the correct course of action for a fielder is ambiguous. A fielder must move backwards for trajectories going to row 1 and forwards for trajectories going to row 5 yet the curvature of the optic trajectory is the same in each case.

5.4.2. The moving fielder

The visual experience of a stationary fielder watching trajectories showed the consistent finding that the optic trajectory tends to curve downwards. In this section, the conditions for upward optic curvature were discovered. To analyse the optic

experience of a moving fielder, a consistent ball trajectory was used (simulated using the ball trajectory estimation program described above) and a simulated fielder began from different start positions and used varied running speeds. The ball trajectory used saw the ball travel 30m and was launched at an angle of 45°, giving a flight duration of 2.6s. In each situation the simulated fielder moves at constant speed from the moment of ball launch.

5.4.2.1. Fielder moves laterally to the interception point

In the first situation, if one imagines the ball being launched directly North, the simulated fielder begins 6m due West of the landing position of the ball and finishes at various positions along the West-East axis. This set-up is illustrated in figure 5.8.

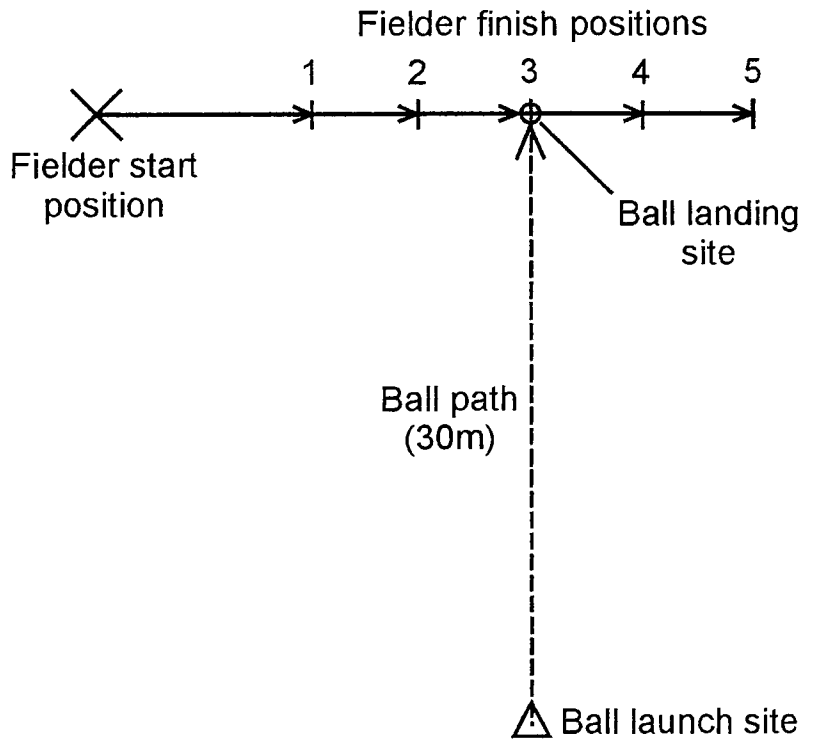


Fig. 5.8 Vertical projection of the set-up of a simulation in which a fielder must move (to his) left to reach the interception point (not to scale).

The simulated fielder moves so that his arrival at each finish position coincides with the ball landing. Therefore, for finish position 3, he arrives at precisely the right time to intercept the ball. For the other positions, he ends up either beyond or in front of the interception point. Tan α and tan β were calculated for the fielder moving to

each finish position, from which a plot of the optic trajectory in the first 1.2s of each trial was constructed and is shown in figure 5.9.

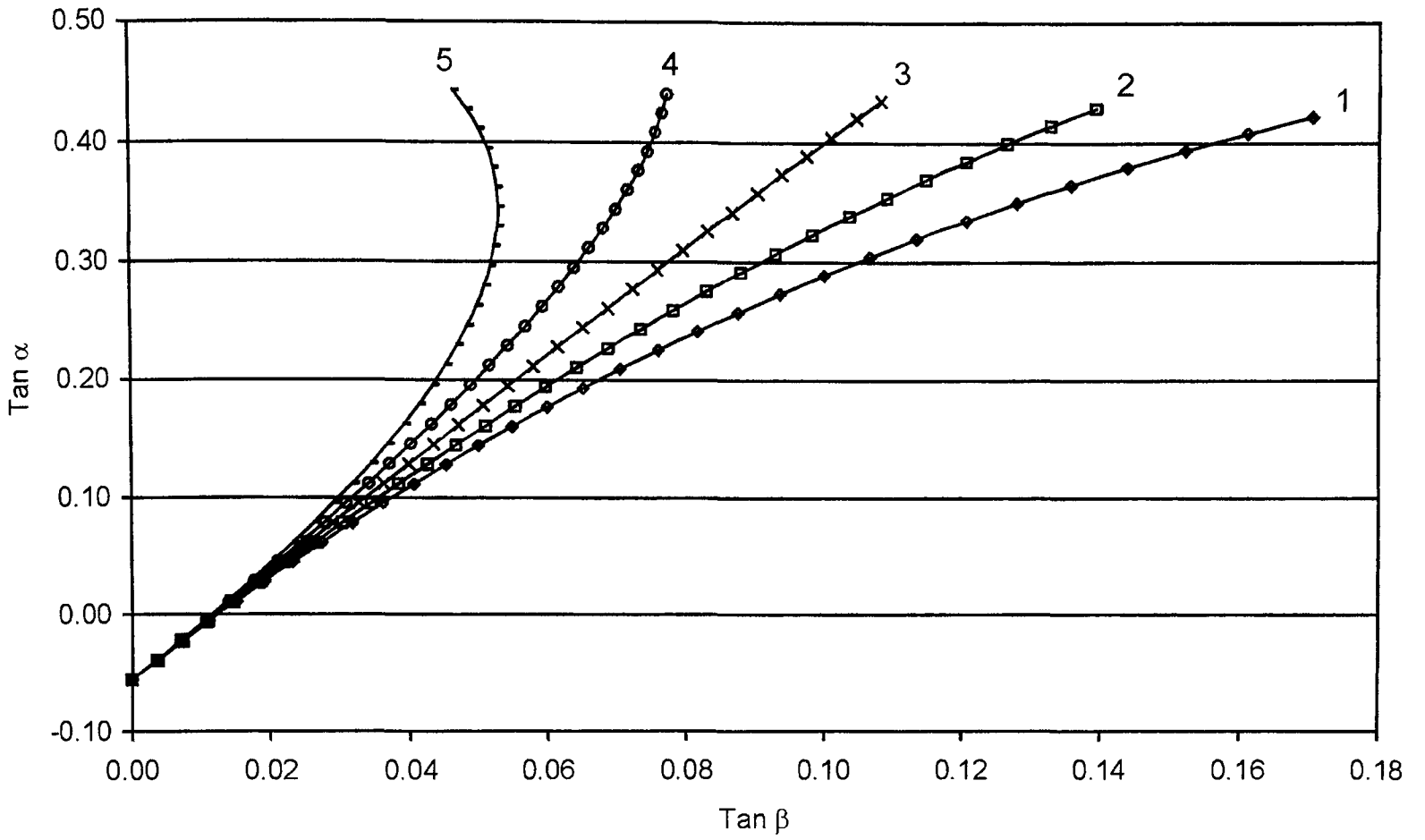


Fig. 5.9 The initial optic trajectory for a simulated fielder approaching the interception point. The numbers next to each plot correspond to the fielder finish positions shown in figure 5.8.

Figure 5.9 shows that the optic trajectory curves up when the fielder is running so that he will end up beyond the interception point. If he is running too fast toward the interception point, the rate of increase of tan β will begin to decrease, relative to the rate of increase of tan α. The relative decrease in the denominator of the ratio (tan α)/(tan β) will cause Ψ to increase and the optic trajectory curves upward. In these circumstances, the optic trajectory provides a valid cue to the fielder. The optic trajectory for the fielder moving to position 3, when he will intercept the ball is not perfectly linear as the fielder is not using an LOT strategy. However, it is remarkably straight and appears to show less curvature than some of the plots used by McBeath, Shaffer, & Kaiser (1995) to indicate linearity.

5.4.2.2. Fielder moves laterally and forwards to the interception point

In this situation, if one imagines the ball being launched directly North, the simulated fielder begins at a position 6m West and 6m North of the interception point. He moves South-East towards the interception point and finishes at various distances along the NW-SE axis. This set-up is illustrated in figure 5.10.

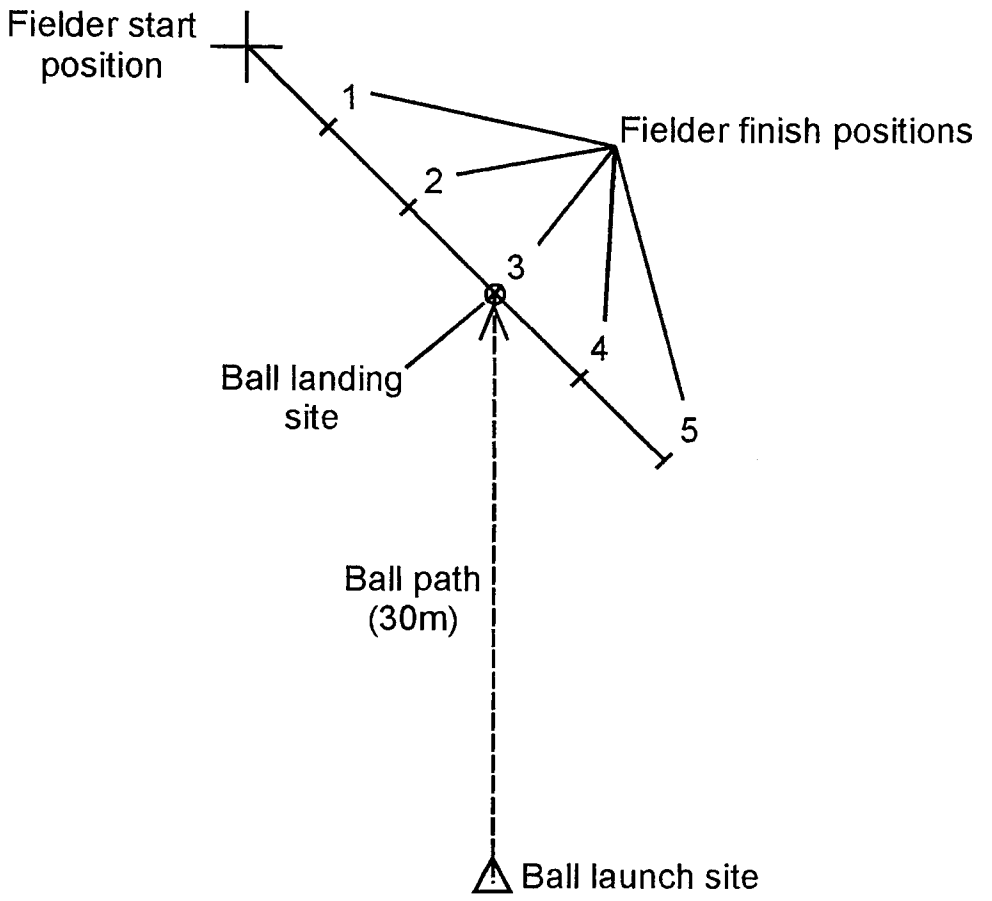


Fig. 5.10 Vertical projection of the set-up of a simulation in which a fielder must move forwards and (to his) left to reach the interception point (not to scale).

Each finish position is successively 2m further East and 2m further South of the fielder's start position, such that positions 1 and 2 are short of the interception point, position 3 coincides with the interception point, and positions 4 and 5 are beyond the interception point. Again, tan α and tan β were calculated for the fielder moving to each position and figure 5.11 illustrates the resultant optic trajectories for the first 1.2s of ball flight.

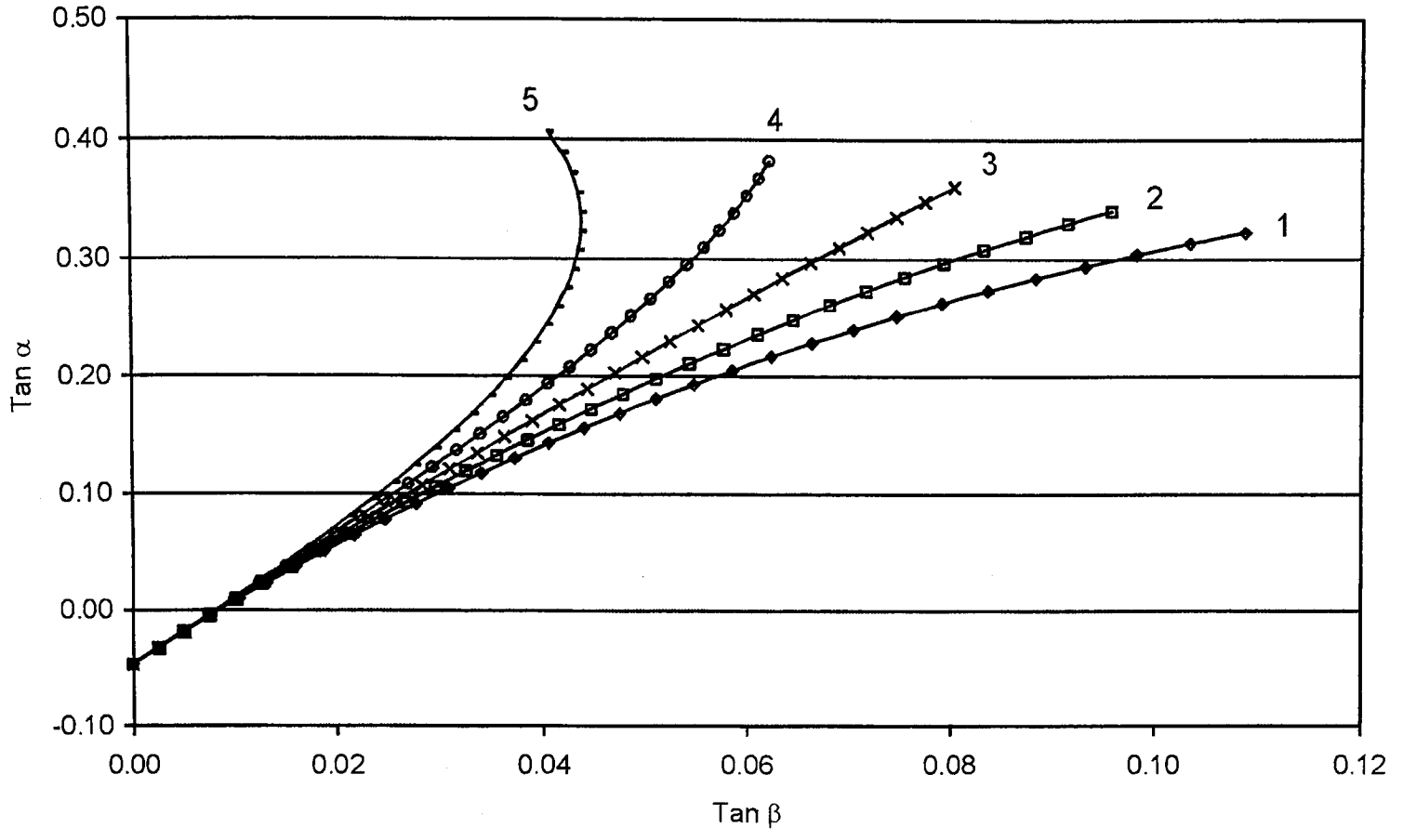


Fig. 5.11 The initial optic trajectory for a simulated fielder running forwards and left towards the interception point. The numbers next to each plot correspond to the fielder finish positions shown in figure 5.10.

The optic trajectories for the fielder moving forwards and left are remarkably similar to those for the fielder approaching the interception point moving left only. It only curves upwards when the fielder moves beyond the interception point. Again, the fielder moving at constant speed in a straight line towards the interception point (moving to position 3) seems to experience a remarkably linear optic trajectory. That aside, the optic trajectory appears to provide a valid cue in this situation. When the fielder needs to move forwards faster (finish positions 1 & 2), the optic trajectory curves down. When he is moving forwards too fast (finish positions 4 & 5) it curves up.

5.4.2.3. Fielder moves laterally and backwards to the interception point

If, again, one imagines a ball being launched directly North, the simulated fielder begins from a position 6m South and 3m West of the interception point. He therefore has to move North-by-North-East to reach the interception point and finishes at various points along the SSW-NNE axis. Figure 5.12 illustrates the set-up.

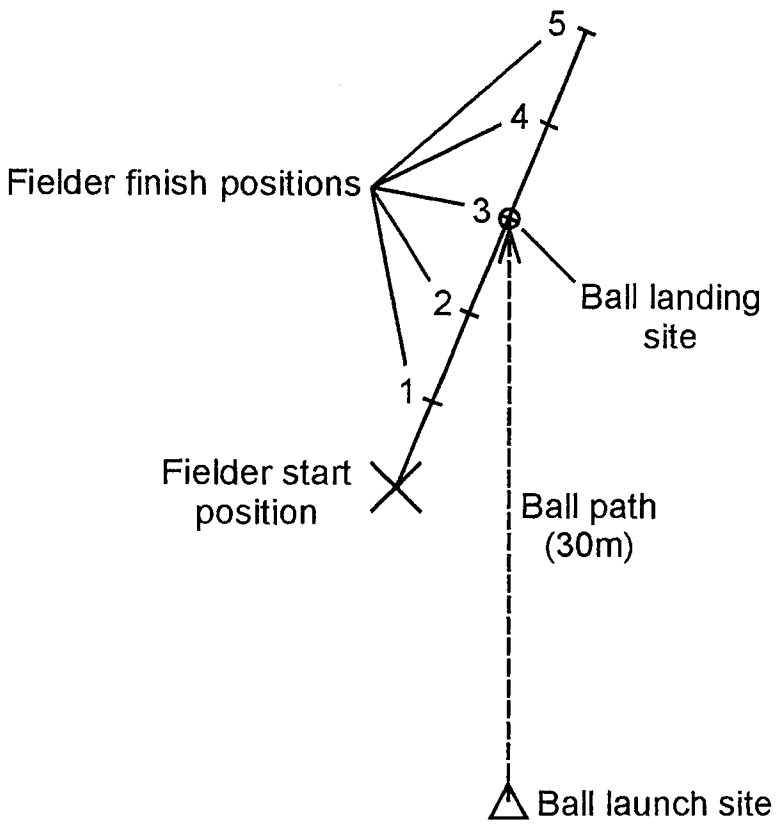


Fig. 5.12 Vertical projection of the set-up of a simulation in which a fielder must move backwards and (to his) left to reach the interception point (not to scale).

In this situation, each finish position is successively 1m further East and 2m further North. As before, position 3 coincides with the interception point. Running to positions 1 and 2, the simulated fielder needs to move faster backwards. Running to positions 4 and 5, he should move backwards less fast. Figure 5.13 illustrates what happens to the optic trajectory of the simulated fielder under these circumstances in the first 1.2s of the trajectory.

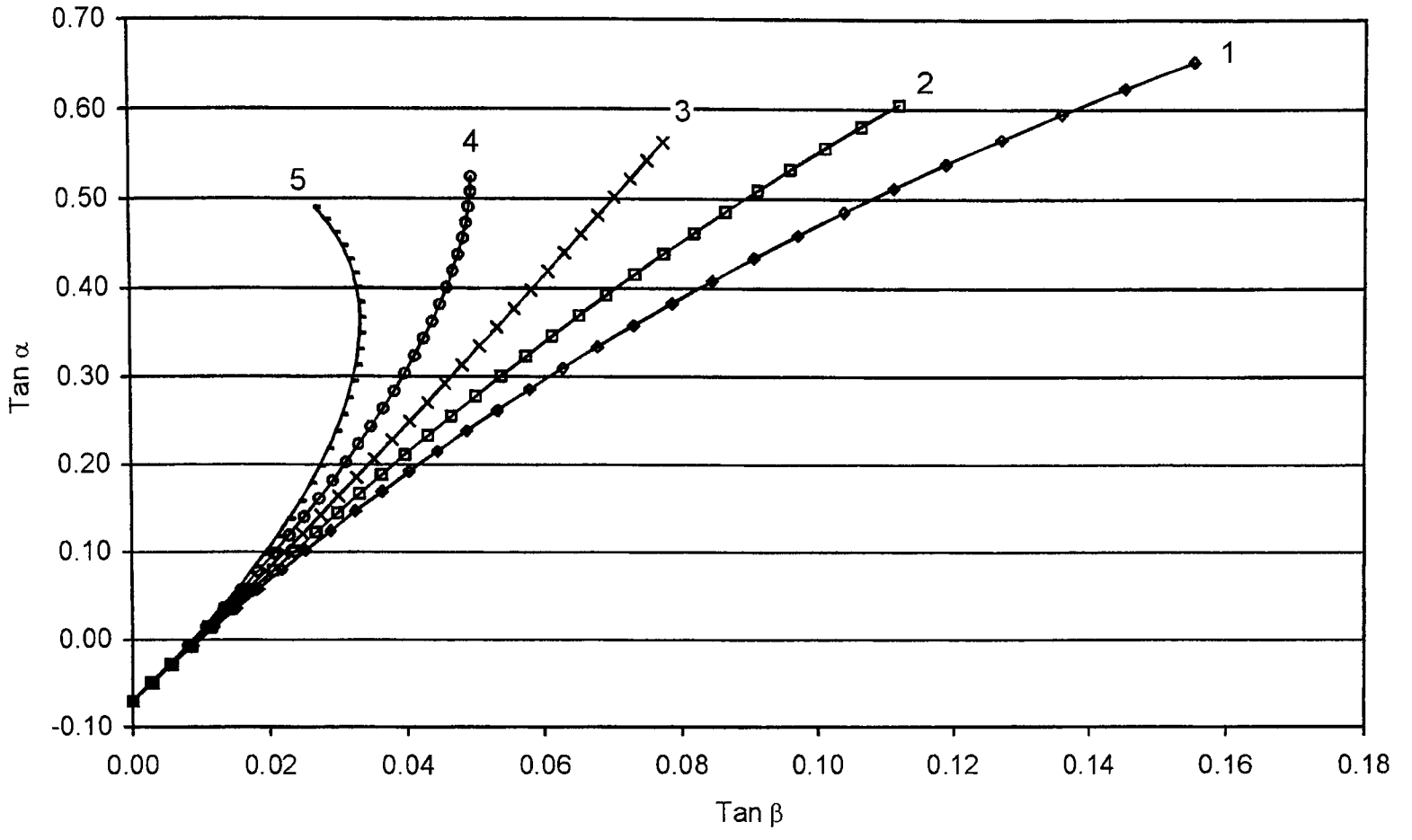


Fig. 5.13 The initial optic trajectory for a simulated fielder running backwards and left towards the interception point. The numbers next to each plot correspond to the fielder finish positions shown in figure 5.12.

The same pattern of variation in optic trajectory as was observed in the two previous situations is observed in figure 5.13. According to McBeath, Shaffer, & Kaiser (1995), the fielder should experience upward curvature of the optic trajectory running to positions 1 and 2 and downward curvature running to positions 4 and 5. The exact opposite of their prediction occurs. In each of the 3 situations studied, it is the lateral movement of the fielder that has determined the curvature of the optic trajectory. The optic trajectory does not provide a valid cue to the correct motion in depth.

5.4.3. Optic trajectory for constant speed, straight-line running paths

McBeath, Shaffer, & Kaiser (1995) claimed:

"...the OAC model predicts that fielders select a running path that is straight with constant speed, resulting in curved optical trajectory. The LOT model predicts that fielders select a running path that curves out with a ∩-shaped speed function, resulting in linear optic ball trajectory."

When McBeath, Shaffer, & Kaiser found that fielders running to catch balls followed curved, variable speed running paths they claimed it supported the LOT model over the OAC model. It was argued in chapter 1 that OAC models do not necessarily cause fielders to follow straight, constant speed running paths. The OAC model described by e.g. Michaels & Oudejans (1992) and McLeod & Dienes (1996) applies to interception in the aligned projection plane. The shape of the running path taken by a fielder intercepting a ball launched in an unaligned projection plane would depend on the utility of the cue to lateral movement that was superimposed upon his movement to cancel optic acceleration. The optic trajectory for the simulated fielders in the three situations described in section 5.4.2 was approximately linear when he would reach the interception point. It therefore seemed wise to test the claim that an LOT path would produce curved running paths with ∩-shaped speed functions. In their experiment, McBeath, Shaffer, & Kaiser (1995) launched balls on a variety of trajectories towards a fielder stood 50m from the ball launch site. They then analysed the optic trajectory observed by the fielder from the moment of ball launch until half a second before interception.

An approximate version of their experiment was analysed using a simulated ball trajectory launched at an elevation angle of 45° and that travelled 50m. This gave a ball flight duration of 3.52s. A simulated fielder was made to move at constant speed

in a straight line toward the interception point from three different positions and arrived at exactly the right time to intercept the ball. Figure 5.14 shows the set-up of this simulation.

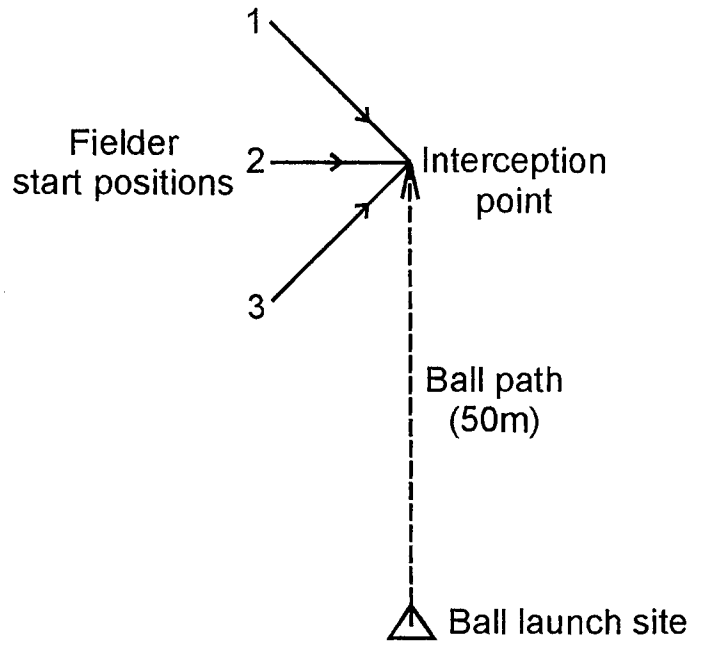


Fig. 5.14 Vertical projection of the set-up of a simulation in which a fielder moves in a straight line at constant speed to the interception point from three different start positions (not to scale).

If one assumes that the ball is launched due North, position 1 is 10m North and 10m West of the interception point. Position 2 is 10m due West of the interception point and position 3 is 10m South and 10m west of the interception point. The optic trajectory of a simulated fielder in a straight line towards the interception point was calculated for the first 3s of the ball trajectory (thus removing the last 0.52s of the flight, as performed by McBeath, Shaffer, & Kaiser (1995)). Figure 5.15 illustrates the three optic trajectories.

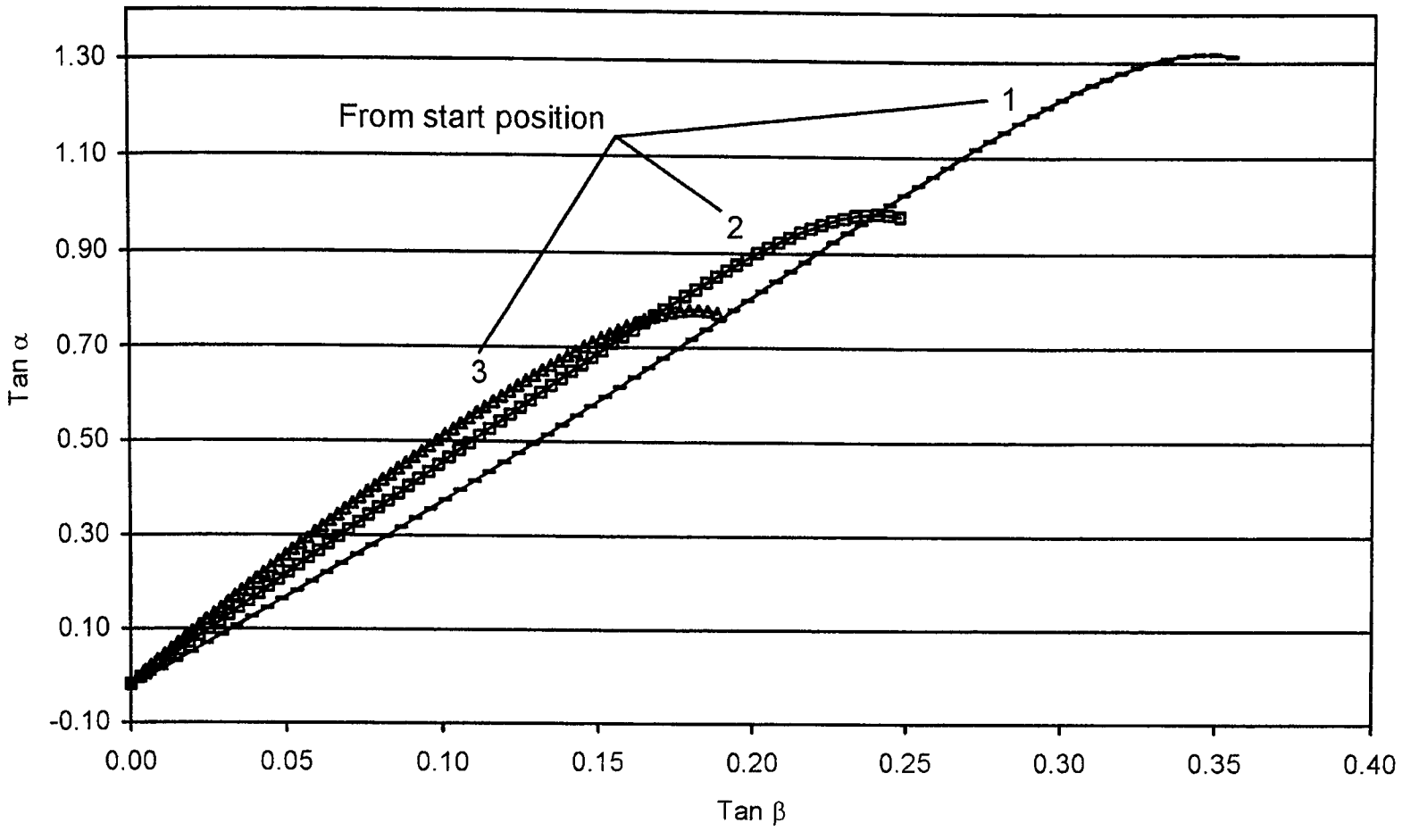


Fig. 5.15 The optic trajectory for a simulated fielder running at constant speed in a straight line towards the interception point. The numbers next to each plot correspond to the fielder finish positions shown in figure 5.14.

The optic trajectories displayed in figure 5.15 show a remarkable degree of linearity (for linear regression model, $r^2 > 0.98$ in each case). This is greater than the r^2 reported by McBeath, Shaffer, & Kaiser (1995) to claim use of a linear trajectory. The fielder in this analysis was running in a straight line and at constant speed yet he still exhibits an approximate LOT. This is at odds with the claims of McBeath, Shaffer, & Kaiser (1995). They argued that linearity of the optic trajectory would cause curved running paths with ∩-shaped speed functions. The evidence from figure 5.15 suggests that running paths that take a fielder on an approximately direct route to the interception point at the right time are likely to exhibit approximate linearity of the optic trajectory (explaining the empirical evidence reported by McBeath, Shaffer, & Kaiser (1995)).

5.5. Discussion and conclusion

McBeath, Shaffer, & Kaiser (1995) declared that the tangents of the vertical and horizontal optical angles (the tangents of α and β respectively) experienced by a fielder watching a projectile could be combined into an 'optic trajectory' of the ball moving across the background scenery. If the fielder moves so that he observes linearity of this optic trajectory, he will intercept the projectile. McBeath, Shaffer, & Kaiser (1995) proposed that a fielder could use the curvature of this optic trajectory to guide his movements towards the interception point. They claimed that this model was superior to models that relied on cancellation of optic acceleration because it required the fielder to use his sensitive discrimination of curvature rather than a relatively insensitive ability to discriminate acceleration. The validity of the LOT model and of the cue provided by the curvature of the optic trajectory was examined.

McBeath, Shaffer, & Kaiser (1996) suggested that the optic trajectory angle can be described equally well by the approximate equality: $\Psi \approx \alpha/\beta$, as by the mathematically correct equality: $\tan \Psi = (\tan \alpha)/(\tan \beta)$. Examining the optic angles experienced by fielders performing in the experiment described in chapter 4 showed that the angles reached values where this approximation is invalid. Demonstrating linearity of α/β is therefore not necessarily a valid demonstration of the linearity of the optic trajectory. However, regression analysis showed that even the plots McBeath, Shaffer, & Kaiser (1995) and Shaffer & McBeath (2002) use to demonstrate linearity of α/β show consistent downward curvature. In fact, downward curvature of the optic trajectory has been a common result in many of the analyses performed in this and the previous two chapters. It was the suggestion of McBeath, Shaffer, & Kaiser (1995) that upward curvature of the optic trajectory would indicate to the fielder that they needed to move backwards faster to reach the interception

point. However figure 5.13 showed that when a simulated fielder began in front of the interception point, it was only when he was forced to run beyond the interception point that the optic trajectory curved upwards. When he would have finished short of the interception point, McBeath, Shaffer, & Kaiser would predict that the optic trajectory would curve upwards, indicating that the fielder needed to move backwards faster. However, the optic trajectory still curved downwards. Upward curvature of the optic trajectory only appears to occur when the fielder is running so that he will overshoot the interception point in the lateral plane. This is because it is the variation in $d(\tan \beta)/dt$ that appears to dominate the determination of the shape of the optic trajectory. The angle α has a maximum value of 90°, which would only occur if the ball were directly over the head of the fielder. By contrast, the angle β can increase to an obtuse angle because it is dependent on the launch position of the ball. When a ball launched in an unaligned plane will land short of a fielder, $d(\tan \alpha)/dt$ decreases whilst $d(\tan \beta)/dt$ can continue to increase. When a ball launched in an unaligned plane will land behind a fielder, $d(\tan \alpha)/dt$ increases at an increasing rate but $d(\tan \beta)/dt$ must increase faster because β can reach an angle greater than 90° whereas α cannot. As a result, β will always tend to increase faster than α, causing the optic trajectory to curve downwards. Manipulating the movements of a simulated fielder, it was found that the only way to make the optic trajectory curve upwards was to force the simulated fielder to run beyond the interception point in the lateral direction. This causes β to shrink and the relative increase in $\tan \alpha$ therefore exceeds that in $\tan \beta$. Real fielders rarely run so that they would end up beyond the interception point. This explains the consistent finding in chapters 3 and 4 that the optic trajectory curves downward irrespective of the movement required of the fielder to reach the interception point.

Shaffer & McBeath (2002) claimed that fielders hold the optic trajectory linear for longer than they cancel optic acceleration for balls that they cannot catch and that fielders must therefore be using linearity of their optic trajectory to guide their movements. This claim is somewhat contentious as it seems that an efficient interception strategy signal the necessity of a change in running speed or path in order to make the catch as early as possible. Shaffer & McBeath (2002) claim that the optic trajectories exhibited by the subjects failing to reach the interception point in their experiment are linear. According to the LOT strategy, there would be no signal from curvature of the optic trajectory instructing them that they needed to change their running to reach the interception point. Yet they do fail to reach the interception point! By comparison, the optic acceleration of tan α provides an efficient cue to interception because it provides a clear signal to a fielder of the correct motion in depth that is required and its cancellation is a sufficient condition for interception. Further evidence that fielders do not use linearity of optic trajectory came from an examination of the variation in α and β over time for a single trial from chapter 4. Initially, the ratio α/β appeared to be constant when it was at this moment that there should be a signal to move. The ratio deviated from constancy as the fielder began to move. This is the diametric opposite of what one would expect if fielders were following the LOT model. According to that, fielders should move to hold the ratio of the optical angles constant. However, the analysis of the empirical data showed the optic trajectory was linear initially and became non-linear as the fielder moved.

A remarkable effect was observed in figures 5.9, 5.11, and 5.13. They showed that a simulated fielder approaching the interception point in a straight line and at constant speed observed an approximately linear optic trajectory. McBeath, Shaffer, & Kaiser (1995) claimed that a fielder using the LOT model would follow a curved

running path that had a ∩-shaped running speed function. To test this hypothesis, a simulated fielder ran at constant speed in a straight line from different start positions to intercept a ball on a trajectory approximating one of those used in McBeath, Shaffer, & Kaiser (1995). If McBeath, Shaffer, & Kaiser's claim was correct, the fielder should experience a curved optic trajectory. However, the optic trajectory of the simulated fielder showed greater linearity than that observed of fielders in McBeath, Shaffer, & Kaiser (1995) which they use to demonstrate the LOT model. This contradictory result suggests that fielders following a variety of running paths towards the interception point may experience reasonable linearity of the optic trajectory.

In chapters 3 and 6, simulations model a fielder following a LOT strategy. The model appears effective in guiding the fielder to the interception point. This might seem surprising given the evidence suggested in this chapter. However, in modelling the strategy, the simulated fielder does not respond to curvature of the optic trajectory as McBeath, Shaffer, & Kaiser (1995) predict real fielders do. The simulated fielder always moves to a position that ensures linearity of the optic trajectory by causing tan α and tan β to increase at a constant rate. Since maintenance of a LOT in this manner is a mathematical solution to the outfielder problem, he reaches the interception point. Figure 5.7 showed that the optic trajectory uniquely specifies the landing location of the ball, so the optic trajectory does contain information about the interception point. However, for each different landing location the optic trajectory showed slight downward curvature. Although maintaining a linear optic trajectory is a solution to the outfielder problem, curvature of the optic trajectory as a cue to interceptive behaviour is ambiguous.

The LOT model is a mathematical solution to the outfielder problem, yet its claim that fielders can use curvature of the optic trajectory to guide their movement appears unwarranted. Consequently, the use of α as a cue to interception strategy (as advocated e.g. Chapman (1968), Michaels & Oudejans (1992), McLeod & Dienes (1996)) appears safe. Analysis of the optic trajectories has shown that curvature of the optic trajectory does not provide a fielder with clear information about the correct course of action. Although the LOT model is an elegant solution to the outfielder problem, the evidence presented in this chapter suggests that human fielders would be unable to use the curvature of the optic trajectory to guide their interceptive behaviour as prescribed by McBeath, Shaffer, & Kaiser. Since the LOT model appears inadequate and the OAC model does not specify how a fielder moves laterally, possibilities for a theory that adds a component of lateral control to the OAC theory are investigated in chapter 6.

6. Alternative strategies to LOT

6.1. The need for an alternative to LOT

McBeath, Shaffer, & Kaiser's LOT strategy (1995) is a mathematical solution to the outfielder problem. Interception is assured since tan α is (indirectly) controlled to increase at a constant rate whilst tan β increases at a proportional and therefore constant rate. If a fielder can run to maintain this relationship, he is guaranteed to intercept the ball because the ball cannot pass beyond him to the side, fall short or fly over his head. McBeath, Shaffer, & Kaiser (1995) showed that the LOT model is a reasonable approximation of human interceptive behaviour. However, chapters 3, 4, & 5 showed that the LOT strategy is flawed in modelling human interceptive performance, supplementing criticisms of the LOT model raised by Dannemiller, Babler & Babler (1996) and Jacobs et al. (1996) in a technical commentary on McBeath, Shaffer, & Kaiser (1995) (see chapter 2). Accepting these criticisms, this chapter seeks a more appropriate model of human interception. Tresilian (1995) proposed a model for interception based on the ideas of Chapman (1968), where a fielder seeks to run so that $d^2(\tan \alpha)/dt^2$ is held at zero. He failed to find a suitable model but suggested that the addition of a more appropriate control variable for lateral movement could yield a satisfactory model. Examples of such models are examined here.

McBeath, Shaffer, & Kaiser (1996) responded to the limitations of the LOT model noted in the technical commentary. They stated that if an alternative strategy to LOT based on OAC were to be accepted, it should account for three empirical findings:

1. Balls hit to the side (as opposed to in the aligned plane) seem easier to catch.
2. Fielders generally run along curved paths with ∩-shaped speed functions.
3. Spatial strategies are noted in other domains of tracking.

The explanation for their first point seems relatively simple to rationalise. Catching in the aligned plane allows control of running in one dimension only. The way a fielder controls his running must be quite specific. To catch a ball projected in an unaligned plane, a fielder controls his running in two dimensions. Therefore, there are a larger number of paths that will lead to successful interception, allowing a fielder more variation in his running strategy. This should render the task easier to accomplish. Furthermore, if the cue to lateral movement were easier to detect than that for motion in depth, a fielder would find it easier to begin running giving the impression that it was a simpler catch. The credence of McBeath, Shaffer, & Kaiser's second item is uncertain. McLeod & Dienes (1996) found that fielders did not produce consistent running speed patterns – running speed variation tended to reflect the distance the fielder had to run to reach the interception point. If fielders had to run a relatively long distance in a short time then they accelerated throughout the ball's flight. Less far, and the fielders' initial acceleration abated and they maintained a constant velocity until interception. When fielders only had to move a short distance, they accelerated and then decelerated (producing a ∩-shaped speed function). However, a consistent feature of the fielders' movement was that in all cases they moved to null optical acceleration. Consequently, the strategies proposed to model human interception in this chapter do not contain any explicit constraint that running paths should exhibit a ∩-shaped speed function. McBeath, Shaffer, & Kaiser's third point is not within the remit of this thesis. However, it would be interesting to investigate whether the concepts developed are relevant to the interceptive/avoidance

behaviour of other organisms. In examining the behaviour of other organisms it would be important to ensure that the task under test was compatible with a catching task. The human behaviour when catching a ball appears related specifically to the projectile trajectory of the ball. It is unlikely that the same strategies would be employed for interception by an organism underwater or one capable of flight.

6.2. Characteristic properties of human interception

There are properties of human interception that are reliably observed in all fielders. Any strategy devised to model human interceptive behaviour should simulate these properties. The two essential features that were observed in chapters 3 and 4 were firstly, a constant increase in tan α until the final moments before interception. This has been consistently recognised in aligned catching experiments (McLeod & Dienes (1996), Michaels & Oudejans (1992)) where the fielder only needs to move in the depth dimension. It is now clear that tan α is also controlled, directly or indirectly, to increase at a constant rate by fielders running in two dimensions to intercept a projectile (McBeath, Shaffer, & Kaiser (1995), chapters 3 and 4). Secondly, fielders follow curved running paths – convex if running backward, concave if running forward, relative to the origin of the ball. The proposed strategies should produce running paths that curve in a similar manner.

Four alternative interception strategies to the LOT model are proposed, all of which could conceivably be used for interception. Each of the strategies advances an imaginary fielder to the correct place at the correct time – they are mathematical solutions to the outfielder problem. Each strategy has as its input the frame-by-frame ball trajectory data from chapters 3 and 4 and this is used to calculate an estimate of where each of the interception strategies would position a fielder at each time interval. The position of the simulated fielder can be compared to where the real fielder was at

the same moment. It is then possible to assess which strategy is most effective in modelling human interceptive behaviour.

6.3. Constraints applied to the simulated fielder

The programs that implement the proposed strategies guide a simulated fielder to the interception point. A simulated fielder, existing as a co-ordinate position in a computer program, is not burdened by Newtonian laws of motion and has no tangible processing or reaction time. To make the behaviour of the simulated fielder more realistic, his motion was modified by the inclusion of certain constraints in the programs. These are outlined below.

6.3.1. Initial movements

For approximately half a second after the ball is released, any movements made by real fielders do not appear to be guided by a specific cognitive program intended to produce locomotion toward the interception point. It is likely that this movement arises to get the fielder moving so that subsequent movements guided by a strategy for interception are easier to implement, improving efficiency of the strategy. To accommodate this motion in modelling fielder behaviour, the first ten frames of the real fielders' actual movements were used to initiate the movement predicted by the strategies. Each frame is separated by an interval of 40msec; therefore, this period is equivalent to waiting 400msec before engaging the interception strategy. This feature was not included in the programs modelling interception strategy in chapter 3.

6.3.2. Limits on movement

In an attempt to produce motion analogous to that produced by real fielders, the simulated fielder is restricted by human-like maximum values of acceleration and running speed. To restrict speed, the fielder was prevented from moving more than

15cm between frames. As mentioned earlier, each frame is separated by an interval of 40msec so this equates to a maximum speed of $3.75ms^{-1}$. Acceleration was constrained by restricting the changes in the distance moved by a fielder in successive time intervals to 0.48cm. This limit equates to a maximum acceleration of $3ms^{-2}$. If the position that the simulated fielder should move to, as calculated by the strategy, exceeds either of these limits on motion then the simulated fielder moves as close to that point as possible, without exceeding the limitations.

The limits on motion are not intended to reflect the absolute maximum acceleration or velocity that a human fielder can attain. However, in the trials, these maximum values account for the vast majority of performance. The fielders' motion exceeded these values several times in some trials. However, this did not appear to reflect the fielder's true motion. For example, if a fielder exceeded the suggested maximum velocity in one frame interval this was usually preceded or followed by a frame interval in which that fielder's velocity fell below the maximum by an equivalent amount. This suggests that there was a slight error in recording the fielder's position and that the fielder's true velocity/acceleration lay somewhere between the two values.

For listings and an explanation of the Visual Basic programs used to model the strategies see appendix A6.1.

6.4. New strategies

Chapters 3 and 4 demonstrated the consistent finding that real fielders move so that tan α increases at a constant rate for the majority of the ball flight. This led to the assertion that, centred directly beneath the ball at eye-level, there is a ring of points for which tan α will be of the value that results in constant $d(\tan \alpha)/dt$ throughout the ball's flight. For a real fielder to achieve a constant rate of change of α, at each

0.04second time interval the fielder must move to a position somewhere on the next ring. Fig 6.1 shows the variation in this ring of points for a simulated ball trajectory.

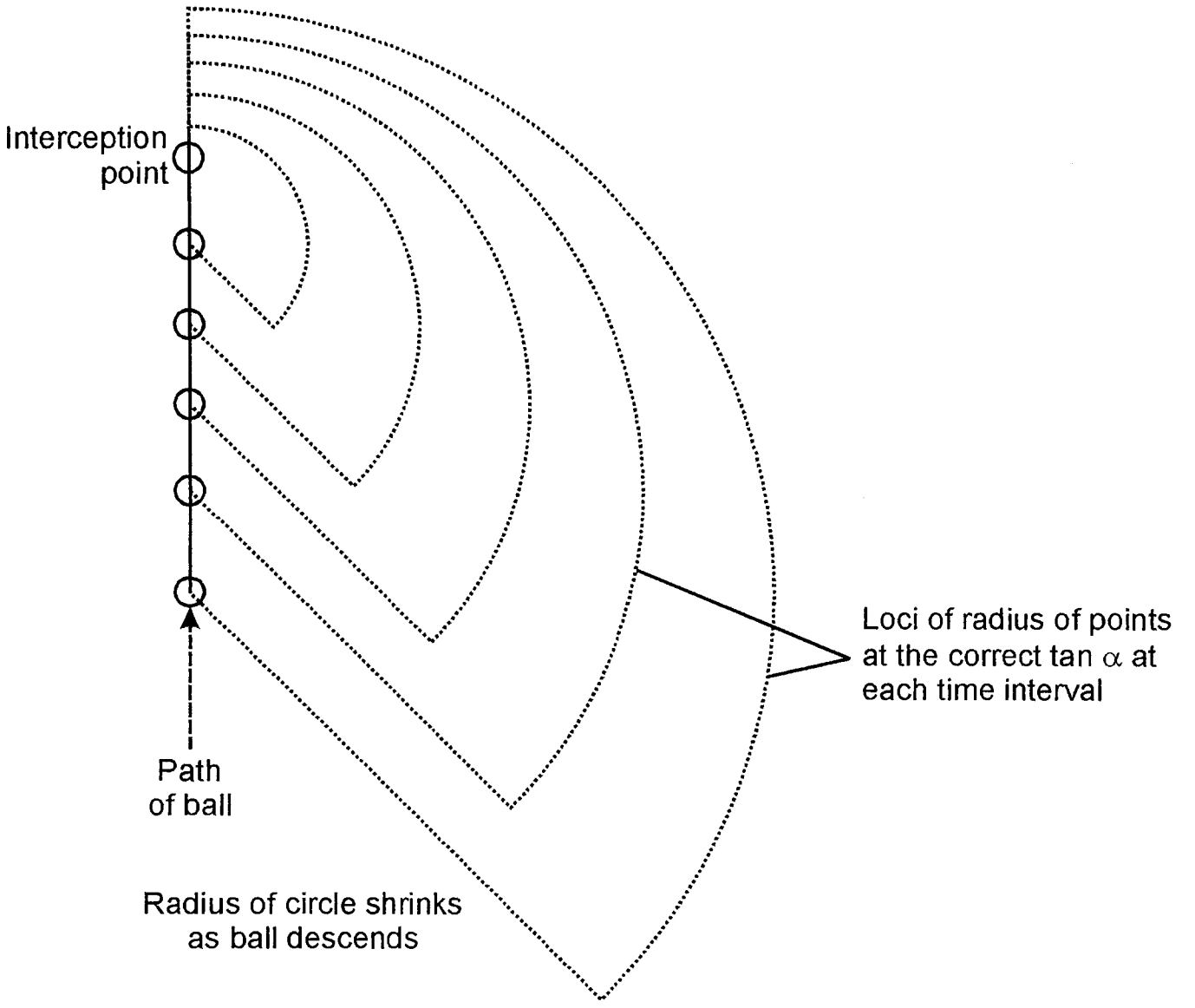


Fig. 6.1 Vertical projection showing the successive circular loci of points at which the correct tan α would be observed for a projectile.

Each ring indicates points at which tan α is at the correct value to maintain constant d(tan α)/dt for that particular ball position. The radius of successive rings becomes smaller as the ball approaches eye-level. Consequently, a fielder keeping d(tan α)/dt constant will get progressively nearer to the ball. The proposed strategies attempt to position the simulated fielder at some point on the appropriate ring at each time interval. Each strategy takes into consideration the maximum values of running speed and acceleration imposed on the simulated fielder and ensures they are not violated.

6.4.1. Minimum energy strategy

Using the rings that give constant d(tan α)/dt (shown in figure 6.1), the minimum energy strategy instructs the simulated fielder to move to the nearest point on successive rings, thereby minimising exertion. This is an appealing strategy since it appears to represent an efficient technique for getting from the start position to the interception point in a consistent and error-correcting manner. It is unclear whether the minimum energy strategy will yield running paths that exhibit the same curvature as those generated by real fielders. However, if it fails to model human behaviour accurately the strategy must be rejected as a valid model of human interceptive performance, no matter how appealing it seems.

6.4.2. Constant δ strategy

The program used to assess this technique is an adapted version of that used to implement the constant δ strategy described in chapter 3. The simulated fielder moves laterally so that he does not need to rotate his lateral angle of gaze in order to maintain fixation of the target projectile. This prevents lateral movement of the ball on his retina. This strategy is appealing because a fielder following the constant δ strategy to intercept a projectile in the unaligned plane reduces the problem of interception to that faced by a fielder attempting to intercept a projectile launched in the aligned plane. The visual experience of the fielder in each case will be a ball ascending vertically with constant d(tan α)/dt. The computer model uses the sequence of shrinking rings that represent the loci of positions which maintain constant d(tan α)/dt, shown in figure 6.1. It also has a more efficient mechanism for dealing with the limits on acceleration and velocity. Figure 6.2 illustrates how lateral movement is controlled using this scheme.

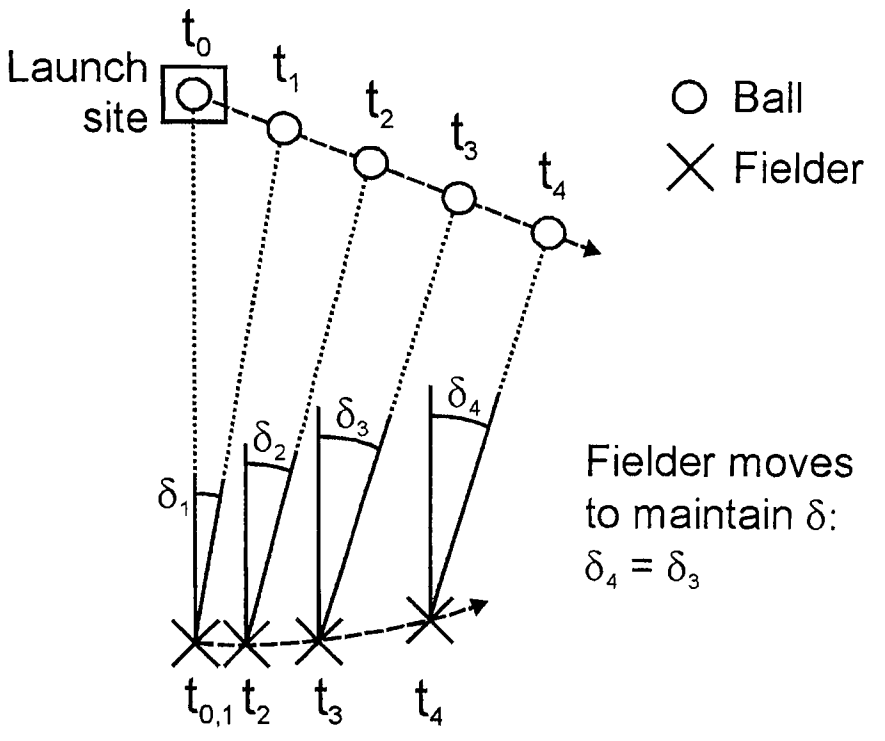


Fig. 6.2 The constant δ strategy (shown in vertical projection).

At t_0, the fielder and ball are aligned and therefore δ equals 0. At t_1, δ has exceeded the threshold for detection of the ball moving outside of the aligned plane and the fielder can start moving to stop this angle increasing. By t_2, the fielder has begun lateral movement but is not moving fast enough to hold δ constant and so δ continues to increase. However, by t_3, the fielder is moving fast enough to hold δ constant and so $\delta_4 = \delta_3$. At some point, the fielder must detect the acceleration of tan α and begin movement in depth according to its sign. If this happens after t_1, then running paths will curve in the manner observed in chapters 3 and 4. The constant δ strategy described in chapter 3 applied this constraint explicitly by ensuring that lateral motion began before motion in depth (and was proposed to reflect this feature of interception). In this version of the constant δ strategy, the characteristic curvature of running paths will only result if the simulated fielder accelerates laterally (to maintain constant δ) faster than the acceleration in depth when moving from one ring to the next (to maintain constant d(tan α)/dt). The angle δ is maintained relative to the original alignment that existed between ball and fielder at launch. However, like the

model proposed by Tresilian (1995), control of δ could be relative to an arbitrary horizontal direction.

6.4.3. Conserved alignment strategy

McBeath, Shaffer, & Kaiser (1995) suggested that this strategy was how the interception strategy proposed by Chapman (1968) should be extended to cope with interception in two dimensions. The lateral position of the simulated fielder is adjusted by matching it to the lateral motion of the ball. This strategy moves the simulated fielder so that he attains and then sustains the alignment that existed between him and the ball at launch. Conserved alignment differs from the constant δ strategies because the angle to be maintained is set before the ball has been launched. The left panel of figure 6.3 shows the conserved alignment strategy as applied to the experimental set-up from chapter 3. The right half shows the strategy as applied to the experimental set-up from chapter 4[1]. The description of how the strategy works applies equally to simulated fielders in both experiments.

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[1] In chapter 3, the initial plane of alignment happened to be parallel relative to the Y-axis of the co-ordinate system used the map the catching area and therefore appears vertical. In chapter 4, although the initial plane of alignment was not parallel to the co-ordinate system used but the strategy still operates successfully in directing the simulated fielder to the interception point.

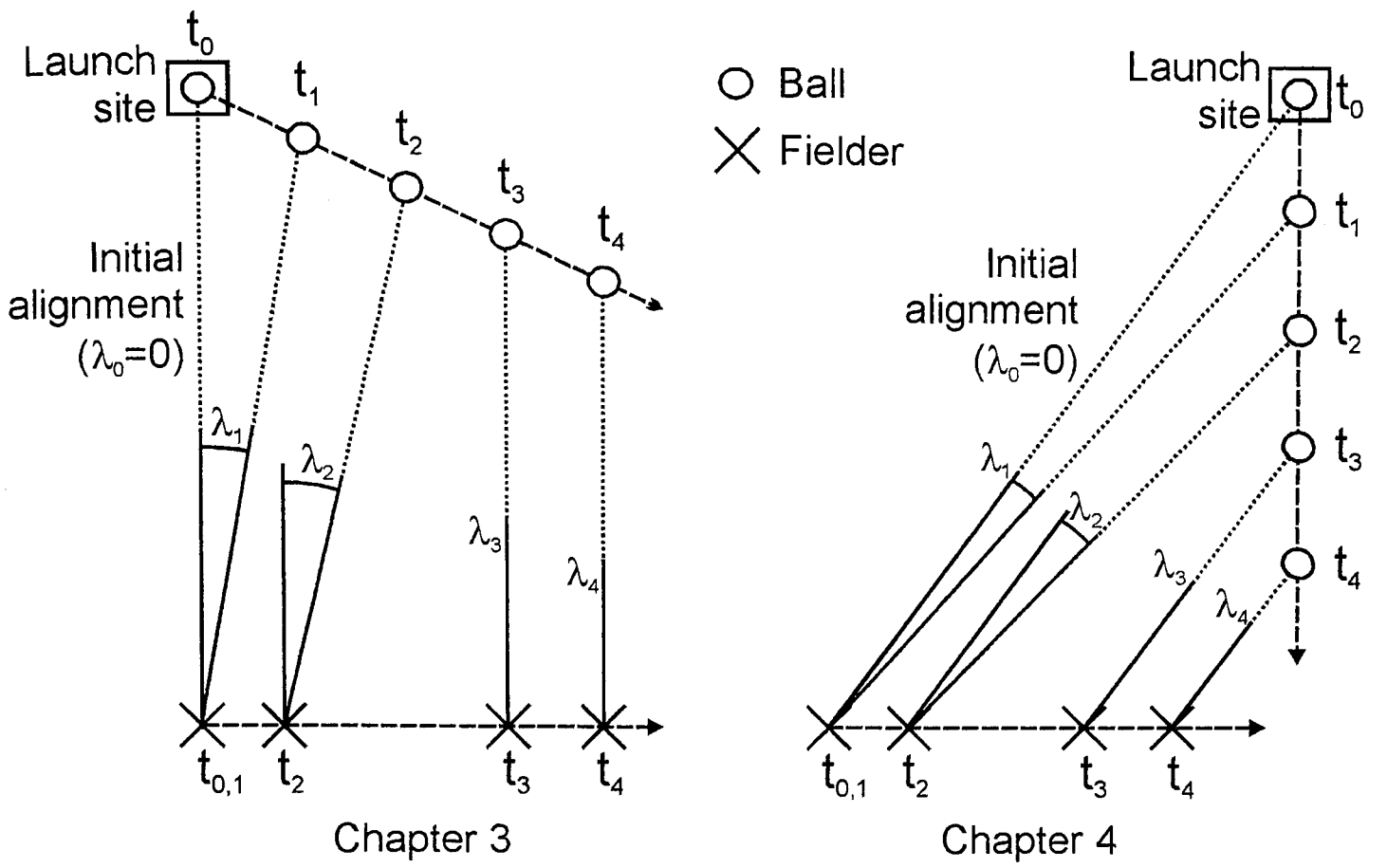


Fig. 6.3 The conserved alignment strategy (shown in vertical projection).

At t_0, the fielder and ball are in an apparently aligned plane. The angle λ, representing the angular deviation from this alignment, is zero ($\lambda_0 = 0$). At t_1, the ball has moved out of alignment generating an angle, λ_1. In this strategy, this is the cue for lateral motion since the fielder must move to restore λ to λ_0. By t_2, the fielder has not attained enough velocity to restore λ to λ_0, in fact in the examples shown figure 6.3, λ_2 is larger than λ_1. However by t_3, the fielder has attained enough velocity to not only stop λ increasing, but has restored the initial alignment such that $\lambda_3 = \lambda_0 = 0°$. After t_3, the fielder must reduce lateral velocity or λ will be induced by the fielder going beyond the point parallel to λ_0. At t_4, the fielder has successfully adjusted lateral velocity to preserve λ. As a result, $\lambda_4 = \lambda_3 = \lambda_0 = 0°$.

The simulation executes this strategy using the shrinking loci of points that keep the rate of change of tan α constant. After the initial pause, the program attempts to place the fielder at a position on the ring of loci that restores alignment to its original

state – nulling λ. Again, successive reduction in the radius of this ring will bring the fielder to within interception range as the ball falls to earth.

6.4.4. Constant γ strategy

This is a unique strategy that links a fielder's running path to the angle through which the fielder has had to turn in order to fixate the ball. Of the five strategies examined, it is the only one to use the direction of the fielders running path as an integral component of determining the subsequent running direction a fielder must take. Figure 6.4 shows a simulated fielder following the constant γ strategy

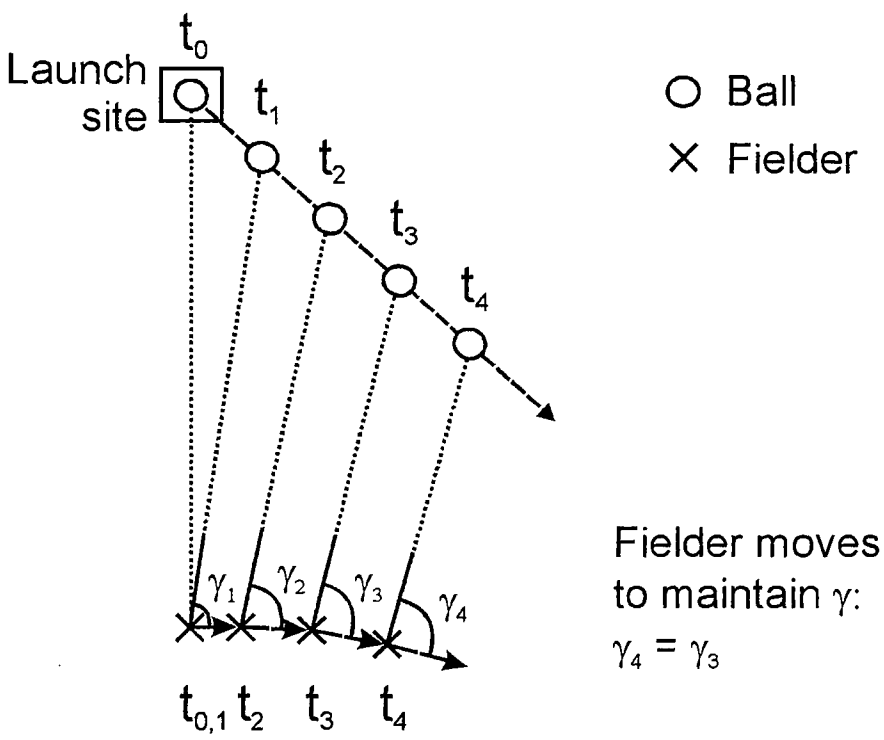


Fig. 6.4 The constant γ strategy (shown in vertical projection).

At t_1, the fielder has detected the lateral movement of the ball out of the aligned plane. He must therefore begin moving in the same lateral direction as the ball to reach the interception point. By moving laterally, an angle is generated between the direction of the ball from the fielder and the direction of movement of the fielder. This angle is designated γ. For a trial where the fielder must move backward to intercept the ball (as shown in figure 6.4), γ will grow before the fielder reaches a

speed that can keep γ constant. Conversely, if the fielder must move forwards, γ will shrink as the fielder accelerates. Movement is then directed so that d(tan α)/dt remains constant (by moving to a position on the rings that give the correct tan α shown in figure 6.1) and γ stays constant. This ensures that the fielder will intercept the projectile and should lead to running paths that curve in the manner expected.

6.4.5. The LOT strategy

For completeness, a version of the LOT model was included in the strategy analysis. The model under test does not use curvature of the optic trajectory to guide fielder movement as prescribed by McBeath, Shaffer, & Kaiser (1995). It simply attempts to move the fielder to a position that ensures constant d(tan α)/dt (thereby ensuring interception) and also constant d(tan β)/dt, giving a linear optic trajectory. The program that was used in chapter 3 was improved so that the simulated fielder moves across the rings of loci that give constant d(tan α)/dt rings. The LOT modelling program attempts to get the fielder to move to a position on each ring that gives him a constant increase in tan β. Once the fielder is up to speed, he should run so that he experiences monotonic increases in tan α and tan β and therefore, a linear optical trajectory.

6.5. Method

The programs devised to model each strategy were run on all trials. Each took the first 10 frames of the actual fielder's movement to initiate the movement of the simulated fielder and to set the appropriate rate of change of the visual angles (or their tangents). From that point on, the input to the relevant program was the X, Y, and Z co-ordinates of the ball in the next frame. It then moved the simulated fielder to a new position based on that information, giving him new X-Y co-ordinates. This continued

until the ball was in its final position i.e. when the real fielder caught it. The movement of the simulated fielder produced by the strategies could then be compared to the movement of the real fielder.

6.6. Results

The five strategies under test were run on trials from the experiments described in chapters 3 and 4. To simplify presentation of the results, the experiments from chapter 3 shall be referred to as the 'roof' experiment (a reference to the site from which balls were projected in each session). Consequently, the experiment from chapter 4 shall be referred to as the 'ground' experiment. Combining data from the two experiments provided 328 trials for analysis. For each trial, a true position of the real fielder and a position of the simulated fielder (as directed by the relevant interception strategy) were obtained for every frame of video footage analysed.

Each strategy produced simulated fielder movement that was sometimes a very close approximation of the real fielder and at other times, the models were less successful. Examples of fielder movements guided by the interception strategies in comparison to the movements of the real fielder are shown in appendix A6.2. The performance of each strategy was assessed by using the X-Y co-ordinate of the real fielder and that of the simulated fielder to calculate the distance between the two (in centimetres) for each analysed frame. Calculating a mean value of the distance of the simulated fielder from the real fielder over all the frames of a trial gave a measure of the performance of each strategy for that trial. Overall performance across all trials in both of the experiments was considered first, then performance in each experiment is assessed separately. The statistics carried out on in this section are shown in appendix A6.3.

6.6.1. Overall performance of each strategy

Figure 6.5 presents a bar graph showing the mean performance of each of the strategies for all trials across both experiments.

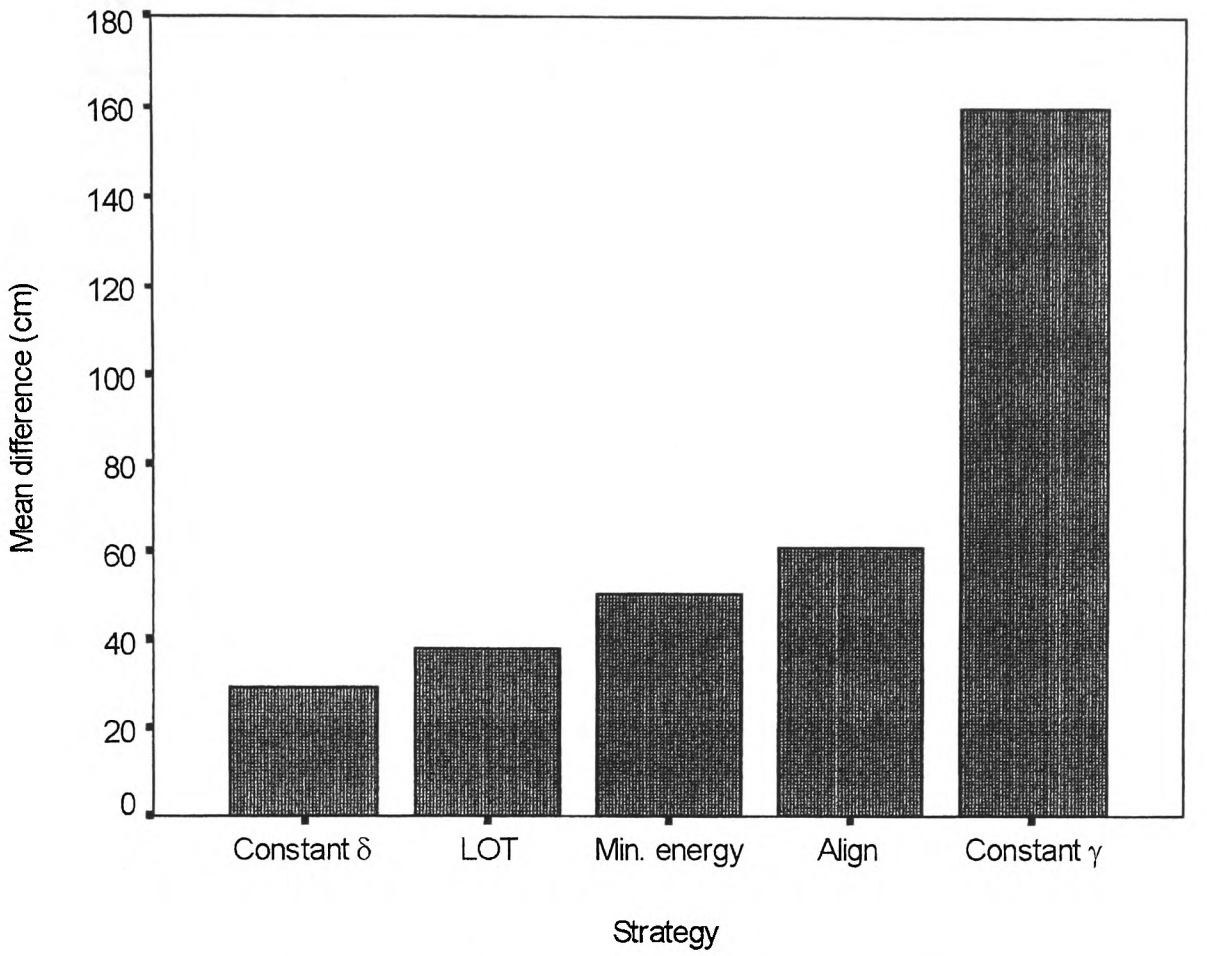


Fig. 6.5 Bar graph showing the overall performance of the five interception strategies.

The poor performance of the constant γ is obvious. The mean distance between the real fielder and the simulated fielder over all trials for the constant γ strategy is far greater than that of the poorest of the four other strategies. The best performing strategy is the constant δ strategy. On average, it places the simulated fielder just under 30cm from the real fielder at each 0.04sec time interval. This is reasonably impressive given the variability in accuracy with which the true position of the fielder could be estimated (Mean accuracy for this estimation was ±15.9cm, see appendix A1). The LOT strategy was next best, followed by the minimum energy strategy and the conserved alignment strategy, with the constant γ strategy clearly worst. Table 6.1

summarises the performance of each strategy (N: Number of trials, Mean diff.(cm): Mean difference between real and simulated fielders over all trials).

Strategy	Constant δ	LOT	Min. energy	Alignment	Constant γ
N	328	328	328	328	328
Mean diff.(cm)	29.4	38.3	50.7	61.2	159.9
SD	13.6	16.8	26.9	30.2	87.8

Table 6.1.

Wilcoxon tests found that the comparison of mean performance of each strategy with its four rivals produced highly significant results ($p < 0.001$ in each case). The exceptionally poor performance of the constant γ strategy meant that it was omitted from further analysis. The reasons for its omission are explained in section 6.7.

6.6.2. Performance in the roof experiment

Figure 6.6 illustrates the performance of the four remaining strategies in the roof experiment.

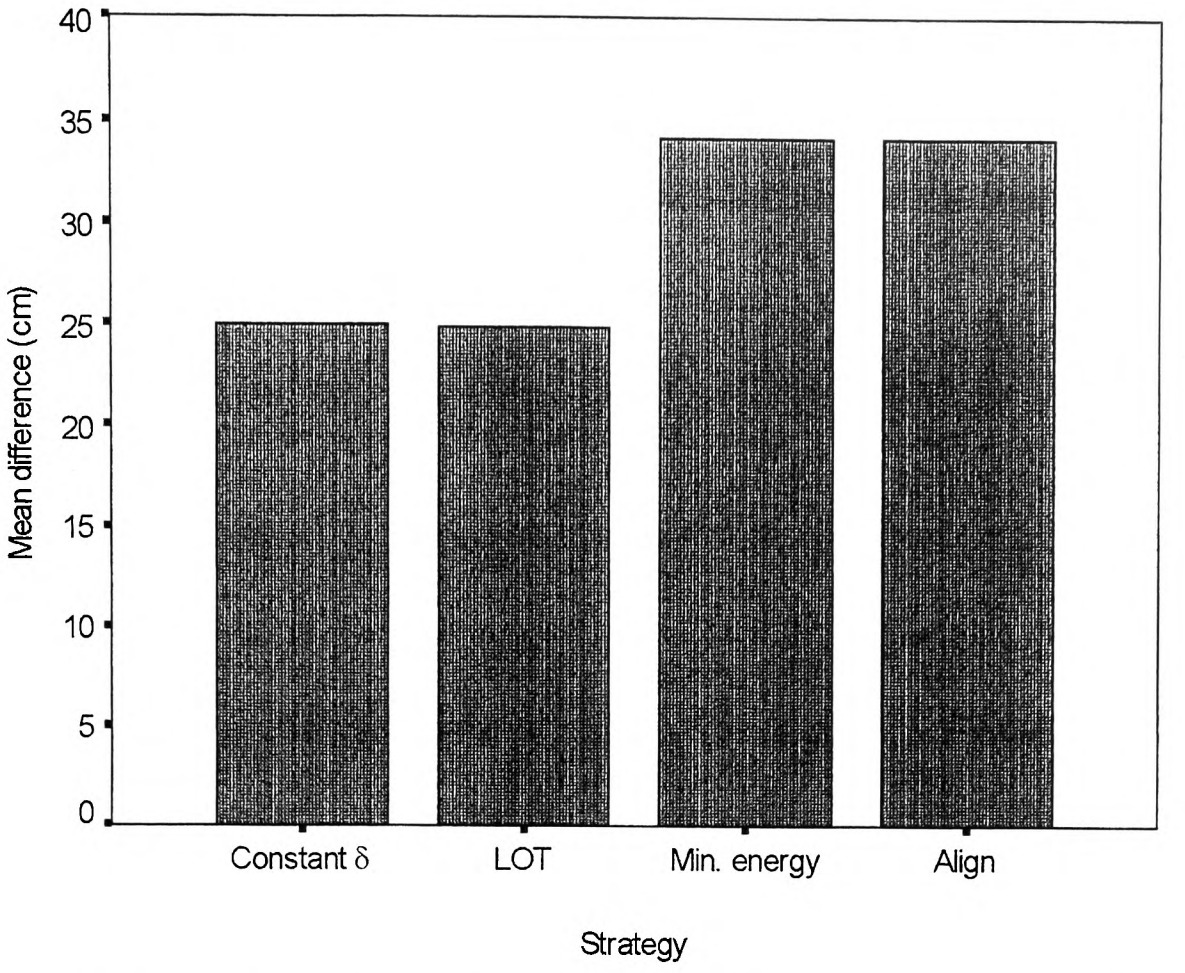


Fig. 6.6 Performance of the four interception strategies in the roof experiment.

The constant δ strategy and the LOT strategy perform virtually identically, placing the simulated fielder, on average, just less than 25cm from the real fielder's position at each 0.04sec interval. The minimum energy and conserved alignment strategies also produce similar performance, both scoring an average mean difference of just less than 35cm. Table 6.2 shows the exact performance of each strategy.

Strategy	Constant δ	LOT	Min. energy	Alignment
N	153	153	153	153
Mean diff.(cm)	24.9	24.8	34.2	34.2
SD	11.1	10.8	21.3	12.4

Table 6.2.

Wilcoxon tests were performed to compare the performance of the four strategies. All comparisons were highly significant ($p < 0.001$ in each case) with the exception of the comparison between the constant δ and the LOT strategies ($p > 0.95$)[2].

6.6.3. Performance in the ground experiment

Figure 6.7 shows the performance of the four strategies in the ground experiment.

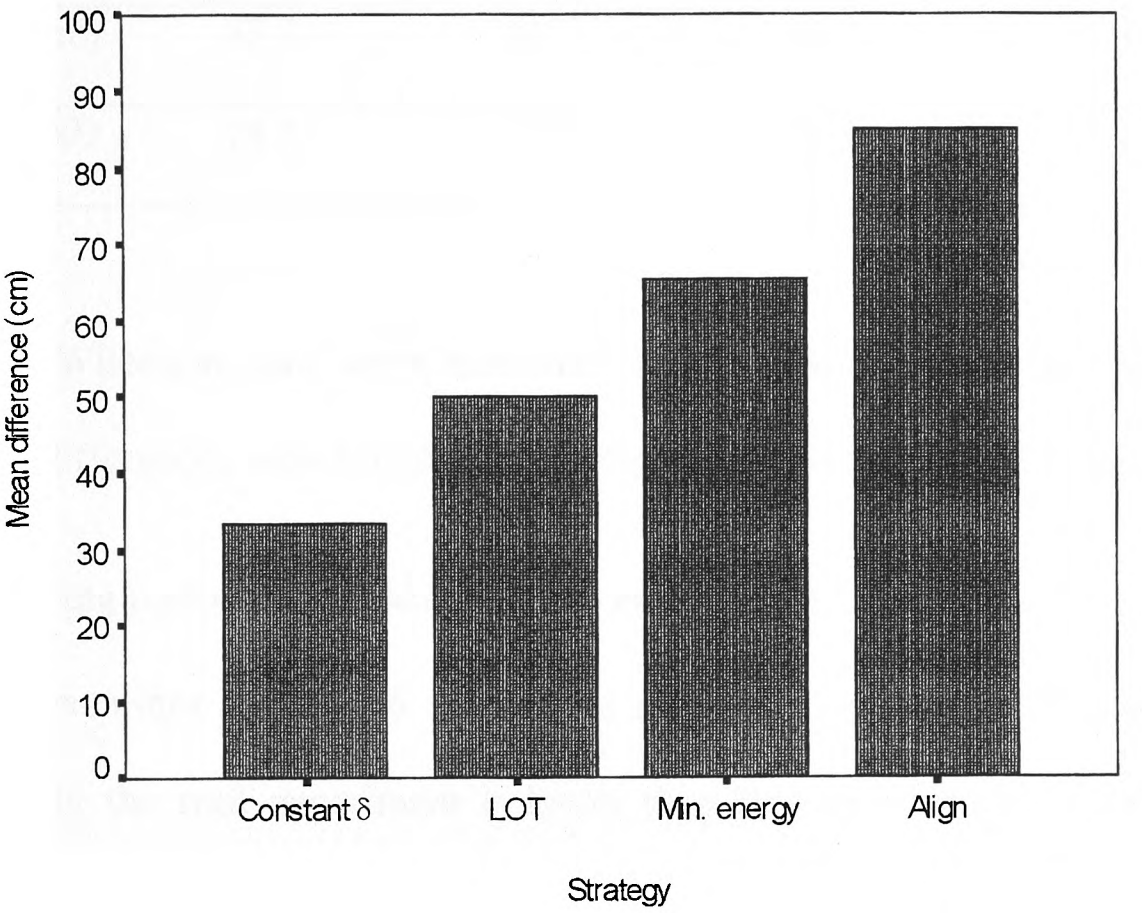


Fig. 6.7 Performance of the four strategies in the ground experiment.

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[2] It was surprising to find that there was a highly significant difference between the minimum energy and conserved alignment strategies, given the closeness of their mean difference values. However, the minimum energy strategy produced the better performance than the conserved alignment strategy in over two-thirds of trials. The significant result is therefore explained by the use of ranks in the Wilcoxon test.

In the ground experiment, the differences between the four strategies were more apparent. The performance of the constant δ strategy was clearly better than that of the other three strategies. Next was the LOT strategy, followed by the minimum energy, and conserved alignment strategies – each an increment of 15-20cm poorer than the previous strategy. Table 6.3 gives the exact figures for the performance of each strategy.

Strategy	Constant δ	LOT	Min. energy	Alignment
N	175	175	175	175
Mean diff.(cm)	33.3	50.0	65.2	84.9
SD	14.5	11.3	22.5	19.2

Table 6.3.

Again, Wilcoxon tests were employed to compare the performance of each strategy. All differences were found to be highly significant ($p < 0.001$ in each case).

6.6.4. Comparing performance across the two experiments

If one examines figures 6.6 and 6.7 (or tables 6.2 and 6.3) it is apparent that performance in the roof experiment is better than that in observed in the ground experiment. The significance of this comparison was examined using a Mann-Whitney U test. The differences across experiment proved significant for each of the strategies ($p < 0.001$ in each case).

6.6.5. Summary

The best performing strategy overall is the constant δ strategy. It was the equal best strategy in the roof experiment and clearly the best in the ground experiment. The LOT strategy was the next most effective producing a good approximation of real fielder behaviour in the roof experiment but doing less well in the ground experiment.

The minimum energy and conserved alignment strategies performed reasonably poorly in both experiments, whilst the constant γ strategy appeared fundamentally flawed. All the strategies, in both experiments, produced performance that was significantly poorer than the mean error in the estimate of the fielder's position ($p < 0.001$ in Wilcoxon tests). Consequently, none are convincing as models of human interceptive behaviour.

6.7. Problems with the proposed interception strategies

The constant δ and LOT strategies were reasonably successful at placing a simulated fielder in the same position as a human attempting to intercept a projectile. The minimum energy and conserved alignment strategies were less successful and the constant γ strategy was rarely effective. The following section investigates why the constant γ strategy is inefficient. Beyond that, the problems faced by the remaining four strategies are examined.

6.7.1. Failure of the constant γ strategy

The constant γ strategy performed poorly in directing a simulated fielder along an intercept path similar to that followed by the real fielder. On occasions, the simulated fielder was sent in a completely erroneous direction. This seemed to reflect a fundamental error in the operation of the strategy. Examining the variation in visual angles experienced by the real and simulated fielder, a basis for this error was revealed. It was found that the real fielder often ended up running so that the angle γ remained constant but that it took quite some time before that was achieved. The simulated fielder (operating within human-like speed and acceleration limits) was able to achieve constant γ almost instantly leading to divergence of their running paths. This can be clarified with an example.

Figure 6.8 shows the vertical projection of a trial in which, to reach the interception point, the fielder had to run to his right and backwards. Data is sampled at 0.16sec intervals and fielder movement for the first two-thirds of the trial is shown. The flight of the ball throughout the trial is shown to indicate the final intercept point. The figure is repeated on the left and right. The left half of the figure has dotted lines linking the position of the real fielder with the position of the ball at that moment. In the right half of the figure, the dotted lines link the position of simulated fielder to the concurrent position of the ball. Remember that γ is the angle between the direction of running of the fielder and the direction of the ball from the fielder's position.

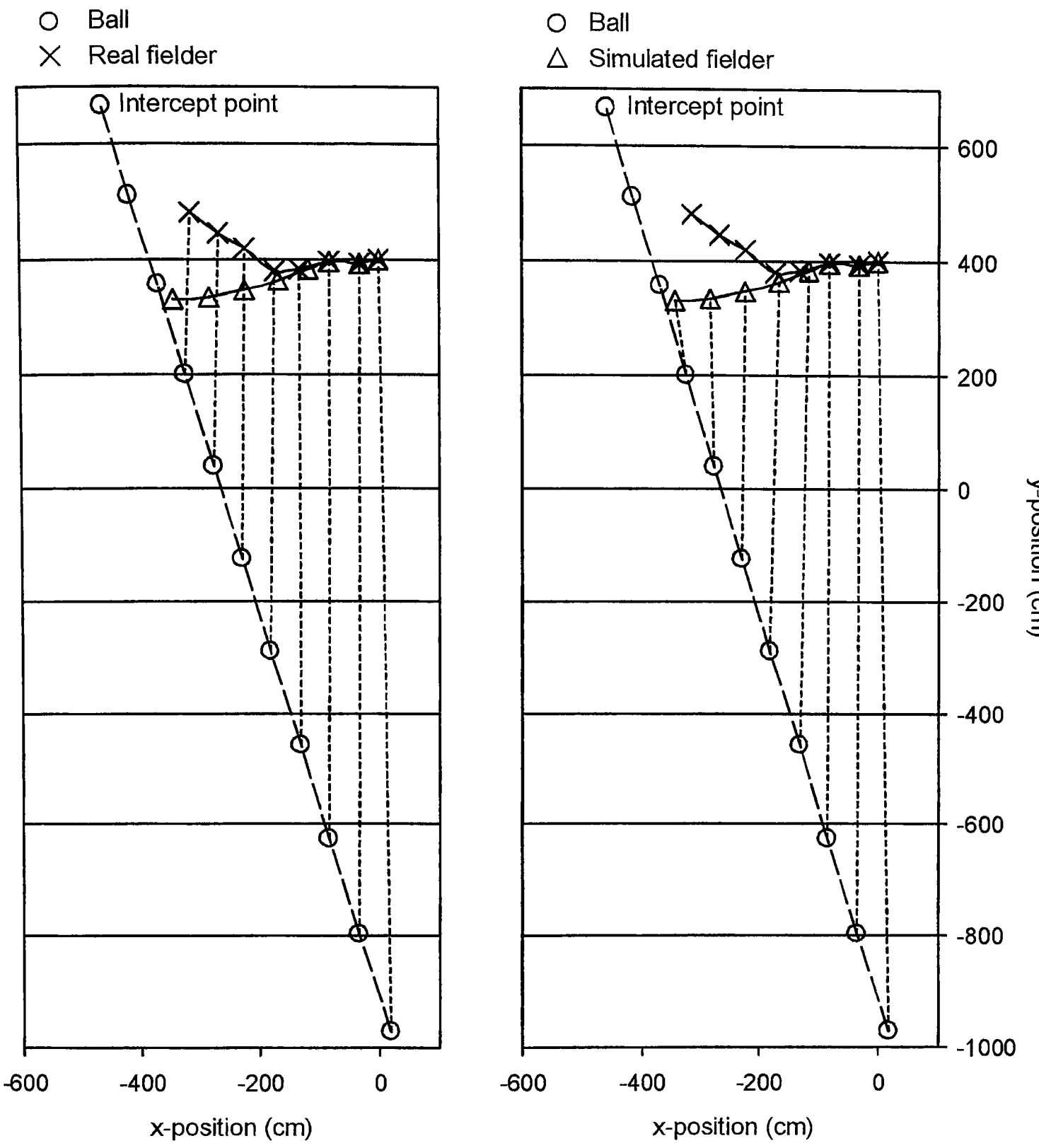


Fig. 6.8 Variation in γ for the real fielder (left) and simulated fielder (right).

It is clear that the real fielder began running toward the interception point in a manner that keeps γ constant much later than the simulated fielder does. This point is reinforced by figure 6.9, which shows the variation in γ and tan α for the fielder positions presented in figure 6.8.

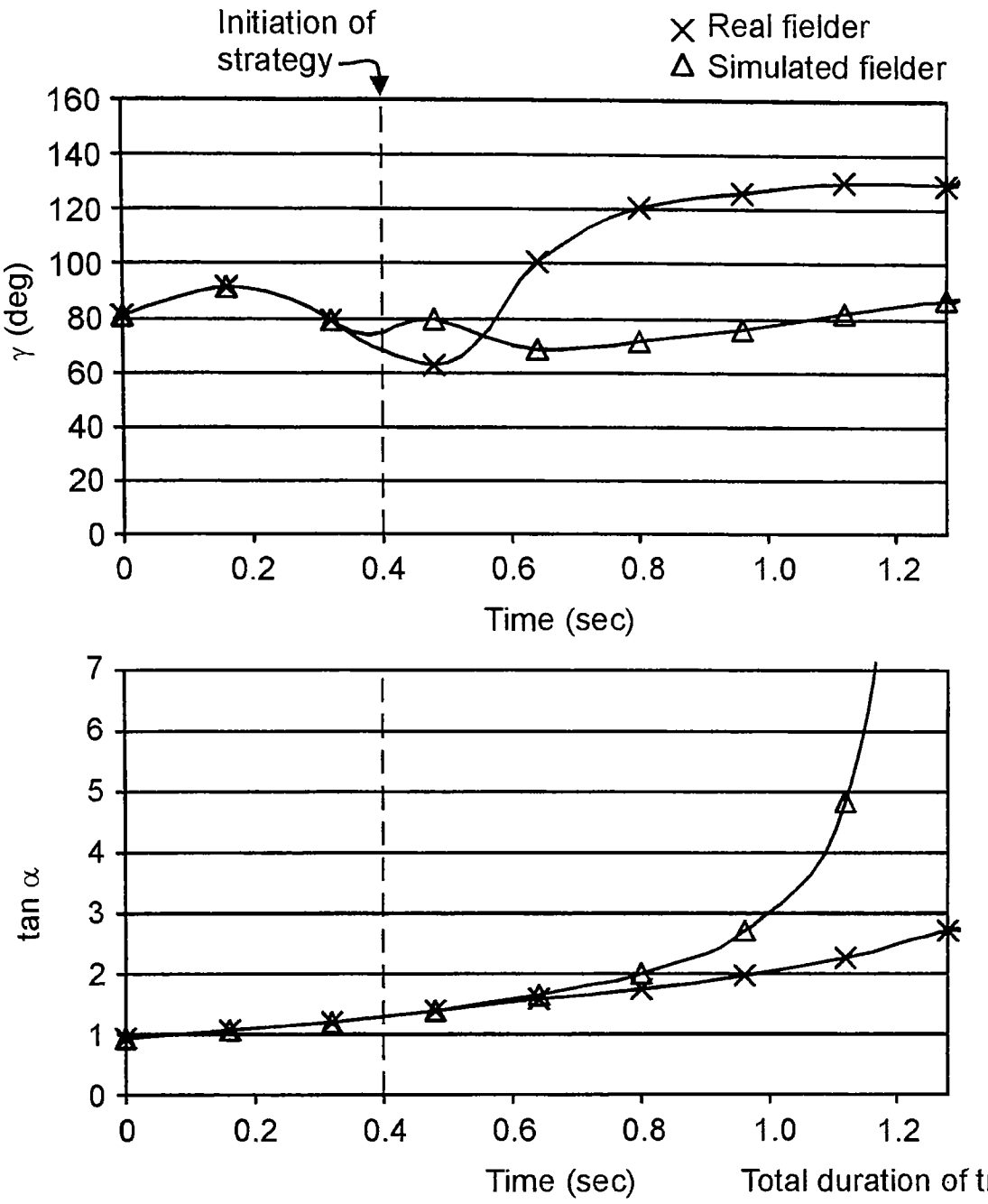


Fig. 6.9 Variation in γ and tan α for the real and simulated fielder in the example trial.

Initially, the lateral movement of the real and simulated fielder kept γ at about 90° but since the fielder cannot keep pace with the lateral velocity of the ball, γ began to decrease slightly. After 0.4sec, the constant γ strategy initiated. The real fielder ran so that γ increased, levelling out after 1sec. By doing so, the real fielder ensured that tan α increased at a constant rate. At first, the simulated fielder was able to move so that γ is constant at about 80° and tan α increased at a constant rate. To achieve this, the simulated fielder had to move forwards but the interception point is *behind* the start position. After 0.8seconds, the consequence of this incorrect movement in depth was the inability to move to a position that kept tan α increasing at a constant rate.

The ball flew over the simulated fielder's head and he could not recover to reach the interception point.

The maintenance of an erroneous γ angle is the downfall of the constant γ strategy. Real fielders did not run so that γ was constant throughout a trial. There was a tendency for γ to level off toward the end of trials. However, the maintenance of γ cannot be guiding their early movement and the constancy of the angle γ is likely to be an indirect effect of fielders following an alternative interception strategy. This fundamental inefficiency of the constant γ strategy led to it not being considered in further analysis.

6.7.2. Failure of the four remaining interception strategies

More detailed investigation into strategy performance revealed that there were some consistent errors produced by each of the four remaining strategies, aspects of the movement of the real fielder that each failed to capture. In failing to put the simulated fielder in the correct place, the strategies produced variation in visual angles inconsistent with that demonstrated by the real fielder. As has been shown in chapters 3 and 4, when real fielders run to intercept a projectile, they tend to move so that tan α increases at a constant rate. This feature was an integral part of the proposed interception strategies. Consequently, tan α vs. time for the simulated fielder usually produced a good fit to the variation in tan α shown by the real fielder. However, the quality of fit to the tangents of the lateral visual angles (tan β and tan δ) was less favourable. In the following sub-sections, the typical failings of each strategy are detailed.

6.7.2.1. Time of strategy initiation

A problem that affected each strategy was sensitivity to the time at which the strategy was engaged (10 frames after the ball was launched). Each used the position of the real fielder in the first 10 frames (400msec). This allows rates of change of visual angles to be registered and to accommodate the initial movements made by the real fielder that do not appear part of a strategy to get him to the interception point. However, problems arise if the real fielder makes an erratic movement between the 9^{th} and 10^{th} frames or if the fielder did not have a consistent reaction time. As has been shown, this effect was particularly devastating for the performance of the constant γ strategy.

The limits on acceleration and maximum velocity applied to the simulated fielder mean that an erratic movement made immediately prior to engagement of the strategy can have a persisting effect on the running path of the simulated fielder. Although the real fielder has similar limits on movement, the erratic movement may have been due to slightly incorrect recording of the fielder's head position as he began to run. Figure 6.10 shows a plan view of such a trial and the effect on the running path of the simulated fielder (using the constant δ strategy). The simulated fielder gets to virtually the exact final position of the real fielder but follows a very different path. If the strategy been engaged one frame later (when inappropriate motion in the Y-axis had been corrected) then a good fit to the running path of the real fielder would almost certainly have been obtained. Similarly, if the real fielder had a slow reaction time for a particular trial, then he would engage interceptive behaviour after the simulated fielder. Although the simulated fielder may have been using the same strategy as the real fielder, he will follow a different path due to the discrepancy in initiation time.

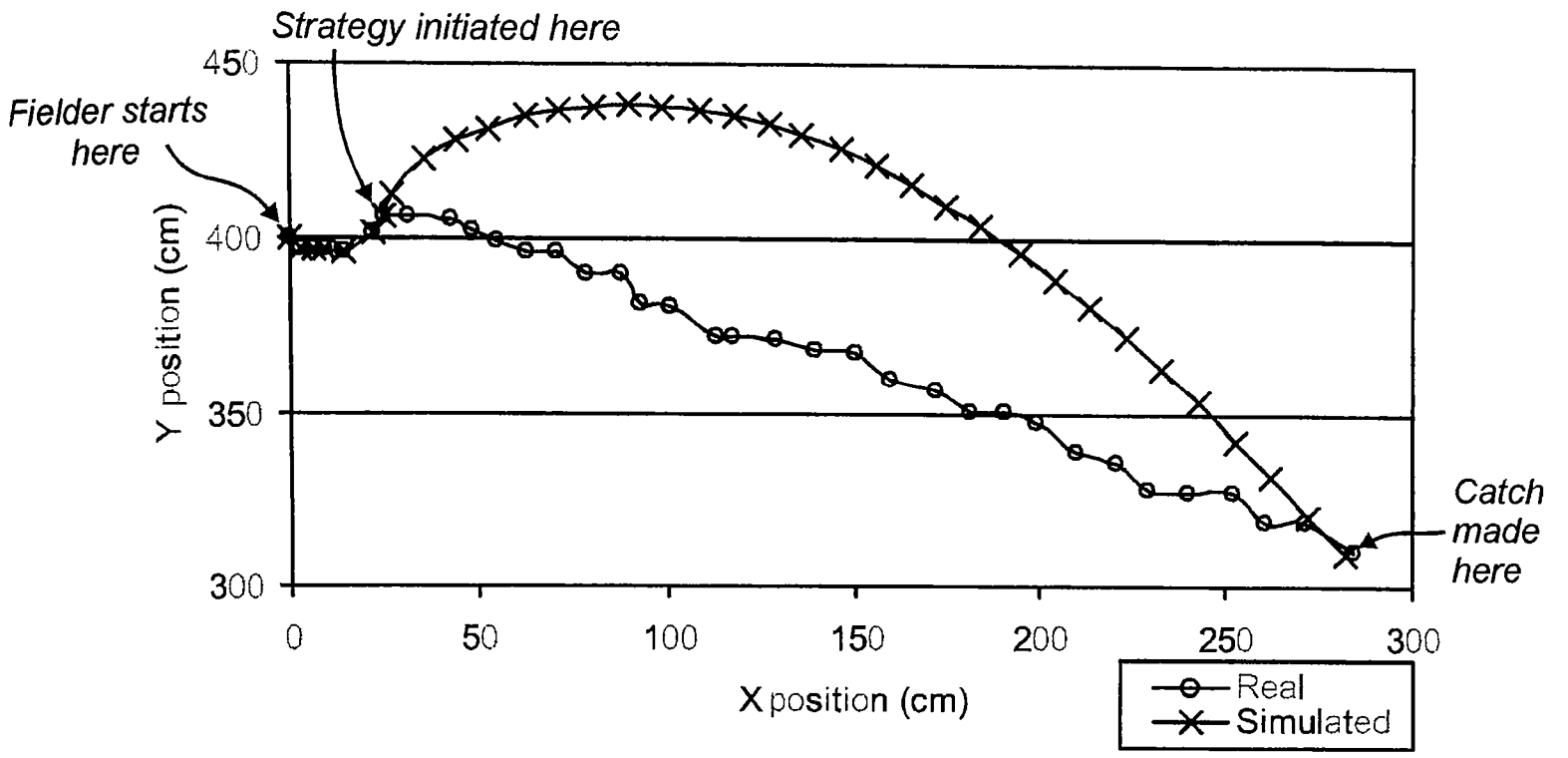


Fig. 6.10 Incorrect timing of strategy initiation causing diversion of the running path of the simulated fielder (fielder positions sampled at 0.04second time intervals).

All the strategies attempt to move the simulated fielder to a position that gives a constant increase in tan α. As long as this pattern is maintained, the simulated fielder gets to the right place at the right time, as achieved by the simulated fielder in figure 6.10. However, the diverted path of the simulated fielder caused a systematic error in the position of the simulated fielder relative to the real fielder.

6.7.2.2. The switch to prehensive behaviour

A further problem with the proposed interception strategies was the change in the interceptive behaviour of the real fielder towards the end of trials, as observed in chapter 4. This is the proposed change from interceptive to prehensive behaviour – when the fielder switches from a strategy intended to cause eye to meet ball (moving so the fielder experiences constant d(tan α)/dt) to one intended to make hand(s) meet ball. No provision was made in any of the interception strategies to account for this behaviour because it depends entirely on the method with which the fielder chooses to catch the ball. They may choose to catch it in the typical manner – in front of their

face with both hands. If this is the case, tan α should increase at an approximately constant rate throughout the trial. Consequently, the proposed interception strategies should get the simulated fielder to virtually the exact spot at which the real fielder caught the ball. However, in some circumstances a fielder may not catch the ball in this way. The fielder may only just be able to reach the ball in time before it hits the ground, in which case, the ball will be caught low and away from the face. Alternatively, the fielder may simply employ a different technique to catch the ball – with both hands at waist height or to their side, simply because it feels more comfortable for that particular trial. If any of the above situations arise, the fielder will experience variation in d(tan α)/dt towards the end of the trial. The interception models do not attempt to account for this behaviour. The result is that the simulated fielder ends some distance from the final position of the real fielder.

6.7.3. Strategy-specific problems

There were unique problems with each of the proposed strategies. Problems with each strategy are discussed in the following sections.

6.7.3.1. Constant δ strategy

The constant δ strategy was most effective at minimising error between its placement of the simulated fielder and the position of the real fielder. However, its control of the simulated fielder's lateral position through maintenance of constant δ was often a poor match to the true variation. In the roof experiment, rather than remain at a constant value, δ tended to undergo a slight increase throughout the trial (although its rate of increase usually decreased). Contrasting with this result is the data from the ground experiment, in which δ, after an initial increase, tended to

decrease as the trial progressed. This meant that the simulated fielder was not directed to the same place as the real fielder and led to the differences in position.

6.7.3.2. LOT strategy

The LOT model suffered a similar problem to that of the constant δ strategy – excessive control of the visual angle tangent responsible for directing lateral movement, in this case tan β. It was shown in chapter 4 (the ground experiment) that the variation in tan β experienced by a fielder can vary from catch to catch. This is even true for two trials in which a fielder starting from the same position catches balls following the same trajectory. For the roof experiment, tan β often increased throughout the trial. Consequently, the LOT model was quite successful at directing the simulated fielder for the roof experiment trials. However, in the ground experiment, tan β variation was less consistent. Sometimes it would increase throughout the trial. On other occasions it would increase and then rest at a constant value and sometimes it would increase and then decrease. Throughout all trials, tan α tended to increase. The LOT model states that the movement of the fielder causes tan α and tan β to remain proportionate to one another. The trial to trial variation in d(tan β)/dt meant that the LOT model was not an effective model.

6.7.3.3. Minimum energy strategy

The most noticeable flaw in the performance of the minimum energy strategy was a tendency for the simulated fielder to make a sudden change in running path about half to two-thirds of the way through a trial. This is particularly apparent in trials where the fielder had to run backwards to catch the ball. It appears that the simulated fielder gets into a position where the minimum energy path deviates from that taken by the real fielder. Circumstances arise when the minimum energy path

(moving to the nearest point that has the correct tan α) does not continue to send the fielder towards the interception point but to nearer positions that still maintain d(tan α)/dt. By not moving toward the interception point, the simulated fielder eventually ends up in a position where he cannot move fast enough to maintain d(tan α)/dt and finishes some distance from the final position of the real fielder.

Trials in the ground experiment where the fielder has to run forward to catch revealed a further problem with the minimum energy strategy. On occasions, the minimum energy strategy causes the simulated fielder to move laterally much faster than the real fielder does and ends up moving forward in the plane of projection of the ball. The simulated fielder reaches the interception point but follows a very different path to that followed by the real fielder. Figure 6.11 shows a plan view of a trial in which this happened.

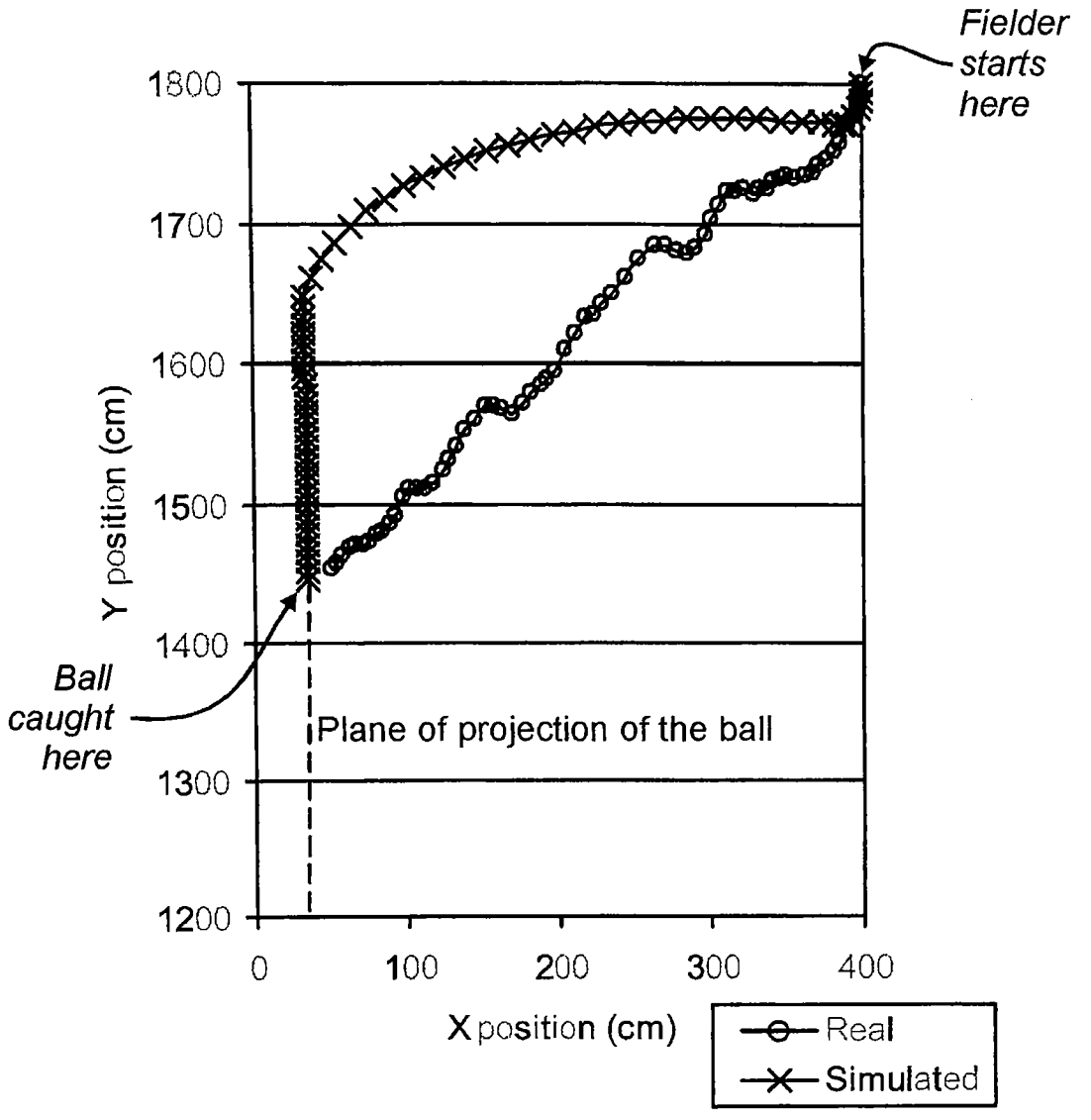


Fig. 6.11 Example of erroneous path followed by simulated fielder following the minimum energy strategy (fielder positions sampled at 0.04second time intervals).

6.7.3.4. Conserved alignment strategy

The conserved alignment strategy had one major problem, less obvious in roof experiment trials but serious in ground experiment trials. This was the tendency to move the simulated fielder too far laterally in attempting to restore the alignment between fielder and ball at launch. This led to running paths for the simulated fielder very similar to that shown in figure 6.11. However, for the conserved alignment strategy, the excessively rapid lateral movement occurred both in trials where the fielder had to move forwards and those in which he had to run backward (cf. minimum energy strategy: only applies in trials where the fielder had to run forwards to catch the ball). The strategy is successful at moving the simulated fielder to a position that maintains $d(\tan \alpha)/dt$ and the fit to $\tan \alpha$ vs. time for the real fielder is

good. Unfortunately, the rapidity of the lateral movement leads to the simulated fielder attaining very different positions on the rings of points that give constant d(tan α)/dt. The poor fit to the real fielders' running paths suggests either that humans do not use a conserved alignment strategy or that the simulated fielder restores alignment with far greater efficiency than the real fielder does.

6.8. Modifications to the proposed interception strategies

The four remaining interception strategies in their current state were inappropriate models of human interception. On occasions, each strategy provided examples of trials where they were suitable models of the behaviour of the real fielder, but none were consistently accurate. In an attempt to resolve the problems with the strategies, modifications were made to the programs that implement the strategies.

6.8.1. Removing prehensive behaviour

It was noted that in the final few frames of a trial, there was often a marked divergence of the paths followed by the real and simulated fielders. This is attributable to the change in behaviour of the fielder from moving his body to the interception point to moving his hands to make the catch. This 'prehensive' behaviour is beyond the scope of the interception strategies. Therefore, trials were cropped so that prehensive behaviour was not included in the analysis of the mean difference in distance between the real and the simulated fielder. This was achieved by discounting frames of the trial after the real fielder had begun to make a synchronous movement of the hands to catch the ball. Removing these frames from the analysis improves the performance of the strategies in modelling human interceptive behaviour by removing

a feature of interception that they are not designed to model – the final movements made by the fielder to make hand(s) meet ball.

6.8.2. Iterative performance optimisation

The remaining modifications used iterative techniques to find the parameters for the simulated fielder that best fitted the running path of the real fielder. Small adjustments were made to each parameter and the combination that gave the lowest mean difference in distance between the position of the real fielder and that of the simulated fielder was considered the most suitable.

6.8.2.1. Optimal frame for strategy initiation

The first parameter to which this rationale was applied was the frame number (i.e. the time) at which the interception strategy took control of fielder movement. This was designed to address the problem of sensitivity to the timing of strategy initiation that sometimes caused the simulated fielder to follow an unusual path. Originally, the strategies were engaged after the 10^{th} frame of a trial (400msec after release of the ball). However, the program was modified so that the strategies were engaged after the 3^{rd} frame, then the 4^{th} frame, then 5^{th} frame and so on up to the 15^{th} frame. Provision was made for such a short reaction time (3 frames = 120msec) to allow for the possibility that fielders began anticipating ball release and preparing to move prior to the start of a trial. Similarly, the possibility of a relatively long reaction time (15 frames = 600msec) was included to allow for fielders who may have been distracted at the time of ball release and for any inaccurate recording of ball release. Although, this should improve the performance of all of the strategies, it is likely that the minimum energy strategy will show a substantial improvement with this modification. Apart from being sensitive to the movement made by the real fielder in

the previous frame, the time of initiation of the minimum energy strategy will have a possibly dramatic effect on the eventual path followed by the simulated fielder. Initiating the strategy at the wrong time may have led to the unusual paths displayed by the simulated fielder following the minimum energy strategy in the ground experiment (example shown in figure 6.11). By varying the time at which the strategy initiates, the simulated fielder may follow a minimum energy path that more closely approximates the behaviour of the real fielder.

6.8.2.2. Optimal maximum velocity and maximum acceleration

A problem that particularly affected the minimum energy and the conserved alignment strategies was a tendency to move off too rapidly in the lateral plane. To compensate for this fault, the maximum velocity that the fielder could attain was varied, as was the maximum acceleration that the simulated fielder could undergo. This may reduce the efficiency with which the simulated fielder can reach the next correct tan α ring (minimum energy strategy) or restore his original alignment (conserved alignment strategy). The resultant running path of the simulated fielder may be more akin to that produced by the real fielder. This modification may also improve the performance of the constant δ and LOT models. The introduction of different maximum velocity and acceleration parameters may allow more scope for variation in the lateral visual angles. For example, tan β for the real fielder sometimes increased at an increasing rate. The LOT model attempts to move the simulated fielder to a position that keeps tan β increasing proportionally with tan α, therefore both increase at a constant rate. Imposing a lower maximum velocity may prevent the simulated fielder from attaining a velocity that allows it to keep the rate of increase of tan β constant. The rate of increase in tan β for the simulated fielder must then

increase, possibly improving the performance of the LOT strategy in modelling the behaviour of the real fielder.

In the interception modelling programs, velocity is considered as the distance a fielder covers from *t* to *t* + *1*, where *t* is the frame number. To vary the maximum velocity that the simulated fielder could attain, the maximum distance that it could travel in a one-frame interval was altered over a set range. This was varied between 6cm/f and 15cm/f in steps of 1cm/f, where f is the time interval from one frame to the next (40msec). This is equivalent to giving the simulated fielder a maximum velocity of between $1.5ms^{-1}$ and $3.75ms^{-1}$, varied in steps of $0.25ms^{-1}$. Acceleration is calculated as the difference between the distance travelled by the simulated fielder from *t* to *t* + *1* and the distance travelled from *t* + *1* to *t* + *2*. The maximum allowed was varied between 0.16cm/f/f and 0.8cm/f/f in steps of 0.16cm/f/f. This is equivalent to varying maximum acceleration from between $1ms^{-2}$ and $5ms^{-2}$, in steps of $1ms^{-2}$.

Varying the maximum velocity and acceleration of the simulated fielder is not to suggest that these are absolute maximum values governing the motion of a fielder. They are simply the limits that best model the interceptive performance of the real fielder in that trial. A real fielder may choose to run or accelerate at a reduced rate to catch a ball if they realise that they have plenty of time to reach the interception point. Introducing the possibility of lower maximum rates of motion is an attempt to allow the simulated fielder to model this behaviour.

6.8.3. Assessing the performance of the optimised strategies

The optimisation of each parameter was not sequential. For each trial, the program ran every possible combination of parameters (13 frames for strategy initiation × 10 maximum velocity values × 5 maximum acceleration values = 650 combinations). Performance of the strategy for a particular trial was assessed by

calculating the mean distance between the simulated fielder and the real fielder in each frame of the trial. The set of parameters that minimised this value was recorded and used for that trial. The mean difference was calculated between the frame from which the strategy was initiated and the frame at which the real fielder began the synchronous hand movement to catch the ball.

The interception modelling programs now took a very long time to run because each program had to implement the strategy 650 times on any one trial, which could last for more than 80 frames. To reduce the amount of computation, 40 trials were selected from the 328 previously analysed: 20 trials from the roof experiment and 20 trials from the ground experiment. Trials were selected from the roof experiment randomly. Trials from the ground experiment were selected so that each subject provided one of each of the four trial types but trial selection was at random within this constraint.

6.9. Results

6.9.1. Performance of the non-optimised interception models on the 40 selected trials

Table 6.4 shows the mean difference in distance between the simulated fielder and the real fielder for the original 328 trials and the same data for the 40 selected trials.

Selection		Constant δ	LOT	Min. energy	Alignment
328 original	N	328	328	328	328
	Mean diff. (cm)	29.4	38.3	50.7	61.2
40 selected	N	40	40	40	40
	Mean diff. (cm)	26.3	35.3	45.2	58.4

Table 6.4.

In the 40 selected trials, the mean performance of all of the interception models was slightly better than their mean performance over the 328 trials from which they were selected. However, a Mann-Whitney test showed that the apparent improvement in performance was not significant for any of the four strategies ($p > 0.2$ in all cases).

6.9.2. Parameters selected using the optimisation process

Appendix A6.4 summarises the optimal parameters selected for each strategy in each experiment.

6.9.3. Performance of the optimised interception models

See appendix A6.5 for details of the statistics in this section. The improved performance of the optimised interception models can be seen in table 6.5. The 'original mean diff.' column is the mean difference between the simulated and real fielder for the same 40 trials using the non-optimised interception models.

Strategy	Original mean diff.(cm)	Optimised mean diff.(cm)	Improvement(cm)
Constant δ	26.3	17.2	9.1
LOT	35.3	25.8	9.5
Min. energy	45.2	27.2	18.0
Alignment	58.4	45.0	13.4
Total	41.3	28.8	12.5

Table 6.5.

The use of optimised parameters was effective in improving the placement of the simulated fielder relative to the simulated fielder. This is apparent in the overall mean, in which the optimised mean difference is approximately two-thirds that of the original mean difference.

Figure 6.12 and table 6.6 show the comparative performance of the optimised interception models in each of the experiments.

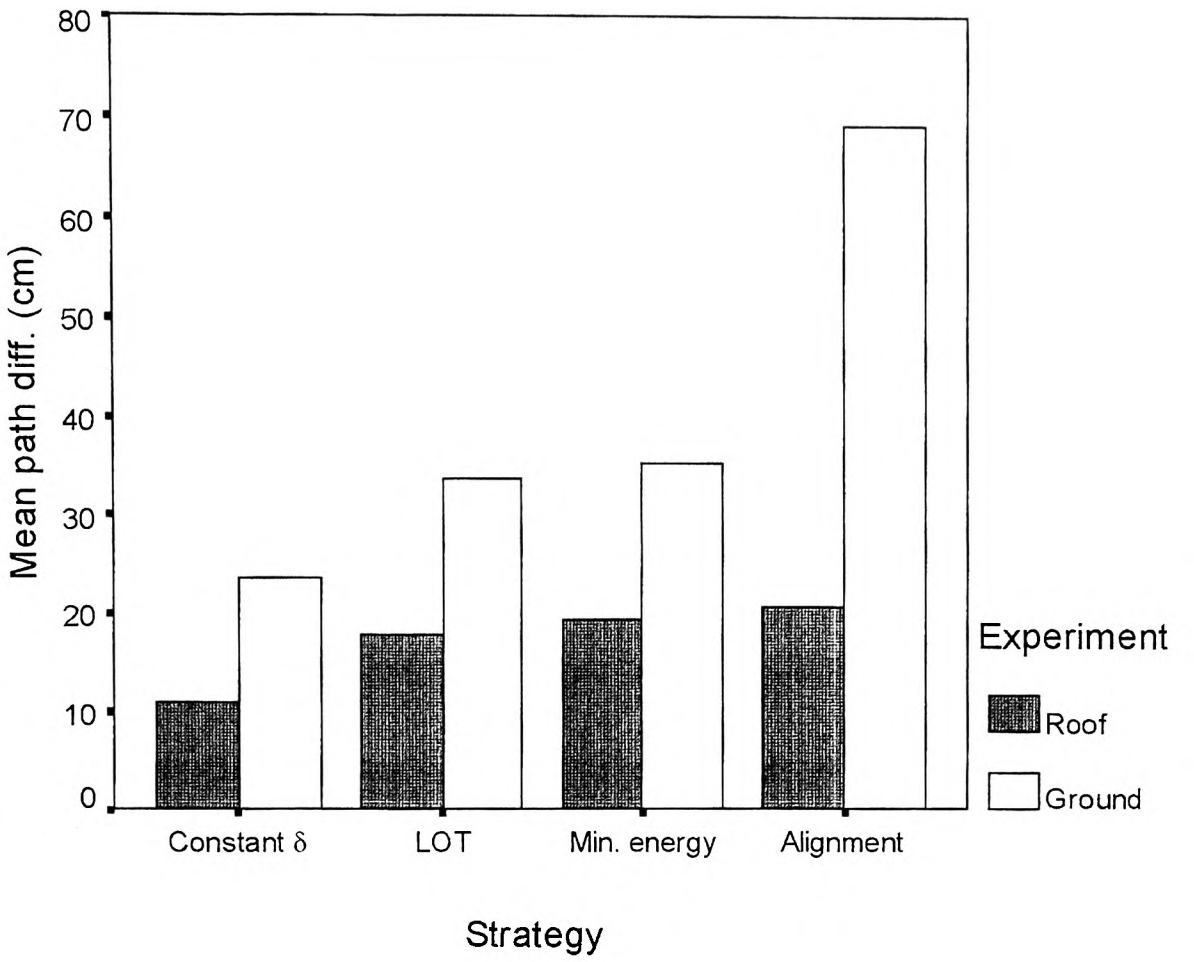


Fig. 6.12 Mean performance of strategies in each experiment

Experiment	Roof		Ground	
Strategy	Mean (cm)	SD	Mean (cm)	SD
Constant δ	11.0	4.9	23.5	9.5
LOT	17.9	10.0	33.7	15.5
Min. energy	19.2	11.2	35.2	12.9
Alignment	20.7	14.4	69.3	25.8

Table 6.6.

All the strategies performed well in the roof experiment, giving a mean difference between the real and simulated fielder of less than 21cm. This is around the same as the estimate of the mean error in the calculation of the real fielder's position in each frame (Mean value = 15.9cm – see appendix A1). The performance of all of

the strategies was poorer in the ground experiment. A Mann-Whitney test showed that the difference in performance between roof and ground experiments was significant for all four strategies ($p < 0.002$ in all cases).

In both experiments, the best performing strategy was the constant δ strategy. The LOT strategy was the next best followed by the minimum energy strategy and finally the conserved alignment strategy. A Wilcoxon test was used to examine the differences in performance across the strategies in each experiment. The superior performance of the constant δ strategy proved to be significantly different from that of all other strategies in both experiments ($p < 0.02$ in all cases). The LOT and minimum energy strategies did not significantly differ in their performance in either experiment. The conserved alignment strategy did not differ from the LOT and minimum energy strategies in its performance in the roof experiment. However, its poor performance in the ground experiment meant that its performance was significantly different from the LOT and minimum energy strategies, as well as the constant δ strategy ($p < 0.001$ for all ground experiment comparisons with the conserved alignment strategy). Combining the performance data for the two experiments and running the same Wilcoxon tests revealed that the mean difference for the constant δ strategy was significantly different from all the other strategies ($p < 0.001$ in all cases). The LOT and minimum energy strategies did not differ significantly, but both differed significantly from the conserved alignment strategy ($p < 0.001$).

In assessing the strategies, perhaps the most important statistic is whether the mean distance between the simulated fielder and the real fielder is significantly greater than the mean error in the positional estimate of the fielder ($\pm$15.9cm). Wilcoxon tests were used to investigate the differences. The only strategy in which

the difference was non-significant was the constant δ strategy ($p > 0.65$). For the remaining strategies, the mean difference between their placement of the simulated fielder and the real fielder was significantly greater than the error in positional estimate ($p < 0.001$ in each case).

6.10. Strategy validity

The superior performance of the constant δ strategy using the original parameters was continued using optimised parameters. It continued to be the most effective strategy. On average, it positioned the simulated fielder significantly closer to the real fielder than all the other strategies in both experiments. The mean difference between the simulated fielder and the real fielder did not differ significantly from the error in the estimate on the real fielder's position and it would therefore be difficult to improve on this achievement. Using optimised parameters, the performance of the LOT strategy was remarkably similar to that of the minimum energy strategy. Both performed reasonably well in the roof and the ground experiment but mean performance was approximately 50% worse than the average performance of the constant δ strategy. Wilcoxon tests showed that this difference was significant. Interestingly, the minimum energy strategy often sent the simulated fielder on a running path that produced constant δ, in ground experiment trials. However, when the fielder had to run backward to catch the ball, there was still a tendency for the simulated fielder to follow an irregular path about two-thirds of the way through the trial. This was particular to trials conducted in the ground experiment. Optimisation of parameters did not remove this trait, which was first observed in the pre-optimised version of the strategy (see 6.7.3.3). The conserved alignment strategy also showed a substantial improvement after optimisation.

However, as in its pre-optimised state, it was clearly the least effective strategy. Its downfall appears to be trials in which the fielder must run forward to catch the ball, in the ground experiment. Under these conditions, the simulated fielder moves too fast laterally so that in order to maintain d(tan α)/dt, the simulated fielder is sent backwards. The simulated fielder is initially sent backwards in order to maintain constant d(tan α)/dt, resulting in a running path entirely incompatible with that of the real fielder.

6.10.1. Further analysis

From the analyses conducted thus far, the constant δ strategy is the most effective model of human interceptive behaviour. However, all of the strategies perform with a reasonable degree of success in some trials. To investigate further the validity of the four proposed strategies, data that might support the use of one strategy over another was collected from the 40 trials on which each strategy was run. The new data collected was as follows:

6.10.1.1. Assessment of visual angle tangent variation

To further understand the performance of each interception strategy, the difference between the visual angle tangents (tan α, tan β, and tan δ) experienced by the simulated and real fielder was evaluated. This was achieved by calculating the mean of the absolute difference between the angle experienced by the real fielder and that experienced by the simulated fielder for every analysed frame of each trial. This measure of strategy performance is important because it is the visual angle tangents that are purported to control the movement of the fielder (simulated and real).

6.10.1.2. Average speed of real fielder

The interception strategies were more effective in some trials and less effective in others. To investigate this phenomenon, the average speed required to intercept the ball was calculated. The average speed required to reach the interception point can be considered to be a measure of the trial difficulty. The higher the average speed required the more difficult a catch is to make. It is possible that a correlation exists between the speed required to reach the interception point and the goodness of fit of the simulated fielder's path to that of the real fielder.

6.11. Results of further analysis

Full details of the statistics accompanying this section are presented in appendix A6.6. The mean velocity of fielders in 20 trials analysed from the roof experiment was 254cm/s (SD = 36cm/s). Mean velocity in the 20 trials analysed from the ground experiment was 168cm/s (SD = 31cm/s).

6.11.1. Errors in tangents of visual angles

Figures 6.13-6.15 shows the mean discrepancy in the visual angle tangents, tan α, tan β, and tan δ for the roof and ground experiment.

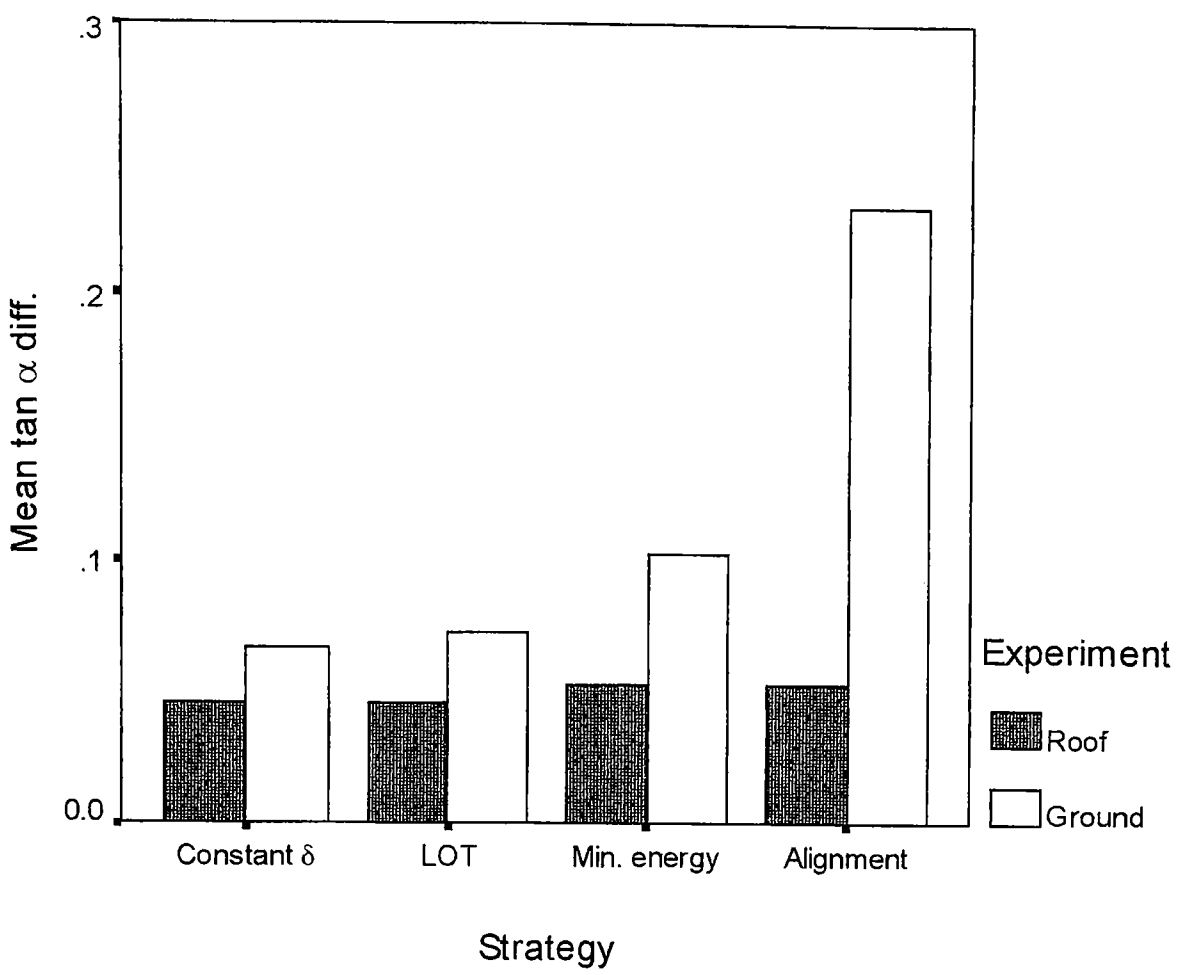


Fig. 6.13 Mean difference from tan α experienced by real fielder.

The pattern of error in tan α is slightly different to that seen for the average difference in path (figure 6.12). The constant δ and LOT strategies are more similar in this comparison. Since we know that a real fielder tends to move so that d(tan α)/dt is constant and both strategies get the simulated fielder to the interception point, there was little difference in their fit to tan α. The poorer performance of the other strategies suggests that they failed to move the simulated fielder to a position that allowed him to maintain constant d(tan α)/dt. They should therefore be considered less efficient. Wilcoxon tests were conducted to compare the mean difference in tan α across strategies. As suspected, the comparison of constant δ strategy with the LOT strategy was non-significant ($p > 0.5$). All other comparisons were significant ($p < 0.01$ in each case).

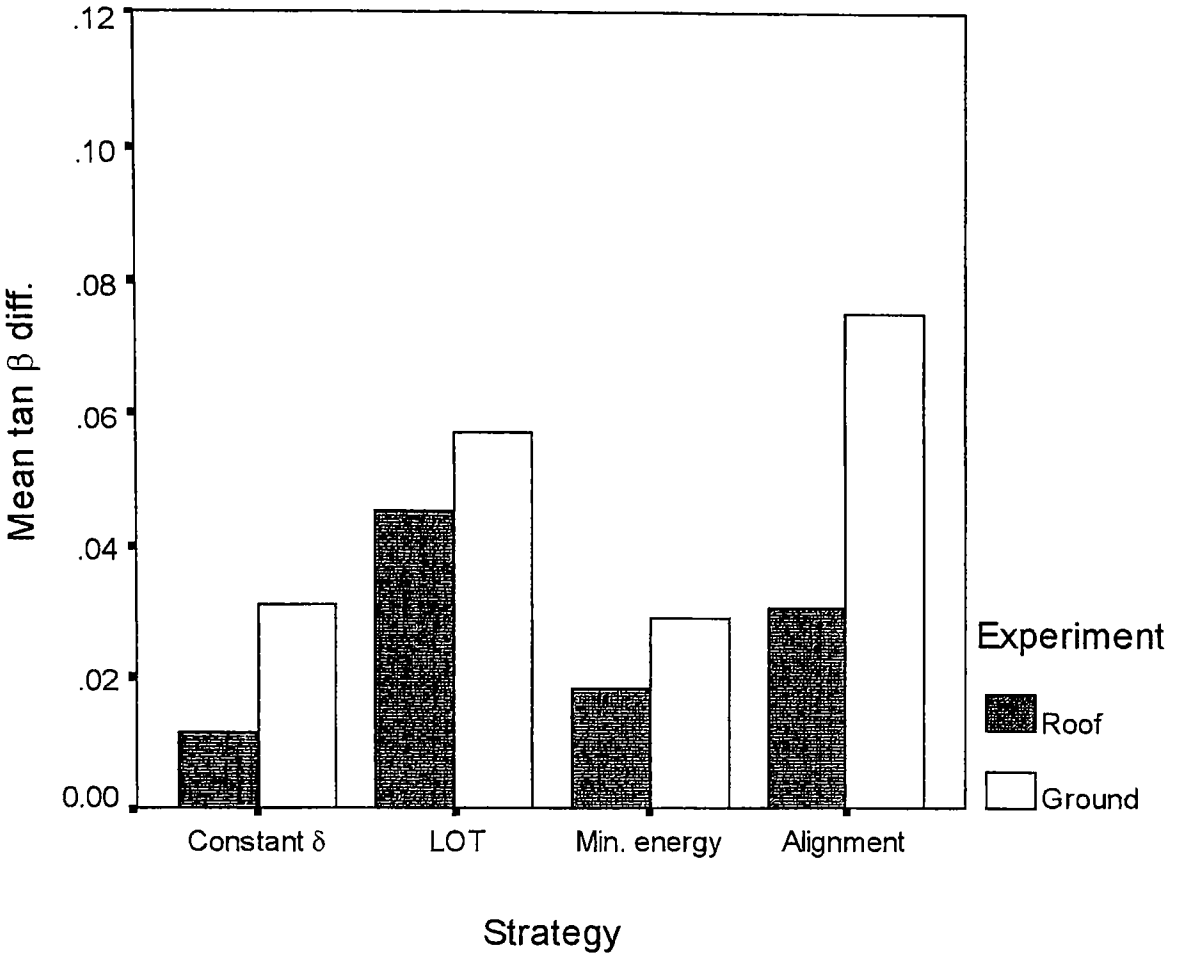


Fig. 6.14 Mean difference from tan β experienced by real fielder.

Wilcoxon tests were performed to compare the mean difference in tan β across strategies. The constant δ strategy and the minimum energy strategy did not differ significantly ($p > 0.3$). Similarly, comparison of the LOT and conserved alignment strategies did not yield a significant difference ($p > 0.6$). All other comparisons were significant ($p < 0.006$ in each case).

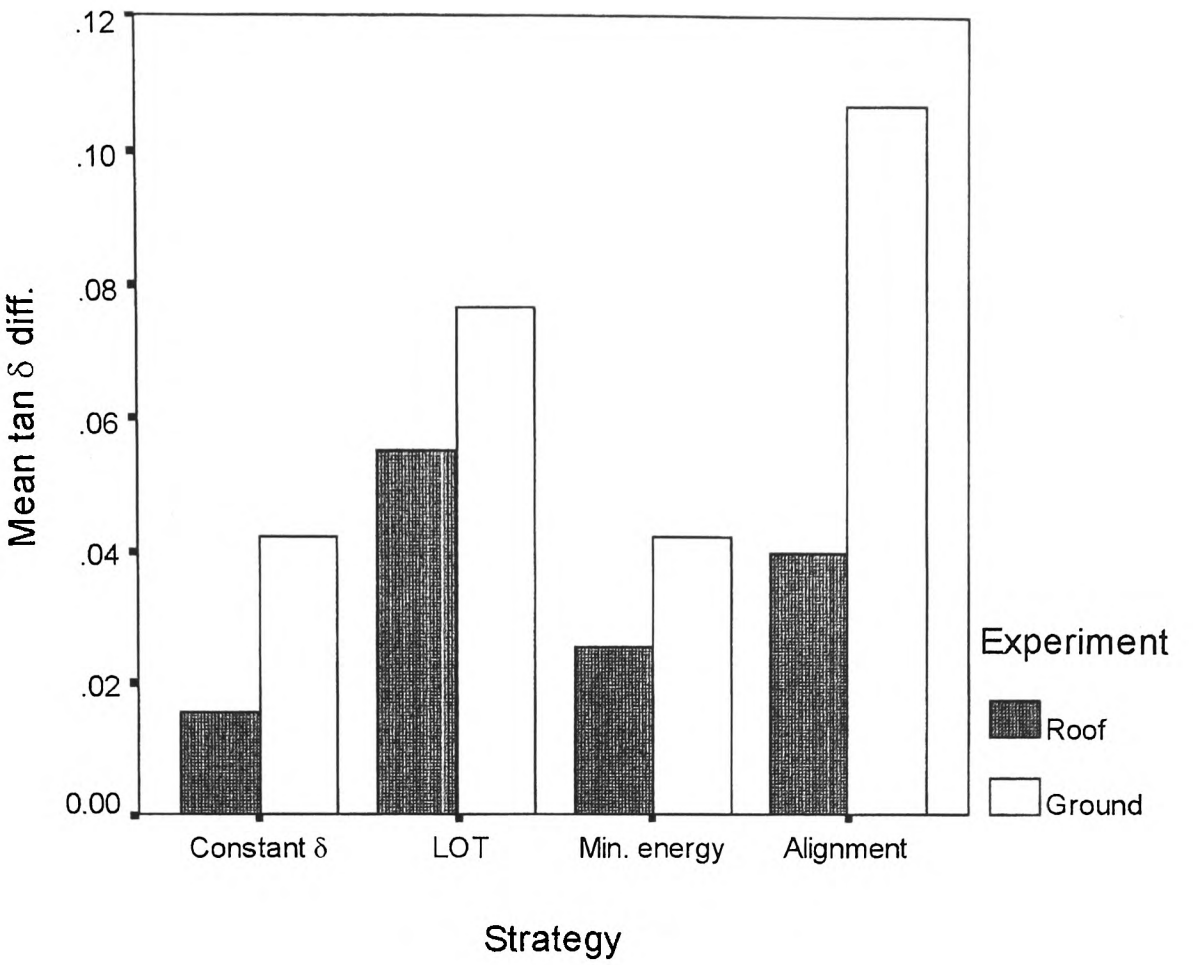


Fig. 6.15 Mean difference from tan δ experienced by real fielder.

Figures 6.14 and 6.15 are virtually congruent, highlighting the similarity between the visual angles β and δ (as used to control lateral movement by the LOT and constant δ strategies respectively). Unsurprisingly, the same pattern of Wilcoxon test results was recorded. Constant δ and minimum energy did not differ ($p > 0.15$), neither did the LOT and conserved alignment strategies ($p > 0.4$). All other comparisons were significant ($p < 0.006$ in each case).

Figures 6.14 and 6.15 also illustrate why the constant δ strategy surpasses the LOT model. Although these two models produced the best performance in terms of path, the constant δ strategy is clearly superior in terms of its fit to the lateral visual angle tangents (tan β and tan δ). The constant δ strategy produced the best overall performance for both angle tangents. Somewhat surprising was the performance of the minimum energy strategy in its mean difference from tan β and tan δ. In terms of

positional error, it did not differ from the LOT strategy. However, it produces significantly less error in terms of tan β and tan δ.

6.11.2. Correlations

Correlations were calculated between the average speed required of the fielder and the mean errors in path, tan α, tan β, and tan δ for each strategy using the Kendall's τ measure of association. The average speed required of the fielder can be construed as a measure of the difficulty of a catch since it is harder to make a catch if the fielder has to run further in a shorter time. The following section examines the correlations between average speed and the calculated error in position, tan α, and tan β for the three most effective strategies over the 40 analysed trial. The conserved alignment strategy is dropped from this analysis because of its poor performance in the previous analyses and tan δ is ignored because its correlations gave the same results as those for tan β.

All three strategies showed a significant (or near-significant) negative correlation between the error in placement of the fielder and average speed required to get to the interception point ($p < 0.02$ in all cases except LOT strategy where $p = 0.07$). This demonstrates that the strategies got were closer to what the real fielder was doing when he had to move faster to make the catch. The correlation between error in tan α and average speed required was non-significant in all cases ($p > 0.3$). Since constant d(tan α)/dt is ubiquitous feature of human interception and each strategy moved the simulated fielder to experience constant d(tan α)/dt. It is not surprising that there is no correlation with the average speed required. For the correlation between error in tan β and average speed required, a different pattern emerges. The correlation is significant and negative for the constant δ strategy ($p <$

0.03) but non-significant for the LOT and minimum energy strategies ($p > 0.4$ in each case). The significant correlation for the constant δ strategy shows that the error in the lateral visual angle tangent becomes less as the speed requirement increases. This corresponds with the decrease in the positional error of the simulated fielder as the average speed required increases showing that the improvement is due to better lateral placement of the simulated fielder at higher speeds. The non-significant result for the other two strategies is at odds with the significant negative correlation between error in position and average speed required. It was argued for tan α that a non-significant correlation indicated that it was likely to be a control variable. However, it has been shown that the variation in tan α observed by a fielder intercepting a projectile obeys a consistent pattern whereas tan β follows no such consistent pattern (see Michaels & Oudejans (1992), McLeod & Dienes (1996), and chapters 3 & 4 of this thesis). Given this variation in $d(\tan \beta)/dt$ and the superiority in fielder placement of the constant δ strategy, it seems likely that the significant correlation observed for the constant δ strategy is a result of it producing a reasonable approximation to the variation in tan β for trials requiring a higher average speed.

6.11.3. Discussion of data reassessment

The best strategy, according to all the measures undertaken, was the constant δ strategy. On average, it placed the simulated fielder closest to the real fielder, a distance comparable to the error in the estimate of the real fielder's position. It also produced the best performance in the comparison of the visual angle tangents experienced by the real and simulated fielders. The LOT and minimum energy strategies were significantly poorer.

Using the correlation data from section 6.11.2 and knowledge of how the strategies operate, it is possible to build up a picture of how the behaviour of the real fielder's behaviour changed as the speed required to reach the point of interception increased. Most significantly, the three strategies tested produced a significant negative correlation between the average speed required of the fielder and the error in position estimate[3]. All the strategies attempt to move the simulated fielder to a position that keeps d(tan α)/dt constant. The three strategies produced non-significant correlations between mean error in tan α and average speed. This is consistent with the widely accepted belief that, at all times, the real fielder is trying to keep d(tan α)/dt constant (McLeod & Dienes (1996), Michaels & Oudejans (1992), chapters 3 and 4).

Unlike the other strategies, the constant δ strategy tended to produce less error in the lateral visual angle tangents (tan β and tan δ) as speed required increased. It appears that the real fielder controlled his position in the lateral plane with respect to the ball more precisely as the required speed increases. It is likely that this is a necessary modulation in the real fielder's behaviour to increase the efficiency with which the fielder gets to the ball. For easier catches, the requirement for efficiency of interceptive behaviour is reduced so that less efficient (and more varied) running paths can still lead to interception. This point is reinforced by the improvement in fit to the running path of the real fielder as average speed increases. The constant δ strategy (like all the other strategies) moves the simulated fielder in a regulated manner, with no provision for variation in its programming. As the real fielder's

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[3] It should be noted that this correlation is only reliable for catches that a fielder can reach before the ball hits the ground. It would be interesting to investigate whether the interception models were still effective for trials where the average speed required exceeded the capabilities of the real fielder.

movements became more deterministic with the increased average speed requirement, so the strategy appeared more effective.

6.11.4. Conditions under which the constant δ strategy is less effective

Analysis so far has revealed that the most appropriate strategy for modelling human interceptive behaviour is the constant δ strategy. However, it has also shown that the strategy is not accurate in all situations. In this section, Mann-Whitney tests are used to compare features of trials in which the strategy was effective to those where it was ineffective. The (arbitrary) threshold of effective performance was chosen as the simulated fielder having a mean positional error of 25cm. If the error in the fit of the constant δ strategy was greater than this value for a particular trial then that trial was classified as 'Poor'. If the fit was better than this value, the trial was classified as 'Good'. This classification yielded 8 trials in the 'Poor' category and the remaining 32 trials were classed as 'Good'. The mean positional error for the Good group was 13.4cm, whilst for the Poor group it was 32.7cm. The statistics for this section are shown in appendix A6.7.

6.11.4.1. Comparison of visual angle tangents

Comparing the mean difference in tan α across the two groups revealed that they did not differ significantly ($p > 0.2$). The mean differences in tan β and tan δ did differ significantly across the Good and Poor group ($p < 0.001$ in each case). For both tan β and tan δ, mean error for Poor trials was around three times greater than the mean error for Good trials. This suggests that the simulated fielder was able to get to the ring of points that gave the correct tan α but was sent to an incorrect position on that ring, causing an error in the lateral visual angle tangent.

6.11.4.2. Motion of the fielder

Given the significant negative correlation between the average speed required of the fielder and error in position, it is unsurprising to find that the difference between the average speed required of the fielder in Poor trials (172cm/s) and that required in Good trials (221cm/s) was significant ($p < 0.03$). However, there was no significant difference in the mean optimum time of strategy initiation (Good: 0.36s vs. Poor: 0.28s; $p > 0.3$), mean optimum maximum velocity (Good: $2.98ms^{-1}$ vs. Poor: $2.38ms^{-1}$; $p > 0.05$), or mean optimum acceleration limit (Good: $3.84ms^{-2}$ vs. Poor: $3.63ms^{-2}$; $p > 0.9$). There was also no difference between the Good and Poor group in the proportion of trials in which the fielder ran forwards (vs. backwards) to catch the ball ($p > 0.9$), ruling out the possibility that the strategy was ineffective for trials requiring a particular movement in depth.

6.11.4.3. Curvature of tan β

Linear and quadratic regression models were produced for the variation in tan β over time for the real fielder in the 40 trials. The mean r^2 score for the linear fit to tan β for the Poor group was 0.60. For the Good group it was 0.86. This difference was highly significant ($p < 0.005$). Furthermore, it was found that the sign of the squared parameter of the quadratic regression models was negative for all of the trials in the Poor group. This downward curvature of tan β vs. time for the real fielder provides evidence against the LOT model because we know that tan α tends to increase linearly with time. It also highlights the weakness of the constant δ strategy since if β decreases δ must also decrease if the fielder is to get nearer to the ball.

6.11.4.4. Regression of tan δ

Linear regression models were also produced for the variation in tan δ against time for the 40 critical trials. Unlike the variation in tan β, r^2 for the linear fit to tan δ did not differ across the Good and Poor groups ($p > 0.2$). There was however a highly significant difference between the sign of the gradient of the linear fit across the two groups ($p < 0.03$). The linear fit to tan δ vs. time had a negative gradient for all trials in the Poor group. In the Good group, the number of the times the gradient was positive did not differ significantly from the number of times the gradient was negative, as one would expect for a variable that approximates constancy.

6.12. Conclusion

The constant γ strategy is not an appropriate model of human interception. The four other interception strategies proposed could accurately simulate the path that a human fielder takes in catching a ball in some circumstances. The most accurate model was the constant δ strategy. It was effective at modelling human interceptive behaviour (especially in optimised form) for trials requiring a higher average speed of the fielder. However, it was ineffective at modelling the variation in running path taken by the real fielder when the average speed required was low.

6.13. Discussion

The trials included in the study comprised 328 trials taken from two different experiments (the 'roof' and 'ground' experiments). In the ground experiment, the ball trajectory was more typical and the ball was airborne for longer giving the fielder longer to cover the similar distance he had to run to reach the ball in each experiment.

6.13.1. Strategies under test

Programs were produced that modelled interception strategy by using data about the trajectory of the ball and the start position of the real fielder to move a simulated fielder to the interception point. The five strategies under test were the constant δ strategy, the LOT strategy, the minimum energy strategy, the conserved alignment strategy, and the constant γ strategy. Each is a unique mathematical solution to the 'outfielder problem' and use the consistent result of previous work (e.g. Michaels & Oudejans (1992), McLeod & Dienes (1996)) that fielders move so that tan α increases at a constant rate. However, it is unclear how a fielder controls his lateral position relative to the ball. The five proposed models offered different solutions to this problem and their performance in modelling the behaviour of humans in catching balls was assessed (see section 6.4 for strategy definitions).

6.13.2. Strategy performance

The first programs that were used to implement the models produced reasonable approximations to the path taken by the real fielder using four of the five strategies under test. The constant γ strategy was found to produce erratic running paths that did not resemble those of the real fielder and it often failed to get the simulated fielder to the interception point. It was therefore rejected as a possible model of human interceptive behaviour. Each of the remaining strategies managed to accurately model the behaviour of the real fielder in a selection of the 328 trials analysed. The mean distance that the simulated fielder was placed from the position of the real fielder was calculated. This provided the measure of the relative performance of each of the four strategies. The overall pattern of performance was that the constant δ strategy tended to be best followed by the LOT strategy, the minimum energy strategy, and finally the

conserved alignment strategy. The relatively good performance of the LOT strategy was slightly unexpected given the evidence that has been produced that suggests human fielders do not run to ensure that their optic trajectory is held linear. However, as mentioned earlier the simulation of a fielder using the LOT model does not use curvature of the optic trajectory to guide his movement (to which most of the evidence produced against the LOT model objects). He simply moves so that he experiences constant d(tan α)/dt and d(tan β)/dt giving a linear optic trajectory. The failure of the constant δ and LOT strategies can be attributed to their moving the simulated fielder to a position which, although it gives him the correct vertical visual angle (α), his lateral visual angle (β or δ) is incorrect. An interesting anomaly was found in the performance (and failure) of the minimum energy strategy. The minimum energy strategy was defined as a strategy that moves the simulated fielder to the nearest position that gave the simulated fielder the correct value of tan α at each time interval of 0.04seconds. By moving to the nearest position, it was thought that a 'minimum energy' running path would result. However, it was found that moving to the nearest position in the early stages of a trial often led to a path that was much longer than the path taken by the real fielder (see figure 6.11), clearly not a minimum energy path. The performance of the conserved alignment strategy suffered because of the tendency to accelerate too fast laterally. It was hoped that the errors in the strategies could be rectified by suitable revisions.

6.13.3. Revisions to the strategies

The overall mean performance of all the strategies was significantly outside the margin of error inherent in the calculation of the position of the real fielder. An attempt was made to rectify the models by improving the programs that implement

the interception strategies so that various parameters were optimised for each trial. The revised strategies were run on 40 trials selected at random from the 328 originally analysed. The 40 trials analysed were selected at random, 20 from each of the roof and ground experiments.

6.13.4. Performance of the revised strategies

The enhancements to the programs made a significant difference to the performance of all of the strategies. The mean difference between simulated and real fielder was reduced in all cases. However, the degree of improvement varied between strategies. The strategy that placed the simulated fielder closest to the real fielder was, on average, the constant δ strategy. This was true of both the roof and ground experiments. The average distance between the simulated fielder and the real fielder over all 40 trials was just over 15cm. The difference between this value and the inherent error in calculating an estimate of the position of a real fielder was not statistically significant, suggesting a very good fit to the real fielders' performance.

The performance of the LOT strategy in the roof experiment was similar to that of the constant δ strategy. However, optimisation of parameters failed to improve its performance to the same extent in the ground experiment. Later analyses revealed the likely reason for the failure of the LOT strategy in the ground experiment. Tan β had a greater tendency to increase throughout the trial when the fielder had to run faster to catch the ball. In the ground experiment, the fielder had a relatively long time to run a short distance to catch the ball. He therefore did not have to run particularly fast to get to the interception point. The tendency for tan β to increase throughout the trial receded. The LOT strategy attempts to move the simulated fielder so that tan α and tan β change in proportion with one another and, for the strategy to work, tan α must

increase monotonically. Tan β must therefore also increase monotonically. Given these constraints, the LOT strategy is unable to satisfactorily model the true variation in tan β for trials in the ground experiment and therefore the lateral position of the simulated fielder does not match that of the real fielder.

Optimisation of parameters caused a significant improvement in the performance of minimum energy strategy. Its performance, prior to the optimisation modifications, was poor relative to the constant δ and LOT strategies and the running paths it produced suggested that it could not model human interceptive behaviour accurately. However, the enhancements to the program implementing the strategy removed its major handicap. The tendency for the simulated fielder to follow a path in the initial stages of a trial that would send him on a path to the interception point that was much longer than the more direct route taken by the real fielder (as shown in figure 6.11) was removed. The strategy now sent the simulated fielder on running paths more similar to those followed by the real fielder but its performance still did not match that of the constant δ strategy. Examining the paths taken by the simulated fielder revealed a possible explanation for this. The problem appeared to lie in trials where the fielder had to run backwards in the ground experiment. As the simulated fielder nears the lateral plane of the ball, by moving to the nearest position that gives the correct tan α the simulated fielder ends up moving to a position where he can no longer maintain constant $d(\tan \alpha)/dt$. Figure 6.16 shows the second half of a trial where the fielder must move backwards to intercept the ball. It illustrates how the path that a real fielder would take diverges from the path taken by a fielder following the minimum energy strategy.

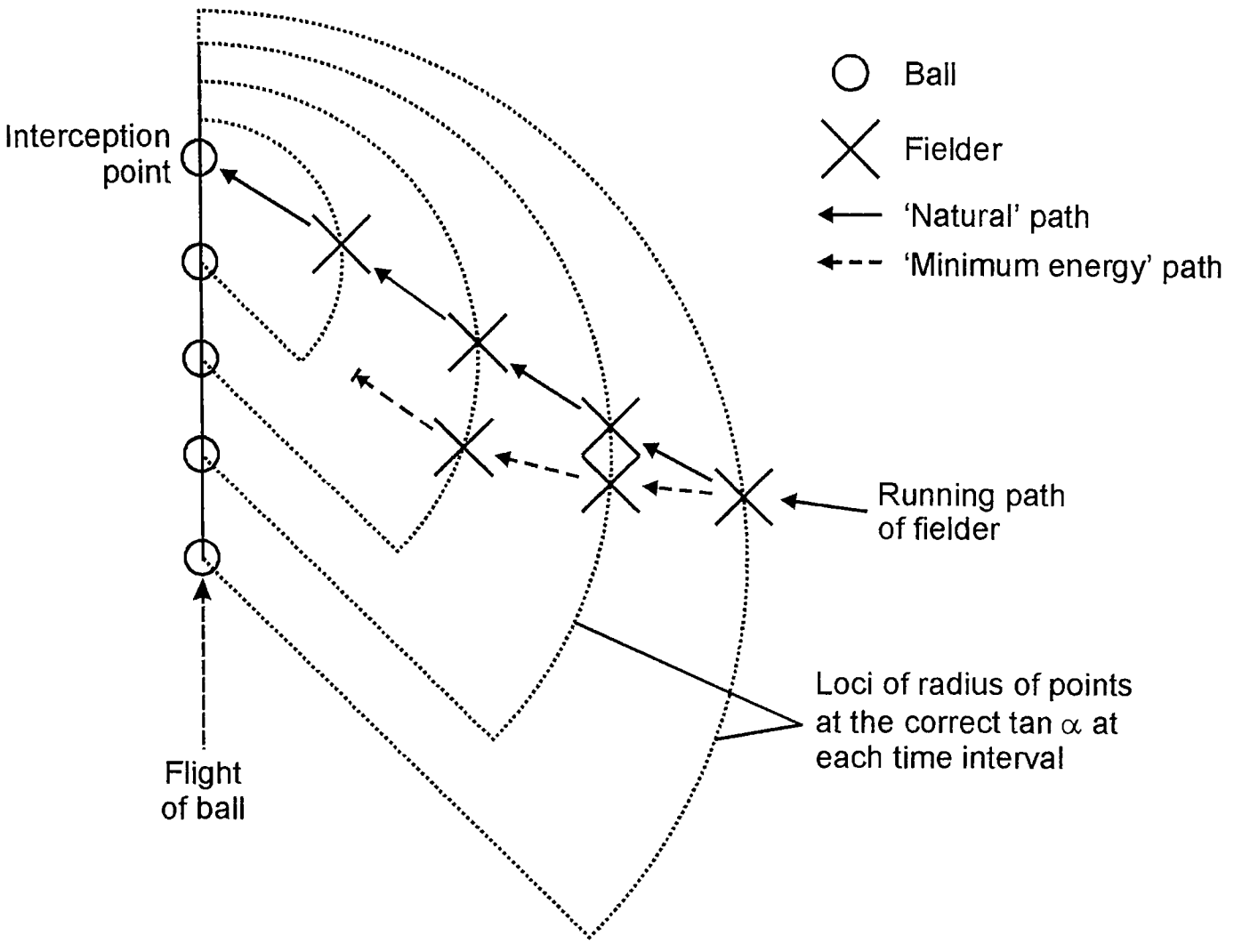


Fig. 6.16 Failure of the minimum energy strategy.

Figure 6.16 demonstrates how a fielder following the minimum energy can end up in a position where he is unable to hold d(tan α)/dt constant because he cannot get to the next constant tan α circle. He therefore cannot reach the interception point. The real fielder does not move to the nearest position that maintains d(tan α)/dt, as prescribed by the minimum energy strategy. The real fielder takes a path that is not the most efficient at maintaining d(tan α)/dt but does take the fielder on an efficient path to the interception point. Following the minimum energy strategy early in a trial could lead the simulated fielder to a position from which it was impossible to reach the interception point. This flaw in the minimum energy strategy makes it an inappropriate model of human interceptive behaviour.

The conserved alignment strategy also showed a considerable improvement through the optimisation process. However, although the mean distance between the

simulated and real fielder was reduced, the curvature of the paths followed by the simulated fielder was still exaggerated in relation to those of the real fielder. The strategy impels the simulated fielder with too great a lateral component to its overall velocity in the initial stages of a catch. This often led to the simulated fielder being unable to maintain constant d(tan α)/dt and thereby failing to reach the interception point (similar to the problem afflicting the minimum energy strategy, although influencing all trials rather than just those in which the fielder ran backwards). Consequently, despite the efforts made to optimise the strategy, the running path taken by the simulated fielder was rarely correct.

6.13.5. Accuracy of modelling human interceptive behaviour

The constant δ strategy was the most effective model of human interceptive behaviour based on the closeness of placement of the simulated fielder to the real fielder. Further investigation revealed that it was also the most appropriate model of human interception with regard to other aspects of interceptive behaviour. Comparisons were made between the variation in the visual angle tangents experienced by the simulated and real fielder. The strategy that produced the best overall fit to the visual angle tangents was the constant δ strategy. Somewhat surprising was the fact that the minimum energy strategy performed significantly better than the LOT strategy and matched the constant δ strategy in its fit to the lateral visual angles (β and δ). This was a counterintuitive result, given the lesser performance of the strategy in terms of the mean distance discrepancy between real and simulated fielders. It seems the mean fit to tan β and tan δ was not affected dramatically relative to the other strategies by the tendency for the minimum energy strategy to send the simulated fielder on irregular running paths for trials where the

fielder should run backwards. A possible explanation for the sound performance of the minimum energy strategy in these criteria concerns the rules controlling the lateral movement of the simulated fielder. Unlike the constant δ and LOT strategies, the minimum energy strategy applies no rule to the lateral movement of the simulated fielder so the optimisation process allowed a good fit to be achieved. The fact that the constant δ and minimum energy strategies were significantly better than the LOT strategy suggests that the real fielder does not move so that d(tan α)/dt and d(tan β)/dt remain in proportion with one another. The constant δ strategy is therefore a more appropriate model of human interceptive behaviour.

The status of the constant δ strategy as the most effective model was retained after examining the fit of the visual angle tangents experienced by the simulated fielder to those experienced by the real fielder. The variation in performance of the constant δ strategy was examined using correlations of the differences in position, tan α, tan β, and tan δ with the average speed required of the fielder to reach the interception point in each trial. The average speed required was taken as a measure of trial difficulty[4]. Correlations were calculated between average speed and the fit to the real fielder's position, tan α, tan β, and tan δ for each strategy. The pattern of correlations for the constant δ strategy suggested that it was more effective as the average speed required increased. The correlation between the fit to tan α and average speed was not significant. McLeod & Dienes (1996), Michaels & Oudejans (1992), and chapters 3 and 4 have shown that fielders move so that tan α increases at a constant rate in all situations. The constant δ strategy was constructed around this

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[4] Other factors can influence catch difficulty. However, the consistent features across the two experiments suggest that it is reasonable to assume that the more difficult a trial was the greater the average speed required of the fielder to reach the interception point.

premise. The ability to move the simulated fielder so that d(tan α)/dt is held constant throughout trials suggests the protocol of the strategy is comparable to that used by the real fielder. There were significant negative correlations between average speed and the other measures of strategy performance – fit to position and the lateral visual angle tangents. The constant δ strategy could not contend with the variation in the running path of the real fielder when the average speed required to get to the interception point was low.

To investigate the conditions under which the constant δ strategy fails, the 40 trials on which the optimised constant δ strategy was run were divided into those where the strategy performed well (Good group) and those where it performed poorly (Poor group). The significant differences that existed between the Good and Poor groups were instructive in explaining when and how the constant δ strategy fails. Firstly, the fits to the lateral visual angle tangents differed significantly across the two groups, as did the average speed required of the fielder. This was expected given the significant negative correlation between those variables. The constant δ strategy places the simulated fielder at an incorrect position on the rings that give constant d(tan α)/dt when the average speed is low. Under these circumstances the real fielder does not hold δ constant. The curvature of tan β vs. time differed across the Good and Poor groups. For Poor trials, the sign of the quadratic component of the regression model was always negative, indicating that d(tan β)/dt decreased towards the end of trials. Furthermore, the sign of the gradient of linear regression models of tan δ vs. time was always negative for Poor trials. Clearly, when the average speed required is low – when it is an easy catch – the fielder gets more into line with the plane of projection of the ball. In doing this, d(tan β)/dt decreases and δ decreases. This cannot be accounted for in the constant δ or LOT strategies. The constant δ strategy specifies

that δ is held constant whilst the LOT strategy has an indirect requirement that $d(\tan \beta)/dt$ is held constant, thus explaining the poor performance of the models when the average speed required was low.

Interestingly, under certain circumstances, the constant δ strategy may not be radically different from the LOT strategy. In proposing the LOT strategy, McBeath, Shaffer, & Kaiser (1995) examined catching experiments similar to those here. However, a major distinction between protocols was the scale of the arena in which the experiments took place. Subjects in the experiments described here had to run about 6m to reach the interception point, catching balls launched from approximately 15m away. Subjects in McBeath, Shaffer, & Kaiser's experiments had to run up to 15m to catch balls launched from 50m away. At this distance, the relative changes in $\tan \beta$ are markedly different. Imagine a fielder applying the constant δ strategy in McBeath, Shaffer, & Kaiser's experiment. As the fielder moved laterally, maintaining δ, there would be steady increase in the angle between the fielder and the launch point. This would cause β to undergo a steady increase. The distance of the launch point means that β will be small, therefore $\beta \approx \tan \beta$. Consequently, $\tan \beta$ would show a steady increase. Assuming the fielder also runs cancelling optical acceleration, a linear optic trajectory will result. The relative closeness of the launch point in the experiments examined here means that fielders' lateral and depth movements will have a more pronounced effect on $\tan \beta$. This possibly explains why McBeath, Shaffer, & Kaiser found that the LOT strategy modelled fielder behaviour so accurately in their experiments but the same cannot be said of the interceptive behaviour of fielders participating in experiments described in this thesis.

6.13.6. Human interceptive behaviour

The constant δ strategy (with optimised parameters) has been shown to be the most effective strategy of those under test. To improve on it, a strategy must be devised which (in conjunction with ensuring constant d(tan α)/dt) exerts control of δ, allowing steady variation in δ linked to the average speed required to reach the interception point. An increase in δ was permitted in the constant δ strategy when parameters were optimised. The simulated fielder could mimic the action of the real fielder by not running at his maximum actual speed but observing a lower limit of his running speed. This allowed tan δ for the simulated fielder to occasionally show a steady increase and produced a significant improvement in the fit of the model to the behaviour of the real fielder. A similar adjustment could be made to allow tan δ to decrease however, the more one manipulates the way the simulated fielder can adjust tan δ, the less the model fits its description as a 'constant δ' strategy. To further complicate matters, δ vs. time varied from trial to trial even when the trajectory of the ball and the start position of the fielder are the same.

This leads to a different approach to the problem. It is possible that fielders do not necessarily use any formal strategy to control their lateral position relative to the ball. A simple strategy for intercepting a ball in the unaligned plane is explained in the following example. A fielder would use the cue that the ball has gone to their left to begin moving left. They would then monitor δ loosely to ensure that it remained roughly constant. More importantly, they would ensure that tan α was increasing at a constant rate because it keeps the fielder moving toward the interception point – it is an efficient and sufficient condition for interception. Variation in δ vs. time would depend largely upon how the fielder decides he would be most comfortable taking the

catch. Although, this conclusion is rather defeatist, the analyses undertaken show that (with the exception of constant d(tan α)/dt) the variation in the visual experience of human fielders is virtually impossible to model with exacting accuracy. Conducting a greater number of trials in a wider range of catching situations may reveal a trend towards a particular control method. The constant δ strategy offers the best compromise in modelling how we catch but it seems that a single, all-encompassing mathematical strategy of interception could not capture the full complexity of human interceptive behaviour.

7. Investigating implicit knowledge in the context of interception strategy

7.1. The conditions of implicit knowledge

The study of implicit learning began with the work of Arthur Reber, over thirty years ago. The phrase was coined to describe subjects' acquisition of the structure of a complex stimulus environment, without necessarily intending to do so. The term 'implicit knowledge' is used to describe the information resulting from implicit learning. This information is not consciously available or is, at least, difficult to express. In the context of this thesis, a fielder might be said to have implicit knowledge of how to catch. For example, if a fielder ran forward to catch a ball but could not explain how they knew that the ball was going to land in front of them then their knowledge of catching could be classified as implicit.

The position of implicit knowledge is currently unresolved. Shanks & St.John (1994) voiced methodological concerns about the supposed unconscious character of implicit knowledge, leading them to suggest that 'Human learning is systematically accompanied by awareness'. In experiments designed to show implicit learning, tests of awareness are used to investigate how aware subjects are of knowledge they are able to demonstrate. Much of the criticism of these studies is based around the apparent failure of the awareness tests to meet the 'Information criterion' and the 'Sensitivity criterion'. Shanks & St.John state these criteria as follows:

- Information criterion:

'Before concluding that subjects are unaware of the information that they have learned and that it is influencing behaviour, it must be possible to establish that the information the experimenter is looking for in the awareness test is indeed the information responsible for the performance changes.'

- Sensitivity criterion:

'To show that two dependent variables (in this case, tests of conscious knowledge and task performance) relate to dissociable underlying systems, we must be able to show that our test of awareness is sensitive to all of the relevant conscious knowledge.'

If one is to use an awareness test to demonstrate implicit knowledge, it must satisfy these criteria.

7.2. The utility of ball catching in studying implicit learning

When considering motor skills, Shanks & St.John's scepticism seems somewhat misplaced. For example, one cannot describe the interaction between optic flow and postural adjustment muscles that keeps them upright. Similarly, an adult can learn to ride a bicycle without being able to describe subsequently how they do it. However, despite these apparently straightforward examples, little work has been carried out examining conscious awareness of the knowledge underlying motor skills. Mathews (1997) noted this absence but claims that implicit learning is suited to the acquisition of skilled action and argues that studies examining actions learnt implicitly over longer periods of time than the classical one hour laboratory experiment are required to gain a fuller understanding of implicit knowledge.

In this experiment, ball catching was the task in which conscious knowledge of the factors influencing performance was assessed. Ball catching is a useful paradigm to use for several reasons. Firstly, the stimulus (the ball) and the target response (the catch) are unambiguous and familiar to subjects, unlike the more abstract tasks utilised in traditional implicit learning experiments such as artificial grammar learning and sequence learning. Subjects' familiarity with the task is compatible with the requirement suggested by Mathews. The subjects performing in the experiments

described here (university students) are almost certain to have had experience of the task for at least 15 years. Secondly, the skill has three of the characteristics that Berry (1994) suggested were typical of implicit learning:

(i) It is associated with incidental learning – children are not given instructions on how to catch other than 'Watch the ball'.

(ii) It generates a sense of intuition – a skilled fielder has an immediate notion about the direction that he needs to run without conscious computation.

(iii) It shows limited transfer – the knowledge that a fielder uses to intercept (or avoid) a projectile can be has little use beyond those two domains.

Thirdly, many studies (Michaels & Oudejans (1992), Dienes & McLeod (1993), McLeod & Dienes (1996)) have shown that the variable used to control catching behaviour is the variation of the catcher's angle of gaze (α) when fixating the ball. Fielders appear to run to intercept a projectile by controlling Tan α so that it increases at a constant rate. Therefore α increases continuously, at a steadily decreasing rate. Figure 7.1 shows α for a stationary observer watching three different trajectories.

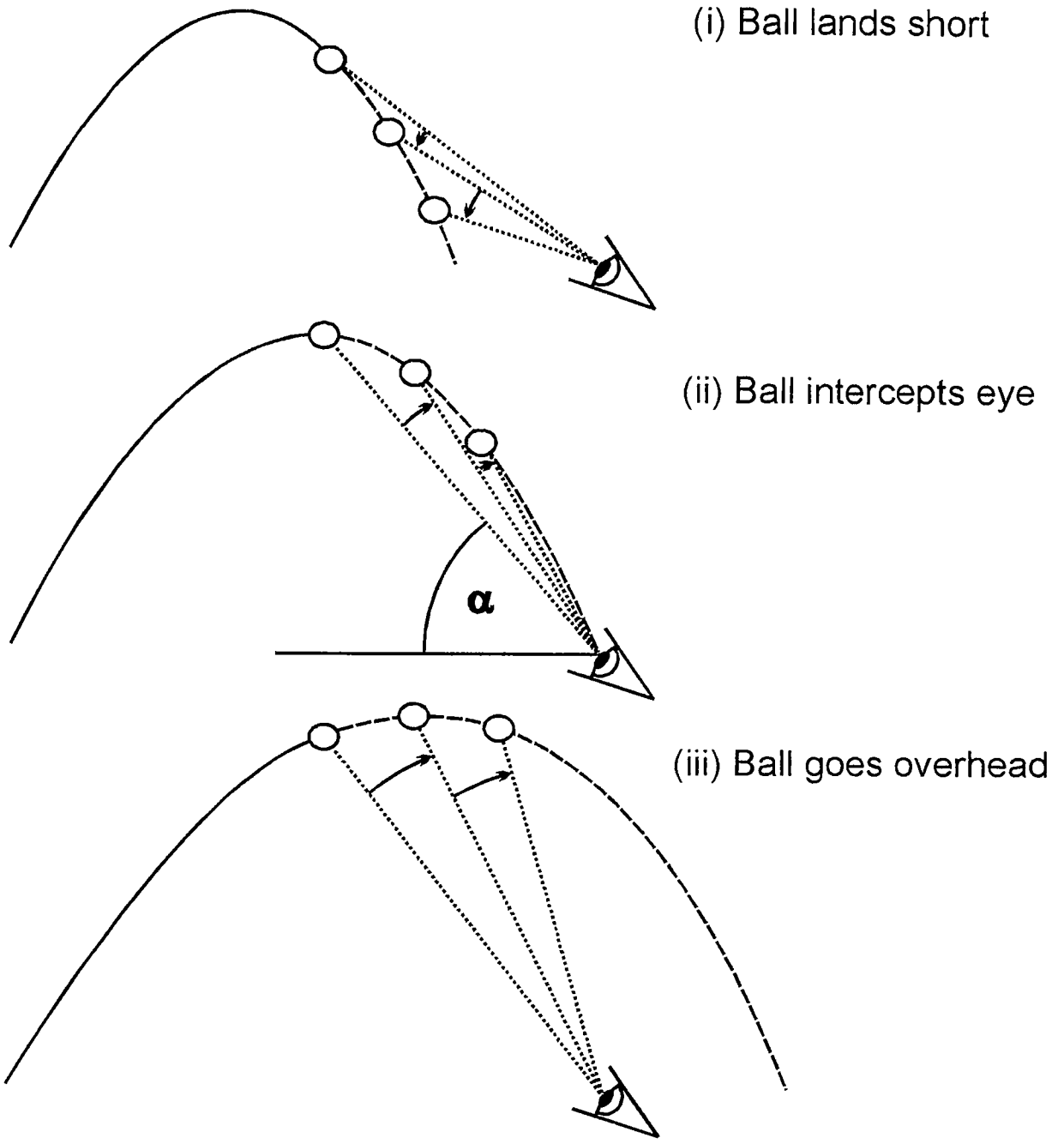


Fig. 7.1 Variation in α for three different trajectories

Section (ii) of figure 7.1 shows α for a ball that will intercept the observer's eye. It can be seen that α will increase throughout the flight, reaching a maximum value of less than 90° at the point of collision. This is only strictly true for balls that will intercept the observer's eye. In a natural setting however, this condition is generally to be avoided. Objects on trajectories that will bring them close to the observer's face produce a looming cue as the ball approaches. This triggers a protective reflex, eye closure, such that the observer does not see the final part of the trajectory when α would rise or fall rapidly (depending on whether the ball falls above or below the eye). Thus, for trajectories that approach the face of an observer,

the pattern of α variation approximates that for projectiles that will intercept their eye – an increase at a decreasing a rate. Parts (i) and (iii) of figure 7.1 show what happens to α when the trajectory does not land close to the observer's head. In (i), α shows an initial increase but after the ball passes its apogee, the ball starts to cross below the observer's angle of gaze at each successive time step. This will begin later in the flight for balls that will land closer to the fielder. The ball is accelerating downward due to gravity and decelerating forward due to air resistance. Thenceforth, α can only decrease for the stationary observer. Section (iii) of figure 7.1 shows a ball that will fly over the top of the stationary observer. The rate of increase in α accelerates with α eventually reaching 90° as the ball passes overhead.

These patterns of α variation will be true of nearly all objects thrown toward an observer throughout their life and are not dependent on launch parameters or air resistance[1]. Flights of all projectiles will fall into one of the three categories of α variation. Fielders attempting to catch a ball appear to make use of this information when formulating a running strategy (Michaels & Oudejans (1992), Dienes & McLeod (1993), McLeod & Dienes (1996))[2]. A fielder who moves so that the change in α matches that observed for projectiles that hit them in the face results in their being in the right place at the right time to catch the ball. If they are watching a ball launched toward them and α begins to decline then they must move forward to intercept the ball. If α continues to decline, then they must move forward faster.

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[1] Exceptions to the described patterns of α variation (leading to the inclusion of the condition 'nearly') include thrown objects capable of generating their own lift in flight, counteracting the effect of gravity, e.g. a Frisbee, a paper dart.

[2] These studies show that the tangent of α increases at a constant rate as the fielder runs, α therefore increases at a decreasing rate.

If the fielder's forward motion has caused α to increase at an increasing rate then they must reduce their forward speed. The exact opposite response pattern applies if α is increasing at an increasing rate initially. The fielder must move backward to intercept the ball and adjust his running depending on how his movement changes the rate of change of α.

McLeod & Dienes (1996) suggest that children acquire this strategy passively by watching balls thrown toward them. Initially, an infant will only catch balls that land in his or her arms. When they realise that they have to move to catch certain trajectories of throw, McLeod & Dienes claim that it is natural that their movements attempt to re-produce the pattern of α variation that has lead to every previous successful catch. The strategy is effective in achieving interception and it is retained by the child. If it is assumed that McLeod & Dienes' assertions about interception strategy are correct, awareness tests can be developed tailored specifically to measure fielders' awareness of the basis of their interceptive behaviour. This tackles the information criterion, as set out by Shanks & St.John (1994). Subjects can be questioned about the information that is used to guide their actions.

7.3. Experiment 1

The aim of this preliminary experiment was to investigate the extent to which fielders are aware of what they are doing as they run to catch projectiles. The concept of angle of gaze was not introduced, subjects were merely asked to explain the basis of their strategy for catching.

7.3.1. Method

7.3.1.1. Subjects

These were 14 males and 4 females, aged 19-27, all of whom considered themselves to be above the average skill level for ball games.

7.3.1.2. Task

Subjects filled in a questionnaire (see appendix A7.1 for the questionnaire) that asked them to imagine a ball being thrown toward them from 20m away. There were four critical questions. The first asked how they would know that they are in the right place to receive a ball that they can catch comfortably without moving. The second question asked how they would know that they had to move forward to catch a ball that would land in front of them. The third asked how they would know that they had to move backward to catch a ball that would land behind them. The fourth question asked how they would know that they were moving at the correct speed to intercept the ball in questions 2 and 3.

7.3.2. Results

Only one subject mentioned angle of gaze[3]. The answers given by the remaining subjects fell into two groups. One group thought that the apex of the flight of the ball was the vital cue to their subsequent action. If it fell roughly halfway between them and the launch point, they considered that they were in the right place to catch the ball. If it was nearer to the launch point, then they had to move forward. If it were nearer to their position, then they would have to move backward. There are several reasons why use of the apex of trajectory is flawed. Firstly, McLeod & Dienes (1996) showed that fielders start to move in the correct direction to intercept a projectile long before it has reached the peak of its flight. In their study, fielders typically began moving after around 800msec to intercept projectiles that were airborne for more than 3 seconds. The ball would not reach its peak until at least 1.5 seconds. Secondly, a fielder fixating a ball that will land near them has scant information about the location of the apex of its trajectory. Angle of gaze merely increases steadily throughout the flight. No indication is given as to where or when the ball has reached its peak. Thirdly, use of the peak of flight would be justified if balls followed precise, symmetrical parabolic trajectories. Brancazio (1985) showed that air resistance causes projectiles launched with the parameters commonly found in ball games do not display symmetrical trajectories and deviate significantly from parabolic. Furthermore, assuming fielders were able to detect the apex of a trajectory and ball flight is symmetrical, then they would know where the ball would land. However, McLeod & Dienes (1996) showed that fielders are usually moving when they take a

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[3] This subject was a mathematics student who attempted to derive the answer from first principles. Though he realised the importance of α, his answers did not correctly reflect the McLeod & Dienes strategy of interception. There was no reason to believe he was aware of this information before considering the questionnaire and he admitted that this was the case.

catch and time their run to arrive at the right place at the right time. This holds true even when fielders have ample time to get to the interception point[4]. They suggest fielders do not have a precise sense of where the ball will land but use an algorithm linking available visual information to running speed.

Subjects' belief that they are able to make use of the apex of trajectory would appear to stem from an erroneous intuition. Their false notion is that they somehow have access to the information that would be available from a third-person side view of the trajectory (like in figure 7.1) and can use it to control their own actions. However, even if the trajectories were parabolic (which they are not) fielders cannot glean this information from a first person perspective. The remaining subjects attributed their behaviour to "experience". This is undoubtedly correct, but no subjects were able to say what it was about their "experience" that enabled interception.

7.3.3. Conclusion

This first experiment confirms what is intuitively obvious – people do not know what it is on which they base their decisions when they run to catch a ball.

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[4] Unless the distance the fielder was required to move was trivially small.

7.4. Experiment 2

It has been claimed that native speakers of a language who use the rules of its grammar correctly yet cannot state those rules display implicit knowledge of them. Shanks & St.John (1994) assert that the rules of grammar might not be represented in a symbolic way but as the connection weights of a neural network. They presume that connection weights are not reportable and claim that use of a representation coupled to an inability to report it did not constitute an example of implicit knowledge. The algorithm that links the variation in α to the control of running speed is a natural candidate for mapping with a neural network. Shanks & St.John might therefore respond with similar criticisms of the result of the first experiment. In the remaining experiments, the subject of investigation was the sensory information that underlies catching, namely α. Angle of gaze is inherently reportable since people can tell if they are looking up or down even if the mapping from this to the appropriate action is not. Subsequent questionnaires investigated subjects' ability to report the variation in their angle of gaze when catching.

In this experiment, the concept of angle of gaze was introduced to subjects. They were asked to imagine what happened to their angle of gaze as they watched balls thrown on different trajectories thrown toward them. Subjects also had to assign a confidence rating to their response to establish how sure they were that the answer they gave was correct.

When investigating the extent of awareness of the basis of our actions, subjects may demonstrate knowledge in forced choice tests of recall but claim to be guessing – they lack *metaknowledge* about the learned information. When this is the case, Dienes & Berry (1997) suggest that this knowledge exists below a *subjective threshold* but above an *objective threshold* of consciousness, terms originating in subliminal

perception experiments. Above the subjective threshold, subjects are consciously aware of knowledge they are using in recall and therefore possess metaknowledge. Below the objective threshold, subjects respond at chance performance levels in all tests of awareness. Between the two thresholds lies information for which subjects lack metaknowledge but is demonstrable in forced choice cued recall tests. The objective threshold of consciousness is where Shanks & St.John would set the boundary between implicit and explicit knowledge. Dienes & Berry on the other hand see the subjective threshold as the dividing line between conscious and unconscious knowledge. A true test of whether knowledge is below the subjective threshold is based on confidence ratings. Two scenarios would show that knowledge is below the subjective threshold of consciousness:

- Subjects perform above chance in a task when they have no confidence in the accuracy of their answers, i.e. they believe they are literally guessing (the *guessing criterion*).
- Subjects are no more confident in right responses than wrong responses (the *zero correlation criterion*).

(Both from Dienes & Altmann, (1997))

To explore subjects' assurance in the accuracy of their responses and whether the angle of gaze information was below the subjective threshold, they were asked to assign a confidence rating to each response given. If the catcher's knowledge of how α is used to control behaviour is implicit, subjects will make incorrect judgements of how α changes in recall. This is possibly due to the (incorrect) common sense notion that because the ball goes up then down, watching a ball that you catch results in α following a similar pattern. McLeod, & Dienes (1993) showed that if a ball is caught at eye level, angle of gaze is always increasing.

7.4.1. Method

7.4.1.1. Subjects

These were 19 males and 5 females, aged 20-25. Their skill level at ball games was ranked where a ranking of 1 indicated below average skill, 2 indicated average skill level, and 3 indicated above average skill level. The mean rank score of skill level for these subjects was 2.17, SD = 1.06.

7.4.1.2. Task

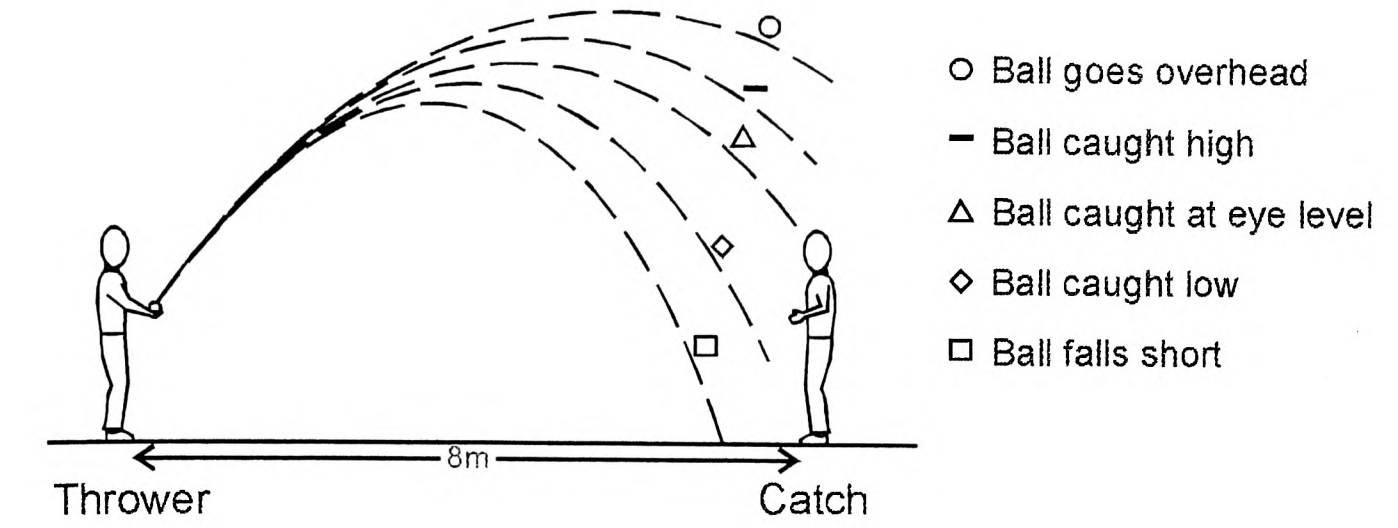
Subjects received a questionnaire (see appendix A7.2). It describes and illustrates angle of gaze. It also explains how it can change as they watch a moving object – the examples given were a rocket launching into the air or a parachutist descending to Earth. Subjects were asked to imagine watching from a stationary position, a ball thrown gently toward them by someone stood 8m away. They were then required to describe their angle of gaze change if the ball were thrown on the following trajectories:

- The ball landed a couple of metres short of their position.
- They caught the ball low at around knee level.
- They caught the ball at eye level just in front of their face (it would have hit them in the face had they missed it).
- The ball was caught high above their head.
- The ball flew right over their head.

Subjects were also asked to supply a confidence rating on a scale from 0 to 10 on their angle of gaze description. If they felt that their answer was a complete guess, they were to indicate so by giving their description a confidence rating of 0. If they

were absolutely certain their description was correct, they were to give their answer a rating of 10.

The upper half of figure 7.2 shows the approximate trajectories for which subjects were required to give descriptions of the variation in their angle of gaze. Subjects were not shown this figure because it would have provided them with an extraneous source of information as to what really happens. The lower half of this figure shows what happens to α when a stationary observer watches balls thrown on the trajectories shown in the upper half. The ball positions were calculated using the method of approximation and numerical integration outlined in Brancazio (1985) and a drag factor suitable for a tennis ball. The balls were given a launch elevation angle of 45° and launch velocities that propelled them on simulated trajectories that lead them to arrive at the correct end-point (see appendix A3.1 for a trajectory simulation program). Angle of gaze was found by calculating the height of the ball above the observer's eye divided by the horizontal distance of the ball from the observer's eye and then finding the inverse tangent of this value.



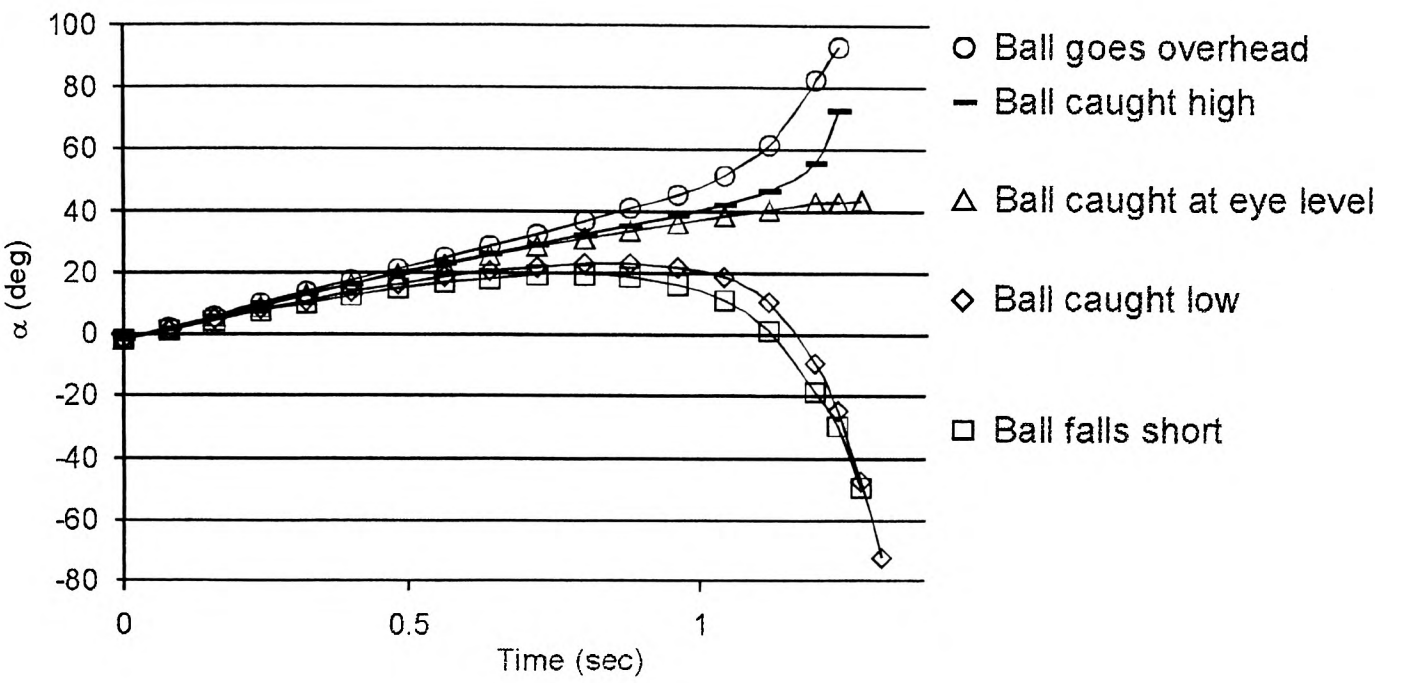


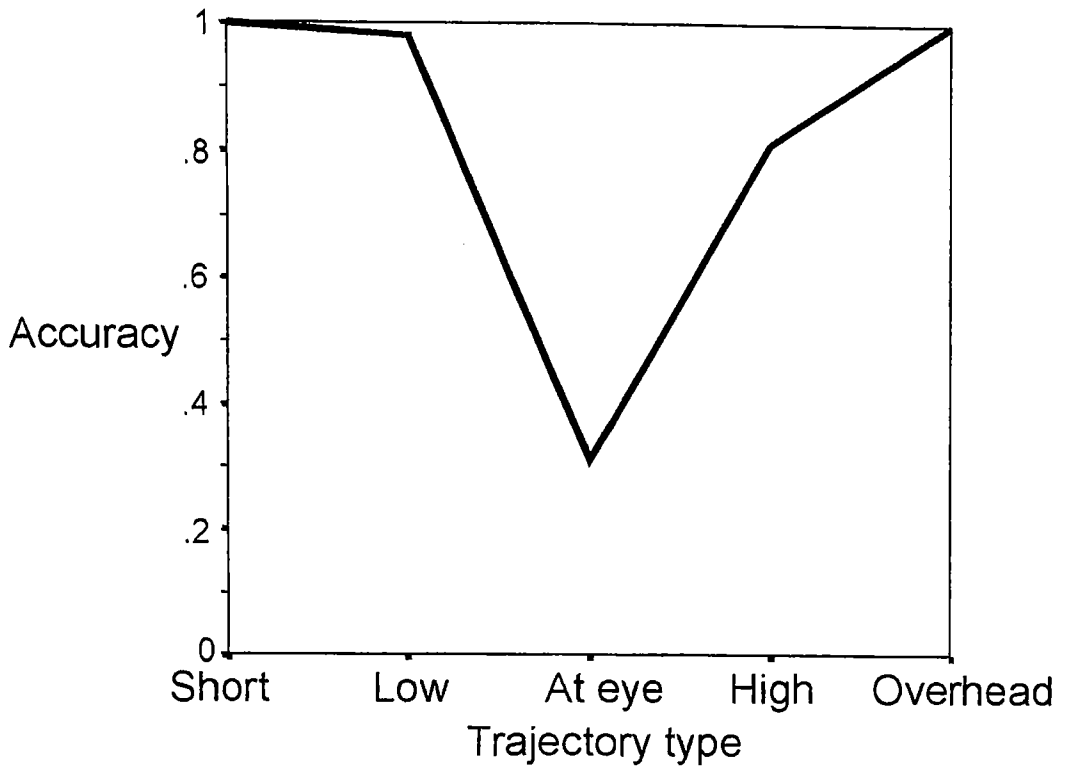
Fig. 7.2 Diagram of the approximate trajectories of each type of throw and their associated α variation.

The exact values of α depend on the launch parameters. However, the general pattern of α variation remains the same for balls thrown toward a fielder in such a manner. Balls on trajectories that finish below eye level (i.e. fall short or are caught low) show an initial increase in α followed by a more rapid decrease. Balls that will intercept the observer's eye display a continuous increase in α at a decreasing rate. Balls caught high or that go over head show an initial steady increase in α but the rate of increase grows.

7.4.2. Results

Details of the statistical tests used in this experiment are given in appendix A7.3. Subjects' responses were scored on a three-point scale. A score of 1 was given to a response that was correct. A score of 0.5 was given to answers that had some correct elements but some wrong. To score 0, an answer had to be fundamentally incorrect. To check the consistency of scoring, three independent judges scored the responses. Significant agreement was found between the judges using a test of concordance (Kendall's $W = 0.21$, $\chi^2(2) = 9.9$, $p < 0.01$).

The results are shown in figure 7.3. The upper half shows the mean accuracy score for each trajectory type of subjects' descriptions of α variation. The lower half shows subjects' mean confidence score for each trajectory type. Two important facts are apparent. Firstly, subjects are able to provide consistently accurate response to all trajectory types other than when the ball is caught at eye level. Wilcoxon tests confirm that the scores for 'ball caught at eye level' responses are significantly less than those for other trajectories ($p < 0.001$ in each case). Secondly, subjects' confidence scores do not correlate with their accuracy. Confidence is the same in all conditions whereas accuracy varies from 100% to 31%. A Friedman test confirms that mean confidence scores do not differ significantly across trajectory types ($\chi^2(4) = 7.3$; $p > 0.08$).



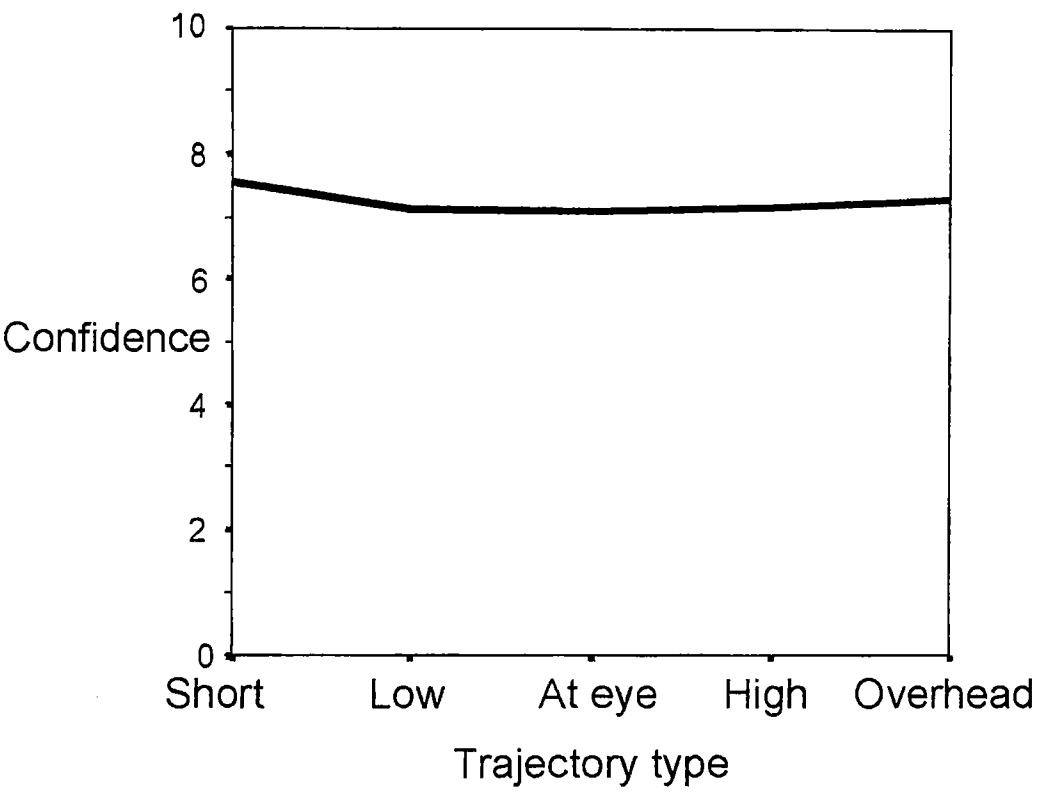


Fig. 7.3 Accuracy and confidence scores for the five different types of trajectory

7.4.2.1. Correlation with skill

The pattern of α variation shown in the lower half of figure 7.2 is associated with many everyday occurrences, not just watching balls. However, it is possible that skilled ball games players who have had more experience of catching and interacting with projectiles are better at judging what happens to their angle of gaze. The average score for 'Ball caught at eye level' trajectory type could have been dragged down by

poor responses by unskilled fielders. To check whether this was the case, a correlation coefficient was calculated between subjects' skill ratings and the response scores for the 'eye level' trajectory type. The correlation was found to be non-significant (Kendal's $\tau = -0.134$, $p > 0.45$). Skill at ball games does not correspond with an ability to accurately report what happens to α.

7.4.3. Conclusion

The majority of subjects reported that when they imagine watching a ball approaching that they will catch in front of their eye, their angle of gaze goes up then down. A third of subjects stated that their angle of gaze increased and decreased symmetrically about the apex of the ball's flight. The lower half of figure 7.2 shows that there is no simple method a fielder could use to detect when the ball was its apex. Angle of gaze increases smoothly as the ball passes its apex. As in experiment 1, it seems as if subjects are using prior knowledge that they have about ball trajectories to decide how they believe their angle of gaze must be changing. For the other trajectories, subjects scored consistently well, with slightly lower performance for the 'Ball caught high' trajectory. This suggests that subjects understood the concept of angle of gaze and the demands of the task.

Interestingly, the trajectory type, 'Ball caught at eye level', is the only one where the obvious intuition about what happens to angle of gaze is different to what actually happens. For short balls and those caught low, it is clear that ones angle of gaze must go up and then at some point follow the ball downwards as it descends below eye level. Similarly, it is logical that for balls caught high or that go overhead, ones angle of gaze must follow the ball continuously upwards to 90°. However, for balls caught that would hit the catcher around the face if missed, it is not immediately obvious that angle of gaze should continue to rise when the ball goes up then down. It

seems this intuition about projectiles overrides the sensory information available with respect to angle of gaze.

It is highly likely that the subjects participating in this experiment are like all those that have been tested previously (Michaels & Oudejans (1992); Dienes & McLeod (1993); McLeod & Dienes (1993,1996); chapters 3 and 4) and use an interception strategy that is based on α. Making that assumption, the result of this experiment is subjects appear unable to report the information used to control how they run to catch a ball. This seems to be an example of implicit knowledge. Supporting this claim is the evidence from the confidence reports, which suggest that subjects lack metaknowledge about their interception strategy. The information that subjects use to control their catching behaviour cannot be available. If it were available but subjects were choosing not to state it then presumably it would at least introduce doubt into subjects' confidence about their answers for 'Ball caught at eye level' trials. However subjects' confidence in the legitimacy of their answers is unwavering across trajectory types, unlike their accuracy. This fulfils the zero correlation criterion – subjects do not have any less confidence about their incorrect answers than they do about their correct ones. Their knowledge of α variation can therefore be said to be below the subjective threshold of consciousness and, according to Dienes & Berry's definition, implicit.

7.5. Experiment 2a

A criticism of Experiment 2 is that perhaps fielders were able to say what was happening to their angle of gaze in all conditions but were mislead by the instructions for the 'Ball caught at eye level' trials. For this question, subjects were asked to imagine a ball that they catch at eye level that would hit them in the face if they missed it. Figure 7.4 shows how this information may have been misinterpreted.

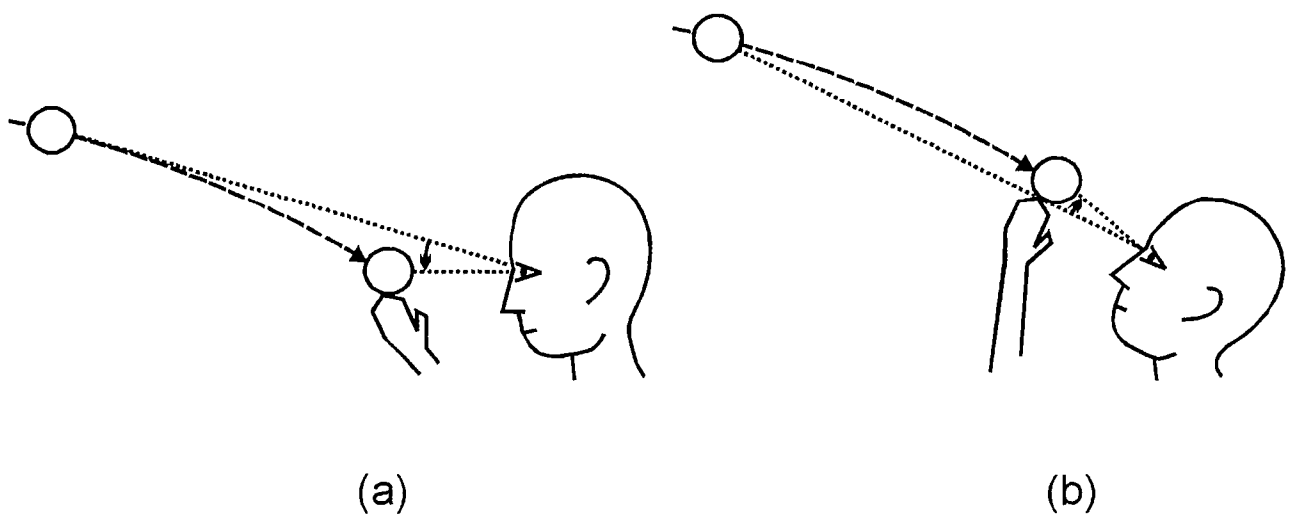


Fig. 7.4 Balls caught 'at eye level'.

Fig. 7.4(a) shows how the questionnaire may have been misinterpreted. The catcher's head is horizontal and the ball is caught at eye level. It could conceivably have struck the catcher in the face if it were missed. The dotted lines indicating angle of gaze demonstrate the problem with this misinterpretation. The trajectory of the ball has descended below the line of gaze angle and from that moment onward α will only decrease. This may have been what subjects were describing when they claimed that their angle of gaze went up then down. The intention was for subjects to imagine a trajectory like that shown in fig. 7.4(b). The catcher has tilted their head back to maintain fixation of the ball and the ball would strike the catcher in the eye should it be missed. This is the usual method people use to catch balls thrown on such a trajectory. To rectify this situation, a modified version of Experiment 2 was performed on a new group of 11 subjects. The instructions for the 'Ball caught at eye

level' question changed to: "Describe how your angle of gaze would change as you watch the ball if it was thrown so that if you failed to catch it, it would hit you in the eye".

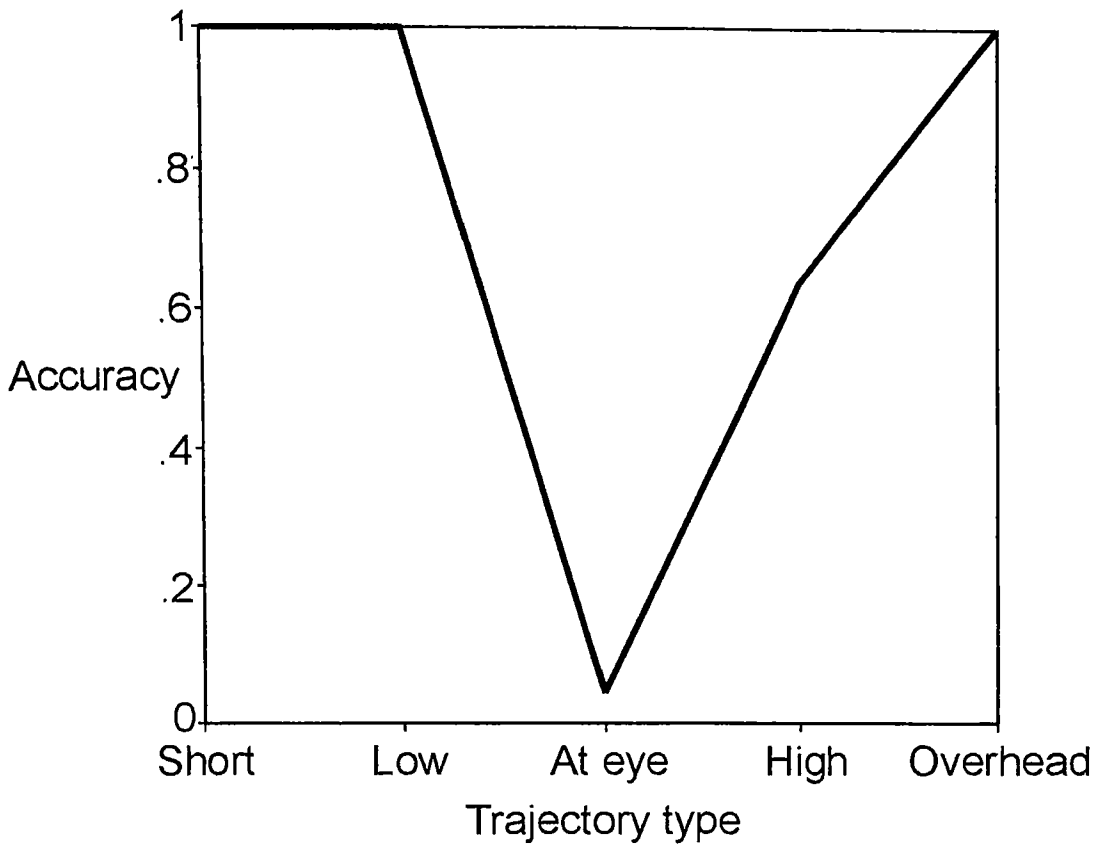
7.5.1. Method

7.5.1.1. Subjects

Of the 11 subjects, there were 5 males and 6 females, aged 23-27. Again, skill level at ball games was ranked (1 indicated below average skill, 2 indicated average skill level, and 3 indicated above average skill level). The mean rank score of skill level for these subjects was 1.91, SD = 0.83.

7.5.2. Results

Details of the statistical tests used in this experiment are given in appendix A7.4. The results are shown in figure 7.5. It is clear that approximately the same pattern of scores as that observed in experiment 2 has been produced. Subjects scored very poorly in the 'At eye' condition – 10 out of the 11 subjects questioned gave fundamentally incorrect answers and therefore scored 0 on that question. In the remaining questions, subjects scored well. Wilcoxon tests confirm that performance in the 'At eye' trials was significantly worse than in any other condition ($p < 0.02$ in each case). Again, subjects' confidence showed no correlation with accuracy. A Friedman test confirmed that confidence did not vary across question type ($\chi^2(4) = 5.4$; $p > 0.2$).



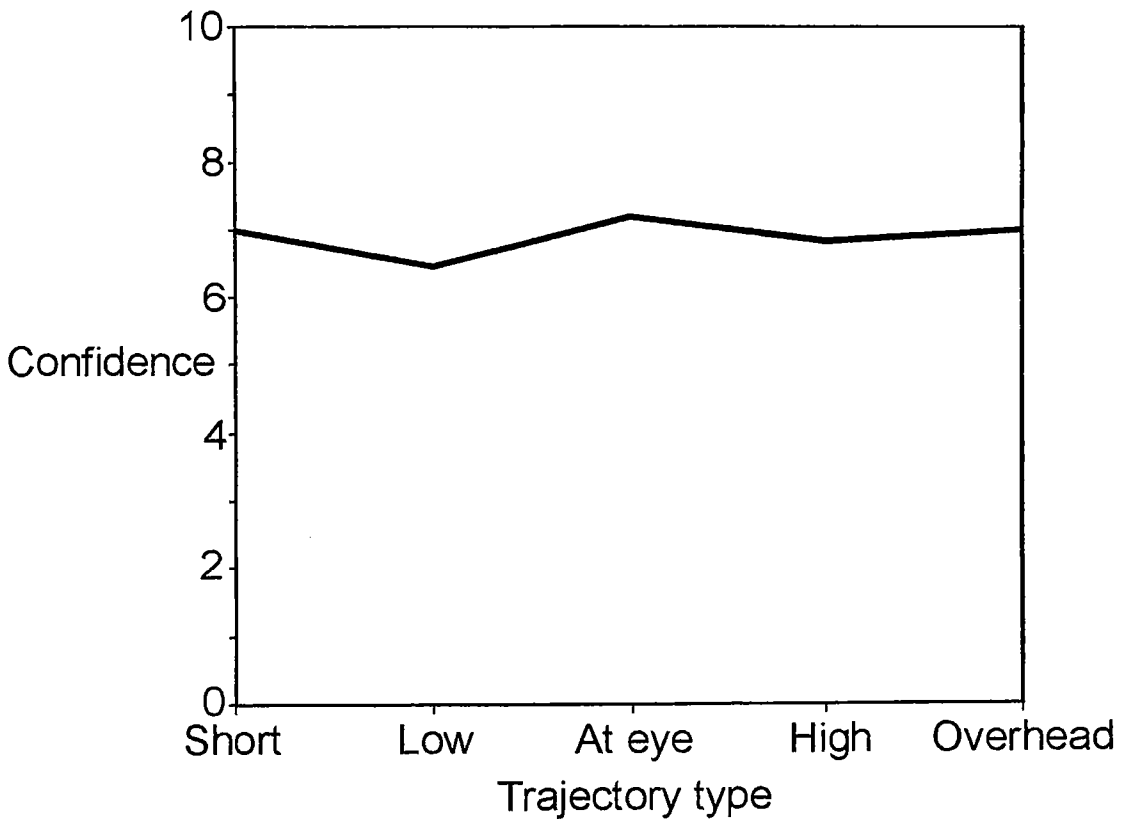


Fig. 7.5 Results for Experiment 2a

7.5.3. Conclusion

Experiment 2a does nothing to undermine the conclusion of experiment 2. It is therefore reasonably safe to assume that subjects did understand what they were being asked. Therefore, the results genuinely show that subjects are much worse at reporting what happens to their angle of gaze for a ball that would hit them in the eye if they missed it.

7.6 Experiment 3

Asking subjects what happened to their angle of gaze as they imagine watching balls thrown toward them revealed a deficit in their performance for trajectories that would hit them in the face in comparison to any other trajectory. A reason for believing that they do have this information is that they use it to control their running to intercept a projectile. A fielder moves in an attempt to reproduce the visual information that is experienced when in a stationary position watching a ball that would hit them in the face. The supposition is that catching demonstrates implicit learning because people possess the information they use to catch but are unable to report it. However, it is feasible that the information only becomes reportable when it is being used to control interception strategy, not when the observer is stationary. Experiment 3 extends experiment 2a by asking subjects how their angle of gaze would change as they ran to catch the ball.

7.6.1. Method

7.6.1.1. Subjects

These were 19 new subjects, of whom 9 were male and 10 female. Age range was 25-29. Their skill ranking (1: below average skill; 2: average skill level; 3: above average skill level) was 2.00, SD = 0.58.

7.6.1.2. Task

See appendix A7.5 for the questionnaire used in experiment 3. In common with the questionnaire used in experiments 2 and 2a, it informed subjects what was meant by angle of gaze. Additionally, subjects were presented with a graphical representation of how angle of gaze increases as an observer moves toward an object stationary in the air and decreases as they move away from one. They were asked to imagine a ball being thrown towards them from a distance of 12m given six different scenarios where they would have to move to catch the ball and report how their angle of gaze changed in each. The first three questions required subjects to imagine running 4m forward to three different ball trajectories. One that they failed to reach in time, one caught low at knee level and one caught comfortably so that it would have hit them in the eye were it missed. The last three questions asked subjects to imagine running backward 4m to catch. The ball trajectories were one caught comfortably that would have hit them in the eye if missed, one caught at arms length above their head and one that flew over their head out of reach. This is illustrated in figure 7.6.

Fig. 7.6 Illustration of the task subjects were asked to imagine in experiment 3.

Running patterns that take the fielder toward the interception point fall into the same three broad categories of variation in α over time as those for the stationary fielder. These are shown in figure 7.7 below. It shows graphs of α vs. time for a simulated fielder performing the task depicted in figure 7.7. The upper half shows how α would change for a fielder covering 4m forward at constant velocity attempting to intercept the trajectories described in the first three questions. The lower half shows how α would change as a fielder moved backward 4m at constant velocity trying to intercept the trajectories described in the last three questions of the questionnaire. Although there are many running patterns that would get the fielder 4m forward or backward, the angle of gaze variation experienced would still resemble

those shown in figure 7.7 reasonably closely. Accordingly, subjects' descriptions should approximately match these patterns.

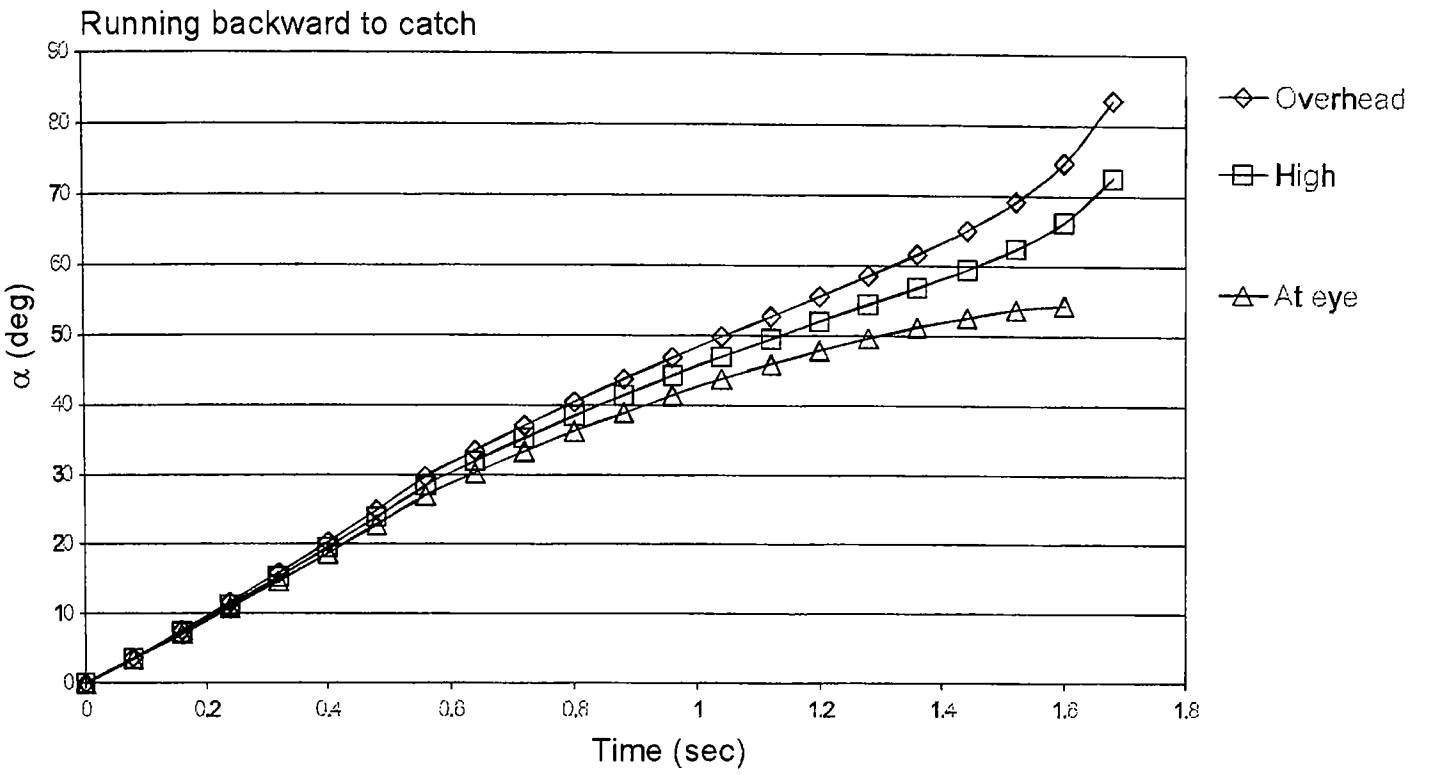


Fig. 7.7 Angle of gaze against time for a fielder moving forwards or backwards.

Scoring of answers remained the same as in the previous experiments. Subjects were again required to provide a confidence rating from 0-10 on the accuracy of their answers. A rating of 0 indicated the subject believed their answer to be a complete guess, 10 indicated absolute certainty that their answer was correct.

7.6.2. Results

For details of the statistical tests used see appendix A7.6. The mean accuracy of subjects statements and the associated confidence ratings are shown in figure 7.8 below.

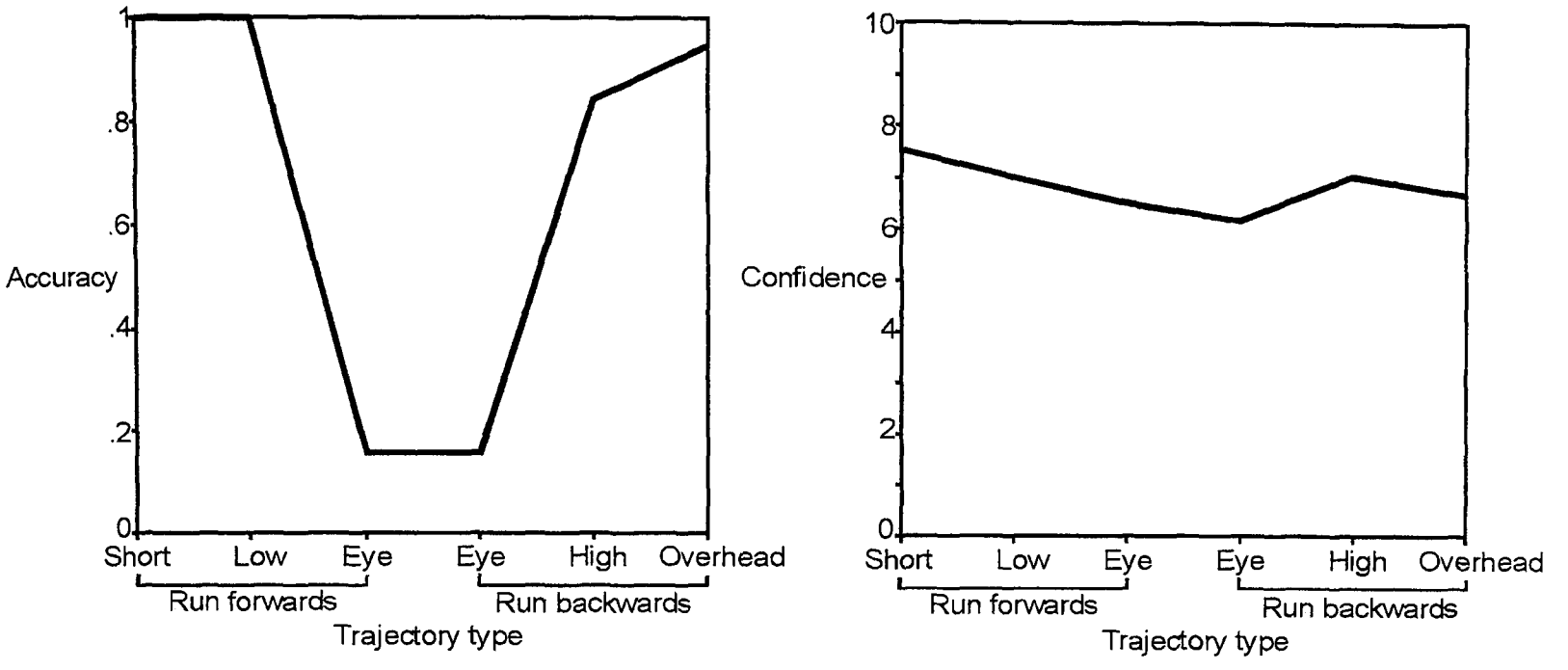


Fig. 7.8 Results for experiment 3.

The results for experiment 3 reproduce the pattern of results found in experiments 2 and 2a. Subjects are able to produce reasonably accurate descriptions of what happens to their angle of gaze for all trajectories except those caught comfortably in front of their face. Wilcoxon tests confirm this result – the scores for the 'At eye' condition are significantly less than all others ($p < 0.001$ in each case). Unlike the previous experiments, the Friedman test of confidence across trajectory type just reached significance ($\chi^2(5) = 11.3$; $p < 0.05$). However, Wilcoxon tests showed this was due to subjects higher confidence for a ball that would land short of their forwards run, not because of lower performance for 'At eye' trials.

7.6.3. Conclusion

Subjects are unable to describe correctly how their angle of gaze would change if they imagine running to catch a ball at the optimal position – just in front of their

eyes. Studies of people catching in a similar manner to that which subjects were asked to imagine in experiment 3 (McLeod & Dienes (1996); Tresilian (1995)) have suggested that α variation is the input to a servo mechanism. If it is increasing at a decreasing rate, they continue running at the same speed; if not they modify their running until that is the case. People appear unable to describe their α variation if they are going to catch a ball. This suggests that the behaviour is controlled by information that cannot be reported – that it is implicit knowledge.

7.7. Experiment 4

Shanks & St.John (1994) concluded that they were yet to be convinced of a clear dissociation being shown between the information controlling subjects' behaviour and the ability to report it. They proposed two criteria that should be satisfied to accept that this dissociation had been shown. These are the 'information criterion' and the 'sensitivity criterion' (see 7.1). Shanks & St.John claim that previous attempts to find unreportable information controlling behaviour have failed to meet these criteria. As was outlined in 7.2, ball catching is a useful task to use in studies of implicit knowledge because many analyses (Michaels & Oudejans (1992), Dienes & McLeod (1993), McBeath, Shaffer & Kaiser (1995), McLeod & Dienes (1996)) have resolved that variation in α is the basis for interception strategy. It is therefore relatively simple to satisfy the information criterion since it is clear that the awareness test must interrogate the subjects' knowledge of α variation. Experiment 4 explored ways of best fulfilling the sensitivity criterion.

Dienes & Berry (1997) claim that free report is a poor measure of all available conscious knowledge, particularly when recall of large amounts of low-confidence knowledge is required. They suggested that cued report and forced choice tests are

more likely to extract any relevant information and as such come closer to satisfying the criteria set out by Shanks & St.John. This is somewhat implausible in terms of this experimental paradigm. Subjects consistently demonstrate no problem in correctly reporting their α variation in all conditions other than 'Caught at eye level' and all with a high degree of confidence in their responses. However, in the light of Dienes & Berry's assertion, a Recognition condition was introduced. In this condition, subjects were given seven different descriptions of what could have possibly happened to their angle of gaze (the correct response was always one of the options) and asked to choose the one they considered most accurate. A Free Recall group was included for comparison. Subjects assigned to this group had to describe their α variation in the same manner as subjects in the previous experiments. They were given no such cues and described their α variation with no assistance.

A suggestion by Shanks & St.John (1994) was that the conditions in which a subject is asked to recall the information should be as similar to the conditions that exist during the execution of the skill. Since imagining a ball trajectory is not the same as experiencing that same ball trajectory, it is possible that subjects are only aware of the information controlling their interceptive behaviour when it is experienced in context. To investigate this possibility, subjects were asked to consider their angle of gaze whilst catching a ball and report immediately afterwards what happened to it.

7.7.1. Method

The protocol was similar to experiment 2 in that subjects were asked to report on the way their angle of gaze changed as they imagined or watched balls propelled on the five trajectories shown in figure 7.2. There were two differences. Firstly, subjects were assigned either to the Recognition or Free Recall conditions and

secondly, their responses were either to imagined trajectories (the Pre-catch condition) or directly after an attempt to catch a ball (the Post-catch condition).

7.7.1.1. Subjects

These were 24 new subjects, of whom 15 were male and 9 female. Age range was 19-31. Their skill ranking (1: below average skill; 2: average skill level; 3: above average skill level) was 2.04, SD = 0.86. Subjects were randomly assigned to the Recognition (N = 16) and Free Recall (N = 8) groups.

7.7.1.2. Pre-catch task

All subjects were given the same instructions as those used in experiment 2. These defined angle of gaze and showed how it varies for an observer watching a target rise or fall. Subjects were asked to imagine the five different trajectories shown in figure 7.2 and give an appropriate response to each. Subjects in the Recognition condition were asked pick the most appropriate description of what happened to their angle of gaze from the following set of options:

- Continuously down
- Up and then down
- Up and then dramatically down at the last moment
- Up and then remained constant
- Up at a decreasing rate
- Up at a steady rate
- Up at an increasing rate

For each trajectory, the options were the same and the correct response was always contained within this set of possible responses. Subjects' answers were scored using the legend shown in appendix A7.7 (Table A7.15). Subjects in the Free Recall

group completed the questionnaire in a similar manner to subjects in the previous experiments, giving as complete a description as possible of how they believed α changed as they imagined the flight of the balls. These responses were scored by comparing the descriptions to the prototypical α variation for each of these trajectories, shown in the lower half of figure 7.2. Each response was given a score using the same system as the previous experiments. Again, subjects were also asked to give a confidence rating from 0 to 10 to their judgements. Giving a rating of 0 to a response indicated that they believed their response to be a complete guess. Giving a rating of 10 to a response indicated absolute confidence in its accuracy.

7.7.1.3. Post-catch task

Subjects watched a series of balls thrown by hand from a distance of 8m (see figure 7.9 for a plan view of the set-up). They were asked to concentrate on how their angle of gaze changed during each trial and encouraged to catch the balls (at eye level if possible). Balls were thrown directly toward the subject and each throw was an attempt to match one of the five prototypical trajectories shown in figure 7.2. Subjects were allowed to move 1m forward or backward to make the catching task more comfortable. This allowed more trials to be caught at eye level and restricting movement to 1m ensured balls could be thrown that would fall short of the subject or go over the subject's head. This meant every subject experienced throws broadly matching each of the five prototypical trajectories.

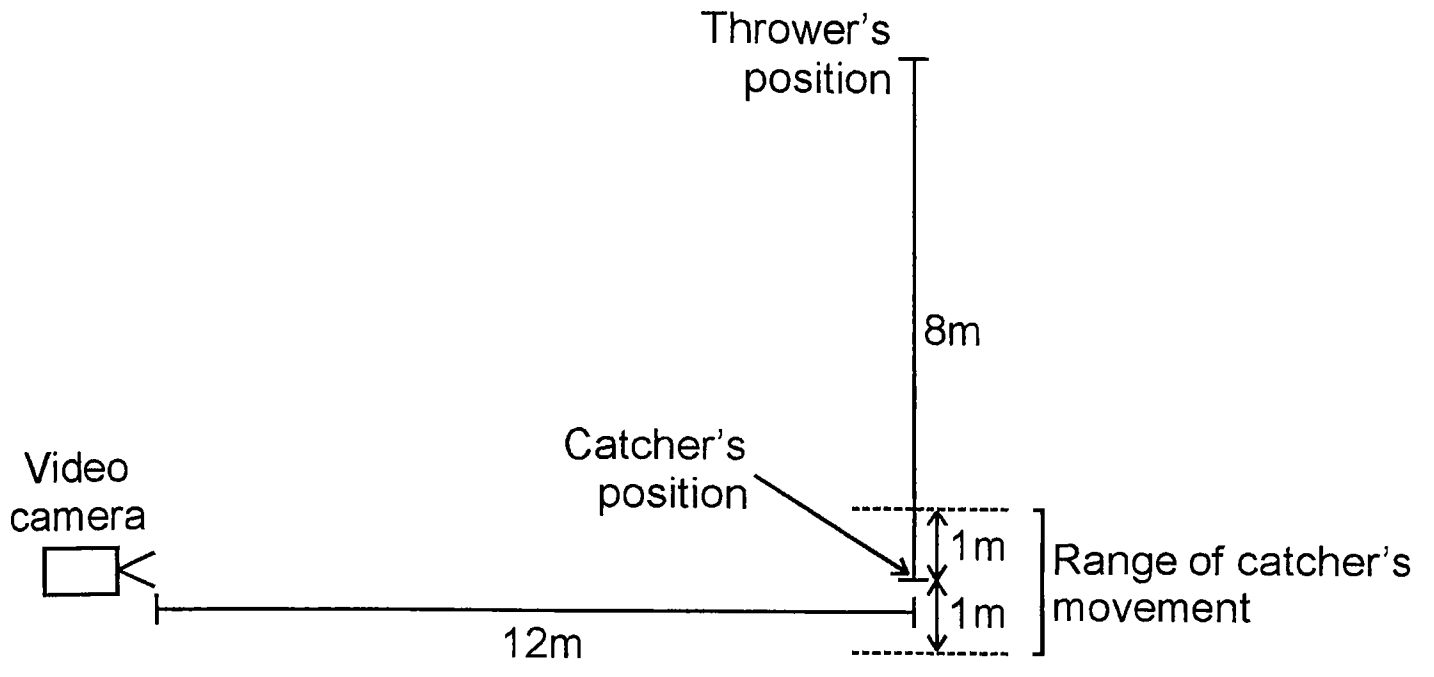


Fig. 7.9 Vertical projection of the experimental set-up for the Post-catch phase of experiment 4.

The launch angle of the balls was approximately 45°, giving flight times of approximately one second. Subjects were asked to respond with their description of their angle of gaze variation from the time that the ball left the thrower's hand to the end-point of the trajectory. End-points were different for each type of trajectory. For balls that were caught, the action of catching the ball was the end of the trajectory. For balls that fell short, the trajectory ended when the ball hit the ground. For balls going overhead, subjects were not required to consider their angle of gaze once the ball had passed beyond the point vertically above their position. Subjects in the Recognition group chose the option they considered most appropriate from the list given above and these were scored using the second table in appendix A7.7 (Table A7.16). Subjects in the Free Recall group gave verbal descriptions and these were scored using the standard procedure. Systematic recording of subjects' responses allowed comparison with the true variation in α they experienced whilst the ball was in flight. Both groups had to supply confidence ratings of 0-10 on their responses.

7.7.1.4. Recording of α

A video camera situated 12m away from the subjects' start position, perpendicular to the plane of trajectory of the ball flights recorded the trials from a side-on position (see figure 7.9). The frame rate of recording was 25 frames per second and the shutter was set at high speed ($1/500^{th}$ of a second) to eliminate blur from the images. The computer program, Vidi-Clik, was used to generate X-Y co-ordinates of ball and eye for each frame of video film. This meant that ball and eye positions were sampled every $1/25^{th}$ second. Vidi-Clik requires the input of two reference points to map the field of view of the camera. The first reference point was assigned as the subject's eye at their start position and given the co-ordinate value (0, 0). The second reference point was the top of a one metre ruler held vertically by the subject at their eye, stood one metre in front of the start position and given the co-ordinate value (1,1). By doing this, the co-ordinates (and hence α values) generated were approximately true. A trial began with the first frame that showed the ball had left the hand of the thrower. For balls that dropped short, analysis ended at the frame immediately before the ball hit the ground. For balls caught, analysis ended when the catch was made. For balls that went overhead, analysis ended when the ball had gone behind the observer. From the 20 trials, the two best examples of each of the five types of trajectory were analysed. The only criterion for selection of a particular trial over another was how closely it fitted the description of that particular trajectory type. The X-Y co-ordinates of ball and eye were used to calculate α for each frame of the trial using the following equation:

$$tan\ \alpha = (B_y - E_y)/(B_x - E_x)$$

where B_y is the y co-ordinate of the ball in each frame

E_y is the y co-ordinate of the subject's eye in each frame

B_x is the x co-ordinate of the ball in each frame

and E_x is the x co-ordinate of the subject's eye in each frame.

Calculating the inverse tangent produced α values for each frame of video footage. The estimates of α were then smoothed using a Hanning window where each value of α is replaced by half of its original value plus a quarter of the value from each of its nearest neighbours.

7.7.2. Pre-catch

7.7.2.1. Results

Appendix A7.8 gives details of the statistics used in experiment 4 (Pre-catch).

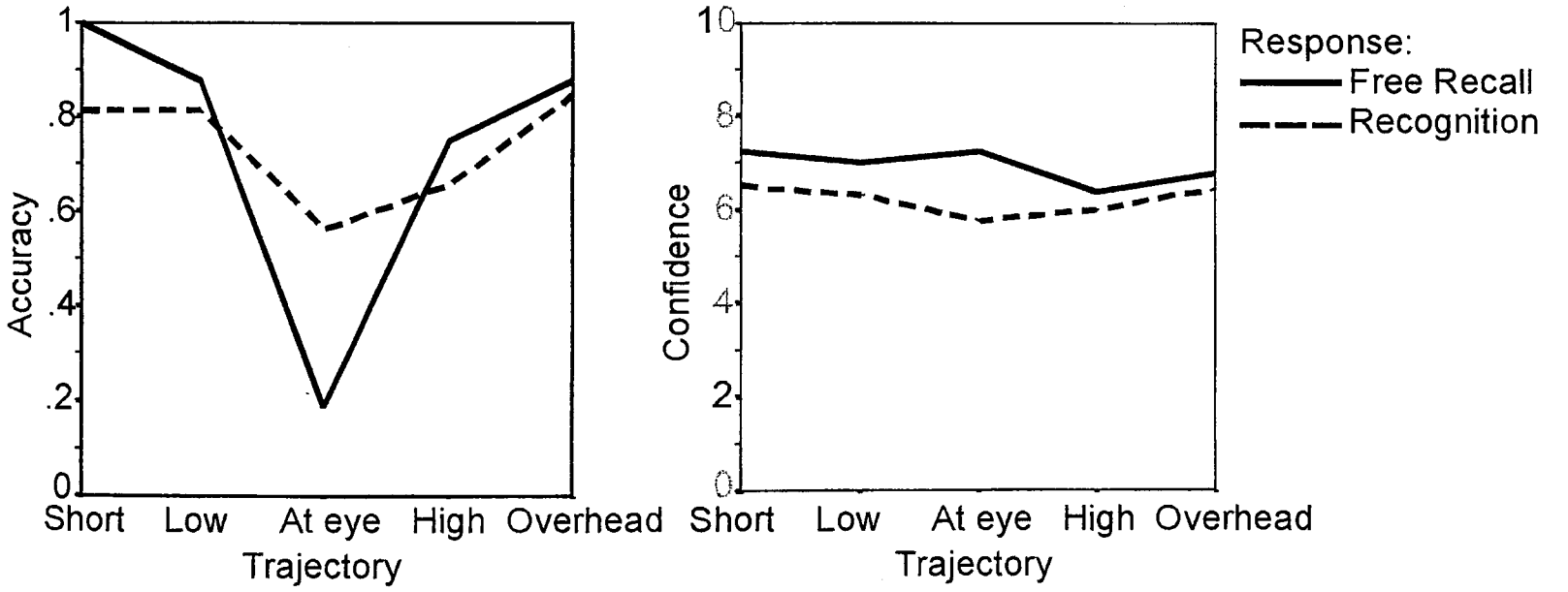


Fig. 7.10 Results for the Pre-catch phase of experiment 4.

Figure 7.10 shows the accuracy of responses for the Free Recall and Recognition groups when imagining the trajectories described in the questionnaire. The accuracy scores of the Free Recall group are similar to those found in earlier experiments. Reports were reasonably accurate for all conditions other than 'Caught

at eye level', where performance was poor. Wilcoxon tests confirm that performance was worse in the 'Caught at eye level' condition than in any of the other trial types ($p < 0.04$ for each comparison). A Friedman test revealed no significant difference in confidence across questions ($\chi^2(4) = 2.1$; $p > 0.7$).

Overall, the mean accuracy of responses was no greater in the Recognition condition than in the Free Recall condition, revealed in a Mann-Whitney U test ($Z = -0.44$; $p > 0.6$). However, a Mann-Whitney U test comparing scores in the critical 'Caught at eye' trajectory showed that performance in the Recognition condition was significantly better than in the Free Recall condition ($Z = -2.1$; $p < 0.04$). This apparent improvement in performance was not enough to prevent the mean score for 'Caught at eye' trials being significantly less than all conditions other than 'Caught high' in Wilcoxon tests ($p < 0.05$ for each comparison). Again, a Friedman test revealed no significant difference in confidence across the different trajectory types ($\chi^2(4) = 2.9$; $p > 0.5$).

7.7.3. Conclusion

In the 'Caught at eye level' condition, subjects' performance in the Recognition condition showed a significant improvement over those in the Free Recall condition. Their responses, however, were still far from perfect – five out of the sixteen subjects gave a response that scored zero. In addition, a slight improvement in score would be expected by subjects in the Recognition condition due to the possibility that they might pick a scoring answer merely by chance. Given that subjects in this condition were supplied with the correct answer, the fact that most still did not select it suggests that angle of gaze information about objects that will intercept the eye is particularly hard to access. It might be argued that subjects in the Recognition condition who fail to recognise the proposed correct answer are simply poor at catching balls. If that

were the case, then they would not follow the strategy employed by skilful catchers, such as those examined in the studies of Michaels & Oudejans (1992), Dienes & McLeod (1993) etc. Consequently, their experience of angle of gaze would be different and perhaps subjects' Pre-catch responses were correct descriptions of their angle of gaze experience, given their non-standard interception strategy. By examining the α variation of subjects in the Post-catch condition, it was possible to show that subjects who fail to recognise the correct angle of gaze description encounter exactly the same visual experience as those who recognise the correct description.

7.7.4. Post-catch

For each catch, the video film was used to find α in each frame of the footage. This allowed plots of α against time throughout the flight of the ball to be constructed. These closely resemble the prototypical pattern of α variation shown in the lower half of figure 7.2. Figure 7.11 shows the pattern of α variation actually experienced by a typical subject for each type of trajectory. It clearly bears a close resemblance to the equivalent graph in figure 7.2 and demonstrates the similarity between the visual experiences of the subjects performing the catching experiment and an observer watching the prototypical trajectories. It is also compatible with the theory proposed by McLeod & Dienes (1996) of how interception is achieved. For further examples of plots of α against time see appendix A7.9.

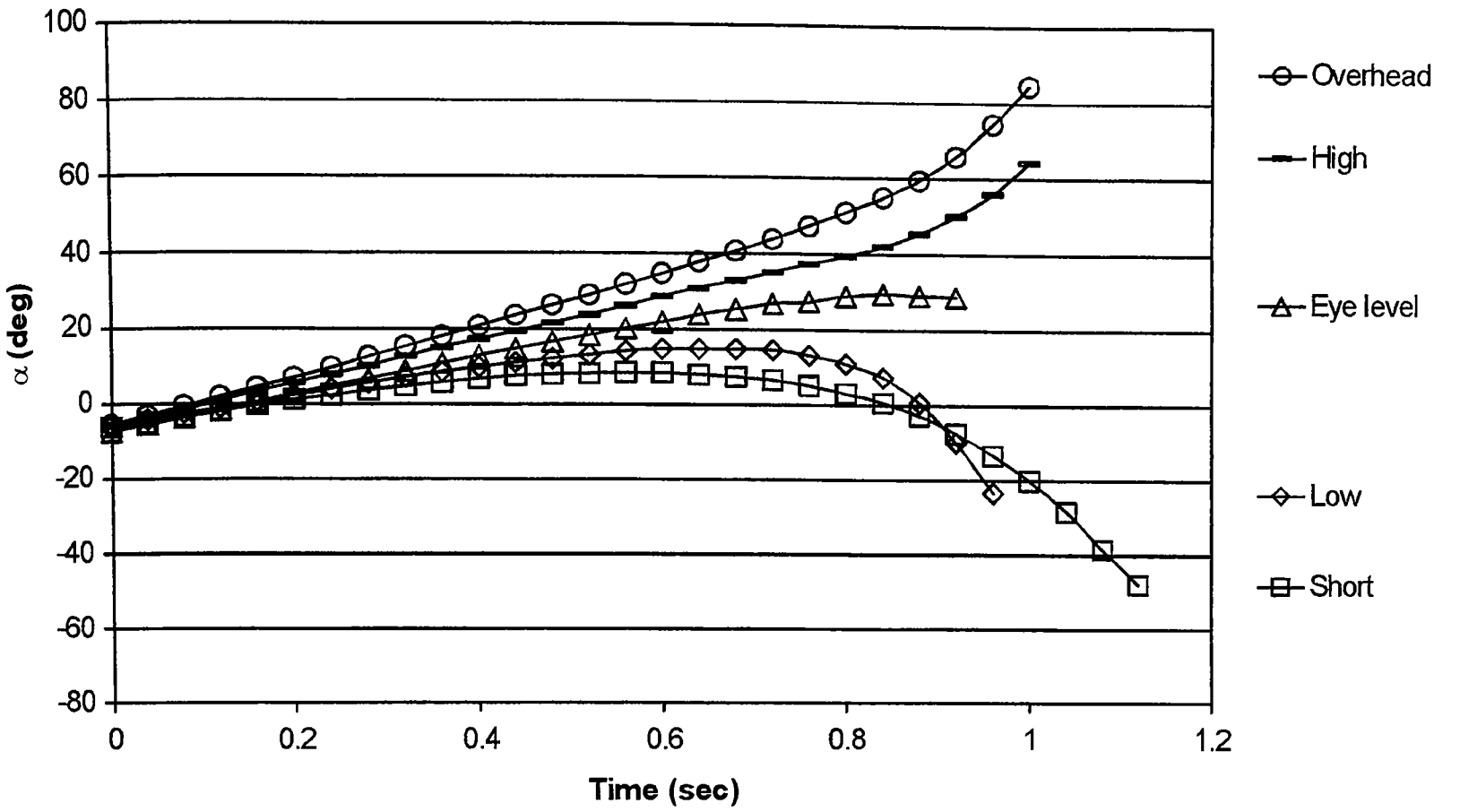


Fig. 7.11 The pattern of α variation for real examples of each trajectory type.

Appendix 7.10 gives details of the statistical tests used in the analysis of Post-catch responses in experiment 4. The statements made by subjects in the Free Recall condition and the responses chosen by subjects in the Recognition condition were then compared to the actual variation in α that they experienced. A rating of 1 was given to a response if it captured the critical aspects of the change in α over time. A rating of 0.5 was given to answers that were partially correct and 0 was given to answers that contained fundamental errors. The reliability of the ratings was checked by comparing the ratings of three independent judges using a Kendall's coefficient of concordance test. This revealed significant agreement between the three different raters (Kendall's $W = 0.33$; $\chi^2 = 19.7$, $p < 0.001$).

Figure 7.12 shows the change in the accuracy of statements about α variation made Pre-catch and Post-catch by subjects in the Free Recall group. It can be seen that performance is slightly improved in the Post-catch condition for the crucial 'Caught at eye level' trajectory type but a Wilcoxon test reveals that this improvement does not reach significance ($Z = -1.59$; $p = 0.11$). Post-catch accuracy in the 'Caught at eye' condition is still only around 50% and still less than all other conditions, except 'Caught high' (Wilcoxon tests: $p < 0.05$ for 'At eye' vs. 'Short' and 'At eye' vs. 'Low'; $p < 0.09$ for 'At eye' vs. 'Overhead').

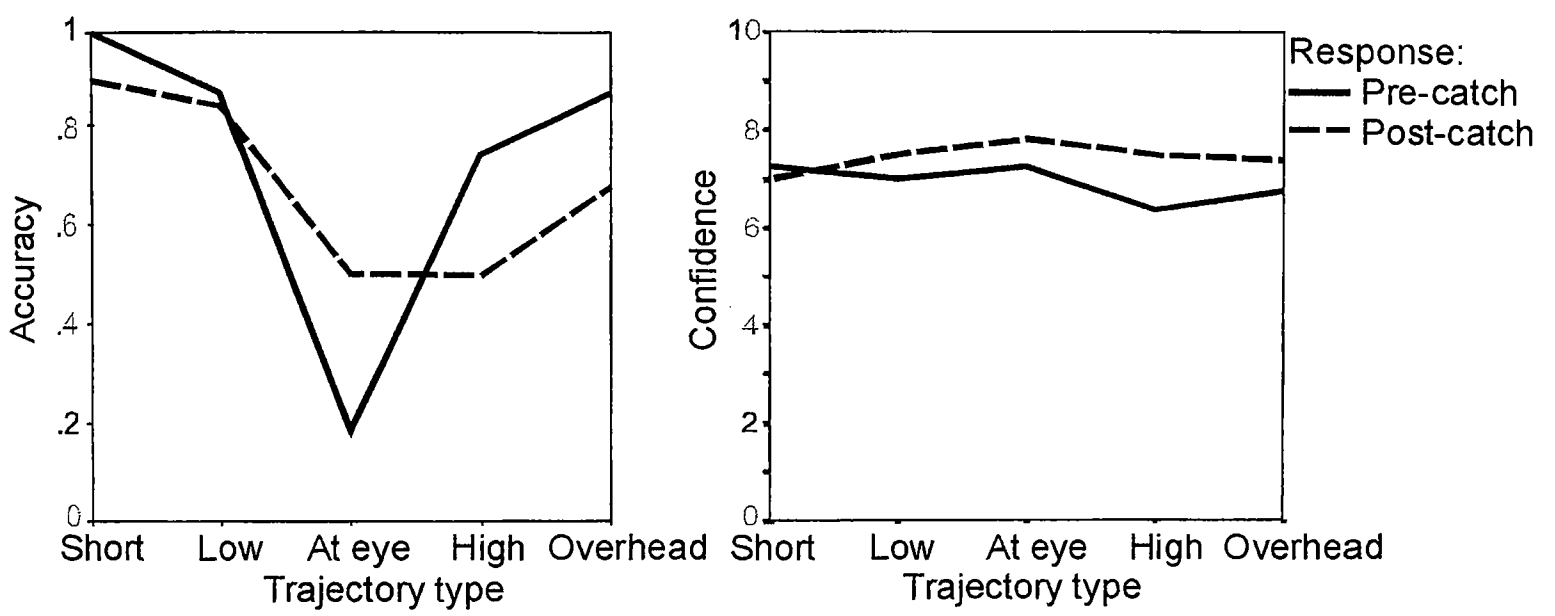


Fig. 7.12 Pre-catch vs. Post-catch mean accuracy scores (left panel) and mean confidence scores (right panel) for subjects in the Free Recall condition.

As ever, a Friedman test revealed that confidence was consistent across trajectory types for Post-trial responses ($\chi^2(4) = 6.3$; $p > 0.15$). Figure 7.13 shows examples of the pattern of α variation actually experienced by subjects in the Free Recall group for the ball caught closest to eye level. Displayed are the α values from the time the ball is released until one frame (40ms) before the ball is caught. It can be seen that when subjects to move to catch balls in this manner, their visual experience is characterised by α increasing throughout the flight. However, their visual experience is often reported very differently. For example, subject 2 described his

angle of gaze variation as "Starts just below 0°, increases to maximum height, then decreases to just greater than 0°". Subject 5 (who has played cricket to county standard) reported his experience of α associated with the trial shown in figure 7.13 as: "Followed the ball up then down to 0°". Subjects seem to make the erroneous intuition that because the ball goes up then down so angle of gaze must do the same. This seems to be more salient than the information they obtained when monitoring angle of gaze during the flight of the ball.

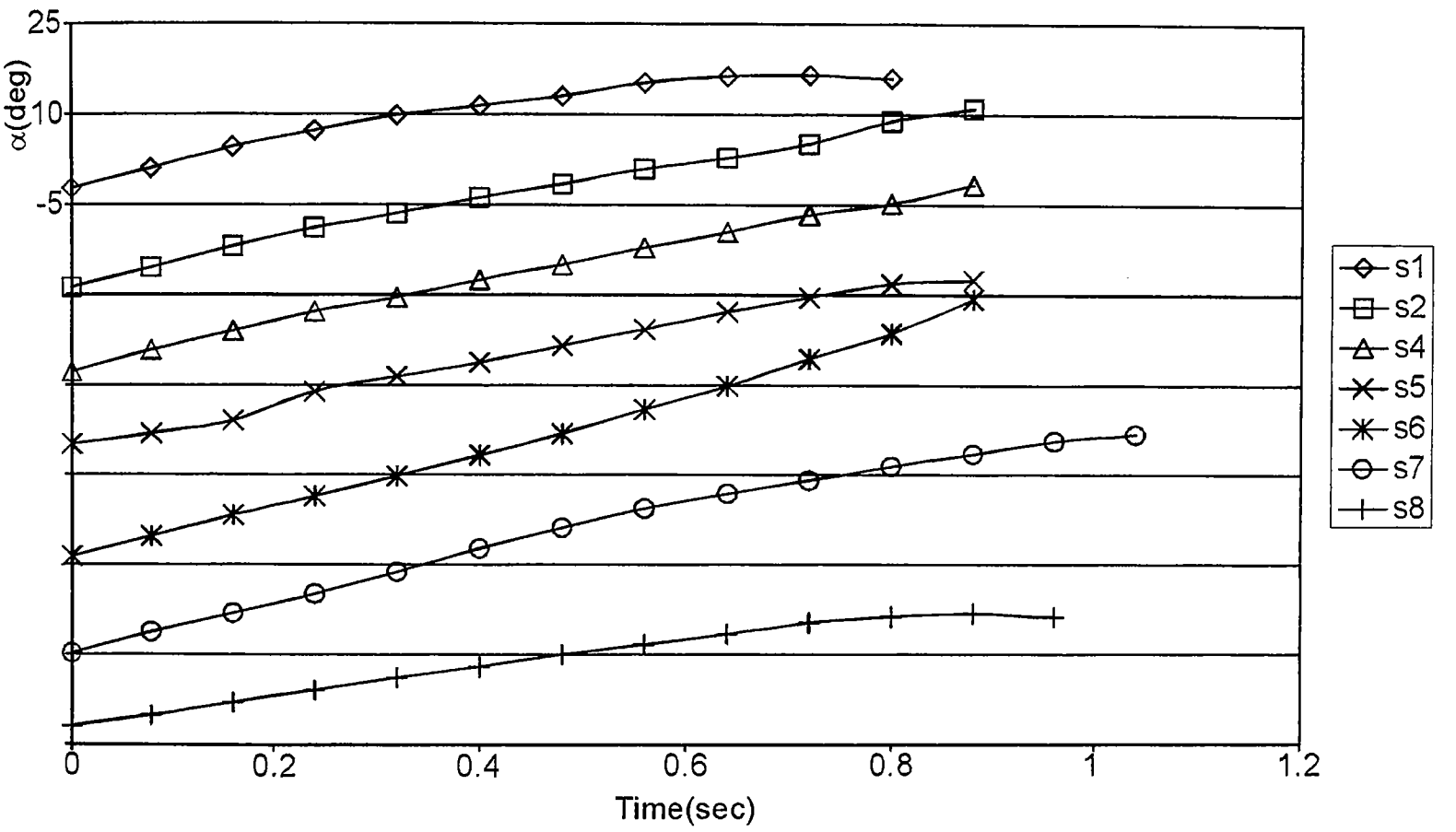


Fig. 7.13 Examples of the α variation experienced by subjects in the Free Recall condition.

The accuracy of responses for subjects in the Recognition condition, Pre- and Post-catch, is very similar, confirmed by Wilcoxon tests (all $p > 0.5$). Critically, performance in the 'Caught at eye' condition, poorest Pre-catch, has not improved Post-catch. In the Post-catch condition, confidence is again constant across trial types (Friedman test: $\chi^2(4) = 2.95$; $p > 0.5$). The data for subjects in the Recognition condition is illustrated in figure 7.14.

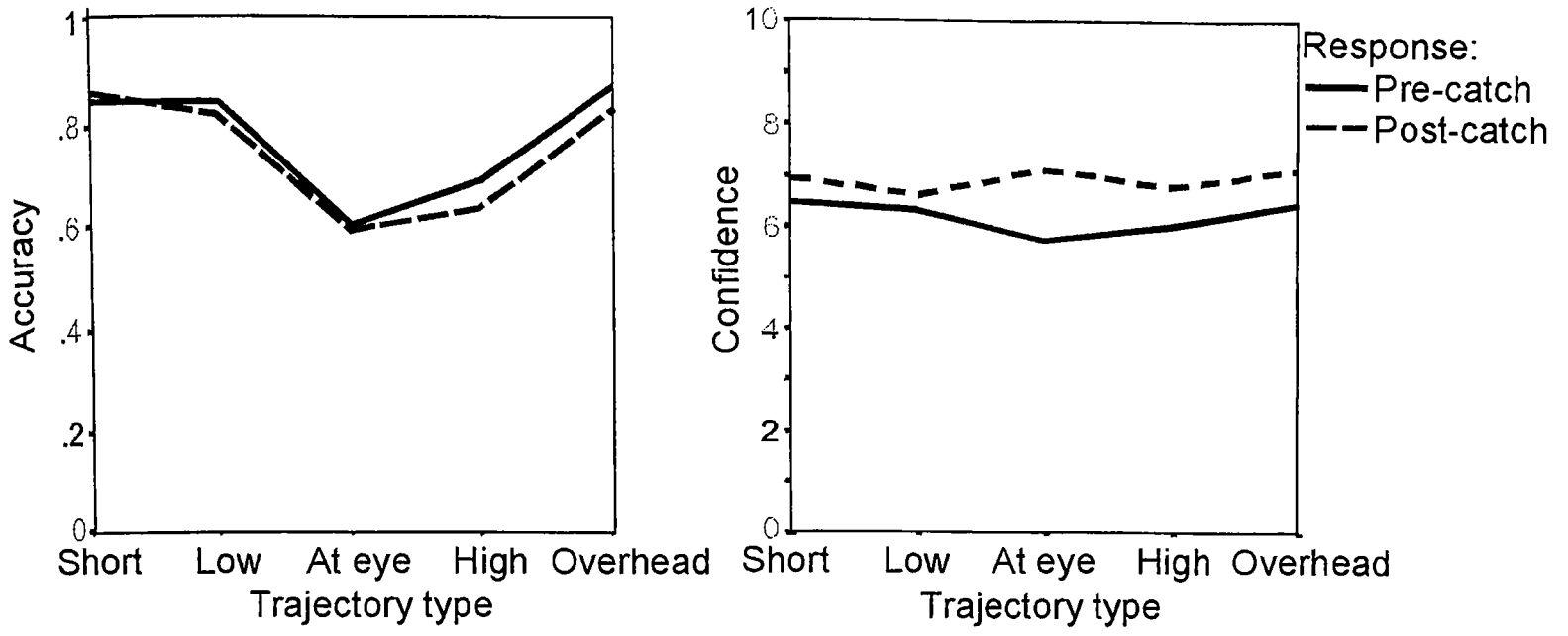


Fig. 7.14 The results of experiment 4 for subjects in the Recognition condition.

Figure 7.15 shows the variation in α experienced by subjects in the Recognition condition for the balls caught closest to eye level. As in the Free Recall condition, the figure confirms that when people move to take a catch at eye level α increases throughout the flight of the ball. The subjects are grouped according to the accuracy of their response. Those scoring 1.0 chose the correct response statement, those scoring 0.0 chose a fundamentally incorrect description. The subjects who experienced the α variation represented by the bottom two lines on the graph both chose the statement, "up then dramatically down at the last moment" as the best description of their experience. The remaining subject who scored 0.0 chose the description, "Up then constant". All the subjects scoring 0.5 chose the statement, "Up then constant" Figure 7.15 demonstrates that their actual experience was of α increasing continuously (except for one case where α decreases a tiny amount in the last 40ms of analysis).

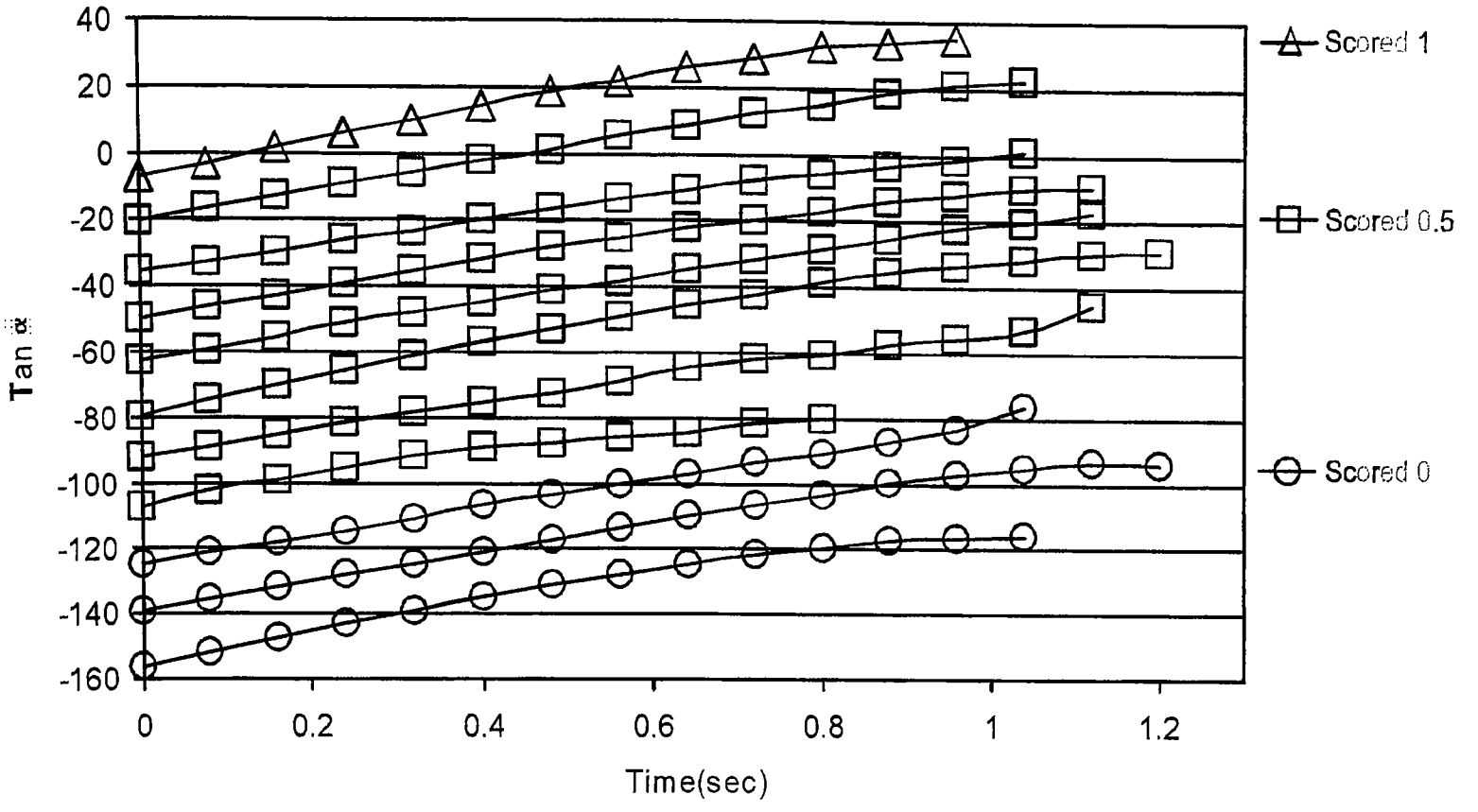


Fig. 7.15 The actual α variation experience by subjects in the Recognition condition for trials caught nearest to eye level.

7.7.5. Conclusion

Experiments 2 and 3 showed that subjects were particularly poor at judging what happens to their angle of gaze when considering balls that would intercept their eye if they were not caught. This critical condition is where subjects receive the information that underlies the strategy used when running to catch the ball. Performance by subjects in the Free Recall group in this condition improved moderately when the awareness test was conducted after a ball had been caught. The improvement was of similar magnitude to that observed when the accuracy of the Free Recall group is compared to the accuracy of the Recognition group for Pre-catch responses to 'eye level' trajectory descriptions. However, subjects in the Recognition group failed to show the improvement in accuracy shown by subjects in the Free Recall group for 'Ball caught at eye level' trials when the awareness test immediately follows a catch. Consequently, this result offers modest support for Shanks & St.John's position – it demonstrates the importance of satisfying the sensitivity

criterion when testing the awareness of information. When subjects actually experienced the trajectory, their assessment of α variation was more accurate than the responses subjects produced when they considered trajectories that they recalled from balls caught in the past. However, performance is still far from perfect. When one considers the measures taken to give subjects the best possible chance of producing an accurate response in the Recognition Post-catch condition, this is somewhat surprising. Subjects are instructed to consider their angle of gaze. They then watch a ball and catch it in front of them at around eye-level. They are then given a number of descriptions and asked to choose the one that most closely matched their experience during the catch. Despite these endeavours, accuracy of response for the critical 'eye level' category was still poor. It seemed highly improbable that subjects would still get the answer wrong, whether they possessed an internal representation of the information or not. That is, even someone who did not know how to catch would be able to report their angle of gaze as they watched the ball. Yet, when their gaze moved steadily upwards, some subjects believed that the statement that best corresponded to their angle of gaze variation was "Up then down". It appears that information about α variation in this critical condition is so hard to report that it is possible that the information is subject to suppression, perhaps to prevent interference with performance of the task.

The slight advantage for subjects in the Recognition condition is perhaps explicable by the knowledge controlling interceptive behaviour existing above or around the objective threshold of consciousness but below the subjective threshold. The decision as to whether this knowledge can be classified as implicit or explicit is then depends on where one places the border between the two distinct types of knowledge. However, this advantage is not significant and there is no improvement

when the awareness is conducted immediately after catching a ball (Pre- vs. Post-catch responses). It seems that the improvement could be the result of subjects selecting correct or partially correct answers by chance.

7.8. Discussion

The apparent inability of people to state the basis of their actions when performing motor skills appears to demonstrate implicit learning. However, perceptual motor skills have not been widely used to investigate implicit knowledge. This is perhaps because it is not always clear how the information that underlies motor skills is implemented or indeed, what that information is. However, in the case of catching, more specifically, how people use the available visual information to get to the right place at the right time to catch a ball, the cognitive strategy underlying the skill is comparatively well specified. Previous research (Michaels & Oudejans (1992), Dienes & McLeod (1993), McLeod & Dienes (1996)) has established that fielders use the variation in angle of gaze (or some derivation of that quantity) to achieve interception of a projectile. This goal of this study has been to investigate what people are able to report about the sensory information that is used in achieving interception and in so doing, shed some light on implicit knowledge and motor skills.

Experiment 1 showed that people do not describe correctly how they would get to the right place at the right time to intercept a projectile launched toward them. Furthermore, they do not mention the sensory information that would be used to control their interception strategy – the variation in angle of gaze. Subjects who did report a strategy (as opposed to those who claimed their interceptive behaviour was based purely on 'experience') described one that relied on information that would not be available to them. They suggested that the peak of the projectile's flight would be the main cue controlling their movement. However, the position and time at which the

projectile reaches its peak are not available to an observer watching the ball in an aligned plane. In addition, the peak itself is not an accurate cue to the final landing position of the ball since trajectories are not precisely parabolic. The position of the ball at the peak of its flight cannot be used to control interceptive behaviour.

Experiment 2 showed that when subjects were introduced to the concept of α, they were proficient at describing how it would vary for a ball that would land in front of or behind their position. However, few were able to describe accurately what would happen when they caught the ball at eye level. Meanwhile, subjects' confidence in the validity of their response was unchanged whether they were right or wrong. This satisfies the zero correlation criterion and offers a clear suggestion that subjects are unaware of the sensory information about which they are being asked. Experiment 3 demonstrated that the observations of experiment 2 were also apparent when subjects were asked to consider how the α would vary when they imagined running to catch a ball.

In attempting to discover what people know about how they catch, experiment 1 offered subjects very little assistance in this task. Subjects were merely asked what they did in different situations. By contrast, experiment 4 gave subjects as many cues as possible in attempt to satisfy Shanks & St.John's sensitivity criterion. The concept of α was explained to subjects and they were told to think about α when watching real balls thrown toward them. The recognition group were provided with statements describing possible α variation and then had to select the one they believed was most similar to that which they had just experienced. Although it seemed unlikely, subjects were still poorer in the critical 'eye level' condition. Subjects are failing to report the information that controls interception strategy. This inability to report or recognise the

information that controls interception appears to be an example of implicit knowledge governing behaviour.

7.8.1. Correct report

It is possible that when subjects correctly describe their α variation (when the ball lands short or goes overhead) their responses are based on an incorrect theory about catching rather than accessing the knowledge responsible for catching behaviour. Their responses would represent the performance of the incorrect theory. In experiment 1, subjects tended to claim that they based their decision about whether to move forwards or backwards on where the apex of the ball's trajectory was. This idea derives from imagining the ball's trajectory viewed from the side, when the apex would be a salient feature. This is as if a fielder was able to generate the upper half of figure 7.2 from visual information available from their aligned position. Subjects' beliefs about what happens to their angle of gaze would then reflect what happens to the ball during its flight since their angle of gaze is following the ball. For balls falling short, the ball goes up then down and it is simple to imagine gaze following a ball on such a trajectory – it must follow the ball up then down, the correct answer. Similarly, for balls that fly overhead, gaze must follow the ball up to at least 90° – also the correct answer. However, for balls that are caught at eye level, it is less simple to imagine what happens to angle of gaze and the side-view theory produces an incorrect answer. A side-view shows that the ball goes up then down but in this condition angle of gaze continues to rise until the ball is caught. The ball does one thing and angle of gaze does another. Correspondingly, this condition is the one in which subjects most frequently give incorrect answers. Support for the idea that the subjects based their responses on a theory about the visual information rather than the information itself is provided by the confidence data. In all the experiments in which

confidence data was collected, not one data set showed any significant discrepancy across trajectory type for subjects' confidence in the validity of their responses. People were equally confident about their answers, whether they were correct or not. This suggests a common source for all judgements (cf. Dienes, Altmann, Kwan, & Goode, 1995; Dienes & Berry, 1997; Dienes & Perner, 1999). The simplest theory encapsulating the results is that people have no access to controlling knowledge in any condition. When the ball drops in front of them or goes over their head angle of gaze provides controlling knowledge as it generates the error signal people seek to null as they run.

The 'at eye' trajectory represents a narrow singularity in the spectrum of α vs. time that an aligned trajectory could produce. In the latter experiments, subjects were asked to describe (or choose a description of) what happens to α when they observe such a trajectory. A conceivable problem that this presents is that this task might be more demanding than that required of subjects when they are asked to describe α vs. time for trajectories other than 'at eye'. Given this discrepancy in task difficulty, the observed pattern of response accuracy is perhaps unsurprising. There are, however, several mitigating factors. Firstly, subjects in the 'recognition' condition in experiment 4 still often selected the wrong description of α variation when given possible descriptions and having just watched an 'at eye' trajectory. Secondly, subjects' confidence that they were giving the correct response was invariant across trajectories. If the task was considerably more difficult, one might expect subjects' confidence in the accuracy of their response to drop but this was not observed.

7.8.2. Features of implicit learning

Dienes & Berry (1997) argued that implicit learning and the resulting knowledge could be distinguished from explicit learning and knowledge by the following features:

- Limited transfer of the knowledge to related tasks.
- Learning tends to be associated with a focus on particular items rather than the underlying rules.
- Robustness of learning.

Application of these guidelines to the present task supports the theory that the knowledge controlling catching behaviour is implicit. Firstly, it is very hard to imagine any other task where knowledge of how to adjust running strategy in response to changes in gaze angle when fixating a projectile would provide any benefit. Secondly, learning how to catch never focuses on the underlying rule – one should move so that α is allowed to increase at a decreasing rate. The only instruction given to children learning to catch does not usually progress beyond "Watch the ball". Learning appears to be concentrated on particular items – catches that are successful and those that aren't. The rule then derives from the difference in visual experience between them. Thirdly, once one has learnt to catch, the knowledge is robust. It is durable – people are able to catch with years interval between occurrences, and I.Q. does not provide any indication to catching skill. When evaluated using the characteristics proposed by Dienes & Berry, the knowledge underlying catching appears to comfortably fulfil the criteria for implicit knowledge.

7.8.3. Correlated hypotheses

It is possible that the variable controlling interceptive behaviour is not angle of gaze but a variable that is correlated with it. If this were true then the knowledge that is controlling behaviour could have been explicit. However, since it has not been asked for, it has not been elicited. In other words, the awareness test has failed the information criterion set out by Shanks & St.John (1994) - the information requested in the awareness test is not the information responsible for the performance. This is the correlated hypotheses problem, postulated by Dulany (1962). Claiming that people use variation in angle of gaze relies on a theory of how people achieve interception. However, it is the only theory in the literature of how people control their motion forwards or backwards to catch a ball thrown toward them. In addition, it does a good job of explaining experimental data (99% of variance explained; Dienes & McLeod (1993); see also chapters 3 and 4). The theory postulates the operation of a servo mechanism that alters a fielder's acceleration to keep the tangent of α increasing at a constant rate with a resultant continuous increase in α at a decreasing rate. Whether this is the strategy that is actually used or not, a consistent finding of all studies into interception is that as a fielder move towards the interception point, α increases. Consequently, whatever variable is being used to control behaviour, it must bear a monotonic relationship to α. The fact that people are unable to translate that variable into a report of angle of gaze is further evidence that it represents implicit knowledge. Conscious knowledge is inferentially promiscuous (Davies (1989)), and can in principle be used in combination with any other piece of conscious knowledge for drawing inferences. The real variable used for controlling behaviour would bear such a direct relationship with α that if it were consciously known the inferential link to α would be transparent. Therefore, the claim remains that the knowledge that

controls catching behaviour must be implicit, notwithstanding the problem of correlated hypotheses.

A related argument is the fact that the design of the experiment would not interrogate the knowledge controlling behaviour at the time that behaviour was being enacted. Subjects were asked to describe the variation in α *after* they had experienced a trajectory. Under the strictest definition then, the experiment does not test for the existence of implicit learning. However, as has been stated conscious shows inferential promiscuity and subjects were given comprehensive cues to aid recognition of the variation in α. It is therefore likely that if subjects were aware of the knowledge controlling behaviour during an 'at eye' trajectory, it would have been simple for them to provide an appropriate description. This they were frequently unable to do.

7.8.4. Network weights and knowledge

Cleeremans (1997) argued that the best account of implicit knowledge is not unconscious symbolic knowledge but the knowledge that lies embedded within connectionist networks. A connectionist network is an appropriate technique for modelling the behaviour examined in this study. Maass & McLeod (1999) constructed a connectionist network that modelled the performance of a simulated fielder intercepting simulated projectiles. The network received α at successive time points as its input and produced the acceleration of the simulated fielder forward or backward as its output. The network evolved using a genetic learning algorithm. The initial network had a basic structure and a range of minor variants. The variants that moved the simulated fielder to the correct interception point formed the basis of the next generation. After approximately 50 iterations of this selective process, a structure evolved that was very successful at moving the simulated fielder to the correct place

at the right time to intercept the simulated projectiles. This structure ensured that the simulated fielder 'ran' at a speed that kept α increasing at a decreasing rate. The network discovered the same strategy as people.

It is not the claim that people have an implicit symbolic representation that tells them to "Run so that α increases at a decreasing rate". The supposition is that this information is encoded in the weights of connections between nodes of a real neural network. The weights implement this rule so that it is represented but not symbolically (Dienes & Perner, 1999, 2000). The rule is represented in a non-conceptual way and therefore cannot be freely recombined with any other representation – that is the nature of the weights of neural connections. This means that the rule cannot be reported because verbal report would require that the knowledge have a conceptual representation. There may be objections to the use of the terms 'knowledge' and 'representation' when discussing a rule that lies non-conceptually in the weights of connections between nodes of a network. However, there seems no reason to restrict the notion of knowledge to symbolic representations that may be conceptualised.

7.8.5. Separation of control and awareness of goals

The proposal that people can be aware of the goals of their actions without being aware of the detail of how the visual-motor system achieves them is consistent with many experimental observations. For example, automated actions such as making a pot of tea are performed without awareness of the detailed visual control of the individual actions (Land, Mennie, & Rusted (1998)). Neuroscientific evidence comes from dissociations between patients showing a separation between frontal and parietal systems in the control of action. Studies suggest that the systems of the

frontal cortex are involved in the overall planning of action, whilst the parietal systems are involved in their instantaneous control (e.g. Posner & Petersen, (1990); Schwartz et al., (1995); Andersen et al., (1997)). In studying dissociations between 'ventral' and 'dorsal' streams of visual processing, Milner et al. (1991) showed that precise actions under visual control are possible by patients who have no reportable awareness of that visual information. In visual form agnosia, there is a severe visual recognition impairment regarding the basic features of shape perception. Milner's patient, DF, a visual form agnosic, has profound difficulty in perceiving and discriminating simple shapes, including their size and orientation. However, her performance is equal to that of normal control subjects in a task requiring her to orient her wrist when reaching to pass her hand or 'post' a hand-held plaque through a slot placed at different orientations. Without apparent awareness of the visual information required to perform the task, DF is able to achieve the required objective. Such striking dissociations lead to the proposal of a hypothesis about the locus of damage in visual form agnosia. Milner & Goodale (1995) have proposed that while visual form agnosia involves damage to the occipito-temporal areas of the 'ventral' cortical processing as identified in the monkey (Ungerleider & Mishkin, (1982)), it may leave the occipito-parietal regions that constitute the 'dorsal stream' largely intact. The suggestion is that the processes involved in interpreting the visual information used to guide interceptive behaviour may also be localised to this dorsal stream of processing and therefore fail to effect awareness in the catcher.

7.9. General conclusion

The results of this experiment provide evidence that the information subjects use to guide their actions when moving forward or backward to intercept a ball is stored implicitly. Subjects have great difficulty in stating what happens to the control

variable, α, when catching a ball around eye level. Running strategy is determined using this information. Support for the implicit nature of the knowledge comes from Maass & McLeod (1999). Their connectionist network account of interception fits with Cleeremans (1997) suggestion that implicit knowledge is best accounted for by the weights of connections in such a network. Further evidence is obtained from neuroscience, where there are many examples of tasks being performed without awareness of how the visual-motor system achieves the objective. This result challenges the position of Shanks & St.John by demonstrating implicit knowledge in the context of motor skills.

8. The signal to run

8.1. How do fielders decide whether to run forwards or backward?

Chapman (1968) reported that an observer positioned at the landing site of a projectile following a parabolic trajectory, experienced a constant rate of change of gaze angle (constant d(tan α)/dt) whilst fixating its motion. He also showed that variation in d(tan α)/dt is a cue to the landing site of a projectile that will not land at the position of the observer. This led to the suggestion that real fielders might use d(tan α)/dt in controlling their motion to get to the right place at the right time. Todd (1981) produced an interesting critique of this hypothesis. The visual information available to an observer interacting with moving objects was examined. Todd presented subjects with stimuli moving on a computer screen to investigate the cues to which human observers were sensitive. His second and third experiments are pertinent to this thesis. They examined the information that allows an observer to perceive where a free-falling projectile will hit the ground. Todd's second experiment used a computer to present subjects with a simulation of 0.75seconds of the movement of an object that appeared to approach on a parabolic trajectory. Subjects had to respond by deciding whether the object would have 'landed' in front of them or at their exact position. The experiment was run under 3 conditions. In condition A, object size and the applied gravitational force were fixed whilst the launch parameters of the object varied from trial to trial. In condition B, object size, gravity and the launch parameters were varied. Condition C was identical to condition A with the exception that the object was presented as a single dot that did not vary in size on approach. Performance was best in condition A, which was significantly better than condition B, which was, in turn, significantly better than condition C. The

experimental conditions and the task in experiment 3 were analogous to those of experiment 2. It differed in the duration of presentation of each event. In experiment 3, the display of a trial terminated when the object reached the top of its trajectory, providing a further source of information. Results were congruent with those of experiment 2. However, this experiment is of no relevance when considering human interceptive behaviour because (where possible) humans begin running towards the interception point before the ball has reached the top of its trajectory (see McLeod & Dienes (1996)). The relatively poor performance of subjects in condition C in both experiments led Todd to suggest that human observers were unable to take advantage of the cue provided by the optical acceleration[1] of a projectile, contradicting the idea that humans might use $d^2(\tan \alpha)/dt^2$ to control interception of projectiles.

Michaels & Oudejans (1992) found evidence to contradict Todd's suggestion. Their first experiment showed that fielders running to intercept hand-thrown or machine-projected balls run so that optical acceleration is held at zero until the final moments before the catch. Performance was equivalent whether fielders performed the task monocularly or binocularly – strong evidence for the use of monocular cues as the basis of interceptive behaviour. However, Michaels & Oudejans argued that this did not represent conclusive proof that fielders were able to detect optical acceleration since locomotion to the right place at the right time will result in roughly constant optical velocity, irrespective of the cues used to achieve it.

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[1] Optical acceleration is mathematically equivalent to $d^2(\tan \alpha)/dt^2$.

To determine whether humans were sensitive to optical acceleration, Michaels & Oudejans' second experiment was similar to condition C in Todd's experiments. Subjects viewed the ascent of a fixed size stimulus (one pixel) on a computer screen. Its motion simulated the movement of a projectile on a variety of trajectories viewed from a stationary position. The stimulus was visible until its trajectory took it out of the viewing 'window' provided by the computer screen or its optical velocity became negative. Subjects had to decide where the stimulus would 'land', whether in front of, at, or behind their position. Subjects also had to supply a certainty rating to their answer – how certain they were that their answer was correct – from one of three options ("Certain", "Fairly certain", or "Uncertain"). A second presentation of the trials required subjects to simply state whether they believed the stimulus accelerated, decelerated, or moved at constant velocity. The two tasks were therefore perceptually equivalent.

The results showed that subjects were significantly better than chance at selecting the correct landing place and acceleration rating, with the latter significantly better than the former. Judgements assigned high certainty ratings were generally better than judgements as a whole but not significantly so. Michaels & Oudejans attempted to separate the optical variables that were confounded with optical acceleration. A multiple regression analysis was performed, identifying the variable that was the best predictor of response. They found that subjects typically based their landing judgements on variables that would not be efficient to use for catching balls in the real world (e.g. height on screen attained by the stimulus) but optical acceleration was the best predictor of responses for the acceleration judgements.

Michaels & Oudejans experiments do not provide concrete evidence that fielders use optical acceleration to determine their interceptive behaviour. They do

show that fielders run so that optical acceleration is cancelled and provide good evidence that their subjects were sensitive to optical acceleration. This result is in direct opposition to the findings of Todd (1981).

Like Todd and Michaels & Oudejans, Babler & Dannemiller (1993) also used computer simulations of trajectory to investigate human sensitivity to image acceleration for free-falling projectiles. The authors recognise the appeal of the interception strategies which use image acceleration as the primary cue (e.g. Chapman, 1968) but recognise evidence such as Todd's questioning the validity of such strategies. In their first experiment, Babler & Dannemiller presented subjects with a 0.3cm disc stimulus on a large computer monitor. The stimulus ascended the screen vertically at a variety of different angular velocities and angular accelerations across trials. Subjects had to decide whether the stimulus was accelerating or decelerating. Babler & Dannemiller found that subjects were more likely to say that the stimulus was accelerating as acceleration increased. They also found a correlation between the likelihood of subjects perceiving a stimulus as accelerating and the average velocity of the stimulus, causing significant bias to judgements. They found the thresholds for detection were considerably lower than those found by Schmerler (1976) and Calderone & Kaiser (1989), possibly due to procedural differences such as the availability of performance feedback. Analysis of variance for the data showed angular acceleration, rather than terminal velocity, to be the better predictor of performance.

Babler & Dannemiller's second experiment extended the first by introducing non-constant acceleration patterns like those produced by free-falling projectiles. The same average angular velocities as in experiment 1 were used. Rates of acceleration increased in magnitude during each trial although the *average* accelerations were the

same as the *constant* accelerations used in experiment 1. Subjects were again asked to indicate whether the image was accelerating or decelerating. Results showed subjects were more likely to give an 'acceleration' response as average acceleration increased. The correlation between probability of giving an 'accelerating' response and average velocities, noted in experiment one, was again apparent. Angular acceleration was again the better predictor of judgements for all subjects. There was no significant difference in discrimination performance between constant and non-constant acceleration conditions. The falling object must undergo a change in velocity of around 20% of its average velocity before the appropriate action can be decided. For a fielder, if a positive acceleration is detected (as is the case for a ball going overhead), move backward. If a deceleration is detected (as is the case for a ball that will land short), move forward. Babler & Dannemiller's findings led them to suggest a possible reason for Todd's failure to find significant acceleration discrimination. Examination of the stimuli used in Todd's experiments revealed that they underwent a change in angular acceleration that was less than the thresholds required for an accurate judgement in their experiments. This being the case, it is unsurprising that subjects in Todd's experiments failed to show significant acceleration discrimination.

Babler & Dannemiller's third experiment required subjects to make the same discrimination of acceleration. However, instead of being asked to state the acceleration of the stimulus directly, subjects were asked whether they believed the stimulus would 'land' in front or behind of them. The projective size of the object was held constant to insure that expansion rate could not influence judgement. Angular acceleration again proved the best predictor of performance demonstrating that image acceleration is a viable cue for judgement of where a free-falling object will land and that image expansion is not a necessary cue. This supports the findings of McLeod &

Dienes (1996) who reported that subjects catching real balls launched at 60° began to move towards the interception point before any expansion of the ball's image. However, the detection thresholds were significantly higher than those found in Babler & Dannemiller's previous experiments, indicating subjects were less accurate at judging landing position than discriminating acceleration and deceleration, despite the two tasks being equivalent. Babler & Dannemiller asserted that the increase in thresholds was the inevitable consequence of subjects using any other strategy for their predictions. In experiment 3, subjects were not instructed to use the acceleration cue so that on some occasions they may have chosen an alternative strategy. This would have lead to the increased production of erroneous responses, which could be responsible for the increased threshold.

Babler & Dannemiller's fourth experiment added a third response to those available in experiment 3. This was to be used if subjects believed the 'ball' would land at their position. An additional group of subjects performed the experiment without feedback on the accuracy of their judgements. The performance of this group would indicate whether feedback provided in the previous experiments had merely trained the observers to a particular response strategy. The addition of the 'at' response option did not have significant effect on subjects' performance. The group that received no feedback on their judgements showed slightly poorer performance than the subjects who were given feedback on each of their responses. This manifested itself as slightly higher thresholds for detection of each trajectory type. However, the results demonstrated that image acceleration significantly influences a subject's judgement of the landing location of free-falling projectiles, even in the absence of feedback. This evidence, along with that of Michaels & Oudejans (1992), suggests firstly, that Todd failed to show human sensitivity to accelerative cues

because he used subthreshold accelerations. Secondly, it suggests that humans can discriminate the optical acceleration of an ascending projectile with sufficient accuracy to determine whether the projectile will hand in front of or behind their position.

In describing how they believed humans achieved interception, Babler & Dannemiller dissected the task into three stages. The first stage is how a fielder uses detection of optic acceleration to begin moving toward the interception point. They suggested that competent fielders show a shorter latency before this occurs compared to poor fielders and that this difference could be due to greater sensitivity to image acceleration. Babler & Dannemiller propose that fielders' subsequent movements null optic acceleration until the final moments of interception when image expansion cues the grasp of the ball.

The experiments presented in this chapter extend the investigations into human sensitivity to image acceleration. Subsequent analyses allowed assessment of the validity of interception models based on cancellation of optical acceleration (OAC models, e.g. McLeod & Dienes (1996)). The protocol of the experiments bears a close resemblance to that used by Todd, Michaels & Oudejans and Babler & Dannemiller but uses real-life stimuli that have been experienced by the subjects rather than computer simulations. In the first phase, subjects waiting at a fixed start position caught balls projected toward them on a variety of trajectories, all in the aligned vertical plane. Their movements to make the catch and the flight of the balls were analysed allowing investigation into interceptive behaviour. Subjects were classified as either expert (competent and experienced at ball sports) or novice (inexperienced at ball sports). Their comparative performance in the interception task and subsequent electronically presented tasks was assessed as an attempt to identify where expert

fielders hold an advantage and to test Babler & Dannemiller's (1993) assertion that expert fielders may show greater sensitivity to optic acceleration.

A video camera at eye level, immediately adjacent to the fielder's start position recorded the ascent of balls fired from the launch machine. It therefore recorded approximately the same visual information that the subject used to determine their interceptive behaviour prior to starting to run. In the second phase of the experiment, subjects watched the video clips of the trials that they had experienced. The clips were presented in such a way that subjects received optic information that corresponded to that which they experienced up to the point that they had begun to move towards the interception point. At that moment, the subjects had made a decision about what to do based on the visual information available. Subjects were asked how they would need to move to intercept such a trajectory based on what they had seen and should have been able to make the correct decision. The results of this experiment act as a test of the validity of using simulations to investigate interception strategy. Such simulations negate any cue provided by binocular stereopsis or by the fielders' head movements that may exist in the real situation. If subjects were unable to accurately determine the correct course of action based on presentations of video-recordings of the visual information that they used to actually catch the ball, it would suggest that presenting such information using a flat monitor screen is invalid in this context.

Like those of Michaels & Oudejans (1992), subjects were asked to indicate their certainty that their judgement of what a fielder should do was correct by giving a confidence rating to that answer. Confidence ratings can be used to investigate whether the knowledge used to control behaviour is implicit or explicit. Cheesman & Merikle (1984) defined the boundary between the two in terms of a subjective

threshold where knowledge is designated as unconscious if there is a lack of metaknowledge about it. To possess metaknowledge about information is to know that you know it. Dienes & Altmann (1997) argued that there are two ways in which a lack of metaknowledge may be demonstrated. Subjects could show no more confidence in correct responses than that which they ascribe to incorrect responses (the *zero correlation criterion*). Alternatively, subjects could show no confidence in answers that are actually correct (the *guessing criterion*). Results failing to meet either of these criteria demonstrate metaknowledge and the knowledge controlling behaviour cannot be said to be implicit. In chapter 7, subjects were significantly poorer at noticing what happened to their angle of gaze when they were stood in the right place to catch the ball. It appeared that subjects lacked metaknowledge about the information supposedly controlling their interceptive behaviour. The evidence suggested that this knowledge was below the subjective threshold of consciousness and could therefore be classified as implicit. If results of experiments presented in this chapter suggested that either the zero-correlation criterion or the guessing criterion have been met then it would suggest that, under these test conditions, subjects are unaware that they know how to discriminate between trajectories to achieve interception.

8.2. Experiment 1 – Method

8.2.1. Experimental apparatus

2 VHS-C video cameras, tennis balls, Tennis Tutor JR. ball launch machine, PC-compatible computer connected to video editing suite.

8.2.2. Subjects

6 graduate students aged 22–31. 2 inexperienced female fielders and 4 male fielders experienced at ball sports.

8.2.3. Catching

The apparatus was set up as shown in figure 8.1.

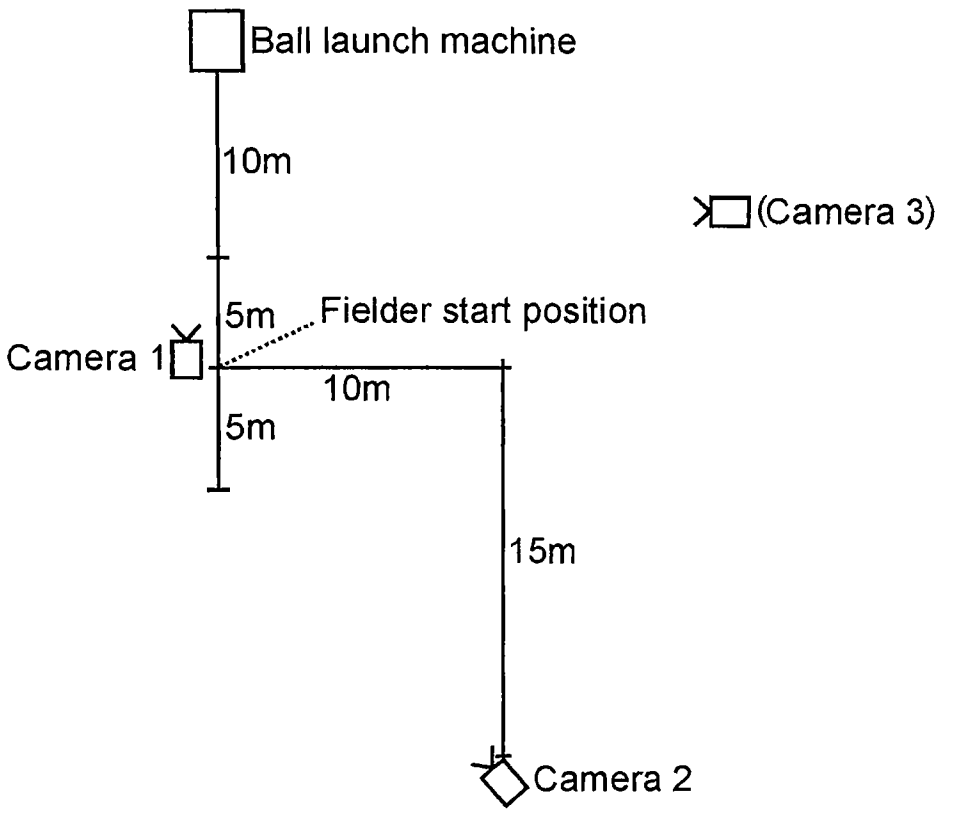


Fig. 8.1 Plan view of experimental set-up.

Fielders each received 30 ball launches and each launch constituted one trial. They were delivered in a pseudo-random order on one of three trajectories. One trajectory propelled the ball so that it would land short of the fielder. To catch it required the fielder to run forwards. A second trajectory launched the ball beyond the fielder so that they had to run backwards to catch the ball. The third trajectory required no movement from the fielder to make the catch – balls launched on this trajectory could be caught comfortably. The ball would strike the fielder close to their face if they did not raise their hands to catch it. These trajectories were termed 'short', 'long', and 'at' respectively. Subjects received 10 examples of each trajectory type.

Balls were launched at an angle of 34° and the ball-launch machine was slightly below ground level so that the launch aperture was at the surface height of the catching area. Variation in ball trajectory was achieved by adjusting the launch velocity applied to the balls by the launch machine to one of three set positions. Using this method, the ball- launch machine could consistently reproduce each type of trajectory. The end of a trial was indicated by contact of the ball with the fielder's hands[2].

8.2.3.1. Recording trial information

Two cameras recorded the information used for analysis (see figure 8.1). Camera 1 was responsible for recording the movement of the ball after launch. It was sited immediately adjacent to the fielders' start position and with the lens at a height of 170cm, the approximate height of the fielder's eye-line. Consequently, the scene it recorded was virtually identical to the view the fielder received before they ran to catch each launched ball. Camera 2 was situated behind and to the right of the fielders' catching area. It was responsible for recording the movement of fielders as they attempted to catch the ball and the release of the ball from the launch machine. This allowed analysis of the fielders' movements from the moment a ball emerged from the launch machine, signalling the start of a trial, to the time the ball was caught. Camera 3 was not present during catching trials, its purpose is explained in section 8.2.4.2.

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[2] There were occasions in which fielders' hands made contact with the ball but they failed to secure the catch. This was treated as a failure of the behaviour controlling grasping of the ball rather than that controlling interception.

8.2.3.2. Estimating the fielder's position

Fielders' movements were analysed using a technique similar to that described in appendix A1. The ball-launch machine consistently launched balls in the aligned projection plane. Consequently, it was assumed that fielders only moved within this plane. Calculation of a fielder's position was therefore simpler in this experiment because fielders only ran in one dimension to catch the ball. A record of fielders' movements was obtained from camera 2 and quantified using the computer program, Vidi-Clik, as per the experiments described in chapters 3 and 4. The reference points were designated as the top of an experimenter's head stood at either end of the catching area. The point nearest the ball launch machine was given the co-ordinate (500, 0) and the point furthest from it was assigned the co-ordinate (-500, 0). Giving no value to the Y reference points meant that the image map was only calibrated in the X-axis. As a result of the assumption that the fielder only moved in one dimension, only movement of the fielder across the field of view of the camera was being recorded and there was no need for calibration in Y.

Camera 2 viewed the catching area from an angle that allowed fielder movements and launch of the ball to be recorded. The perspective of this viewing angle required the Vidi-Clik co-ordinates to undergo a transformation before they gave an accurate representation of the fielder's true position. The format of the conversion equation was a simple polynomial:

$$x_t = ax_v^4 + bx_v^3 + cx_v^2 + dx_v + e$$

where:

x_t represents the true x co-ordinate

x_v represents the x co-ordinate as recorded using Vidi-Clik

Calibration of the parameters of this equation were computed using the computer program, SigmaPlot, and 11 reference points. These were the measured positions of an experimenter stood at 1m intervals along the 10m of the catching area. Figure 8.2 illustrates how the true positions compared to the representation in Vidi-Clik.

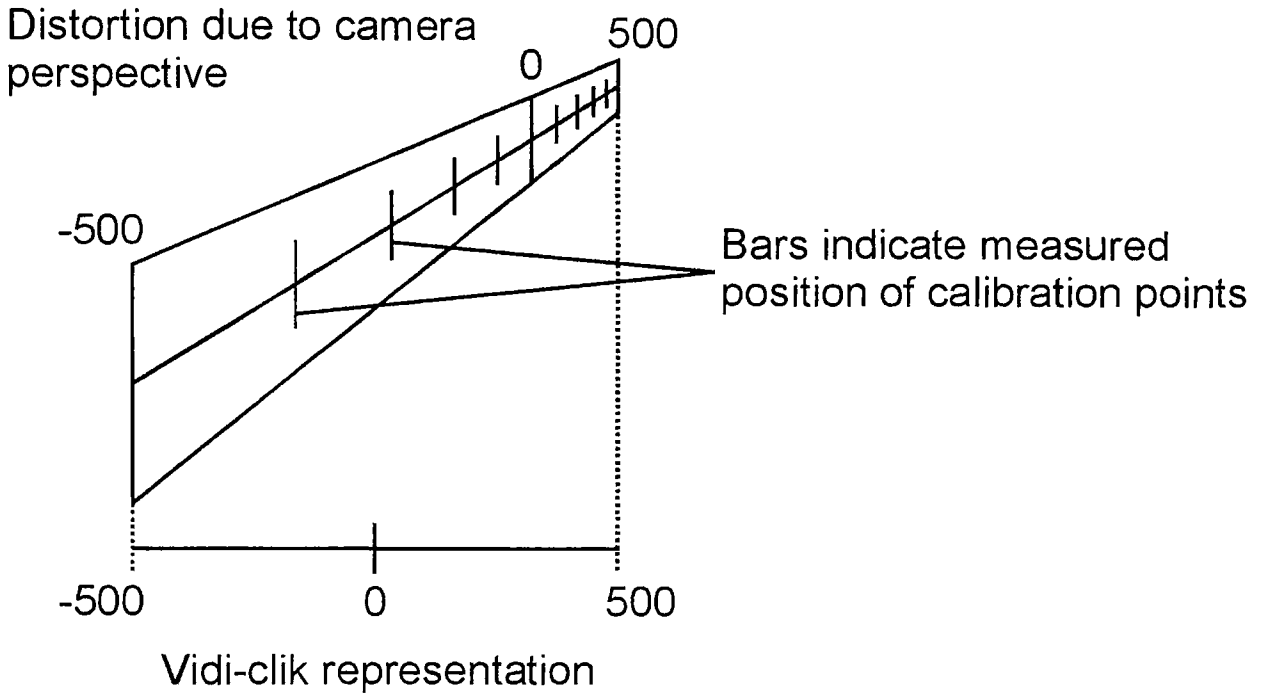


Fig. 8.2 Distortion of co-ordinate positions due to the perspective of view from camera 2 (measurements in cm).

The calculated parameters for the conversion equation used in this experiment are shown in table 8.1.

Parameter	Value
a	4.67×10^{-10}
b	2.78×10^{-7}
c	2.52×10^{-4}
d	0.935
e	-92.86

Table 8.1.

Although the parameters a and b appear small, they contribute significantly to the accuracy of the conversion equation. For the 11 measured positions, the mean difference between the true position and the corresponding Vidi-Clik co-ordinates transformed by the conversion equation was 2.8cm, with a maximum difference of 7.2cm.

The start of a trial for analysis was the first frame of video footage in which the ball was visible after emerging from the ball launch machine. From this frame onward, the fielder's position was recorded by positioning the cursor at the top of the fielder's head and clicking. By repeating this procedure for each frame of the trial until the fielder made contact with the ball (signalling the end of the trial), the Vidi-Clik co-ordinate of the fielder was recorded at intervals of 0.04sec (the interval between frames of video footage). To convert this data into true positions, each Vidi-Clik co-ordinate was fed into the conversion equation, giving an estimate of the fielder's true position in each frame.

8.2.4. Presentation of visual information

The footage recorded from camera 1 was replayed to subjects to present them with visual information equivalent to that which they received when they had to catch the ball. The footage had to be edited so that for each trial, a subject was only shown the trajectory of the ball up to the point where they decided to move.

8.2.4.1. Editing film footage

To show subjects the precise amount of information specified, it was necessary to find out when they moved in each trial (where this was necessary). This was achieved by producing graphs of the fielders' movements against time, using the positional estimates calculated from their Vidi-Clik co-ordinates. Examples of these

graphs are shown in appendix A8.1. The time at which the fielder began to move was designated as the frame at which they began to move in the correct direction toward the interception point. The video clips of each trial were then edited so that the subjects would see the ball trajectory up to that point. For trajectories that did not require the fielder to move to make the catch, there was no defined cut-off point at which to end presentation of the video footage. Consequently, the average time at which a fielder began to move in the remaining trials was used as the boundary, based on the assumption that if a fielder had decided he needed to move, he probably could have begun to do so by that point. To prevent subjects being surprised by the sudden presentation of the ball trajectories, three seconds of video footage prior to the launch of the ball were also included. The resultant video clips were separated on the videotape by 15 seconds of blank screen.

8.2.4.2. Ensuring correspondence of presented visual information

Subjects were required to watch the video clips showing the trajectory of the ball and decide how they would respond if they had to catch the ball. The same monitor screen was used throughout the experiment. The viewing area measured 210 × 282mm. Subjects had to be positioned at the correct distance from the monitor so that the change in visual angle as they watched the ball on the screen approximated the change they experienced when they watched the real trajectory (the 'screen distance'), illustrated in figure 8.3.

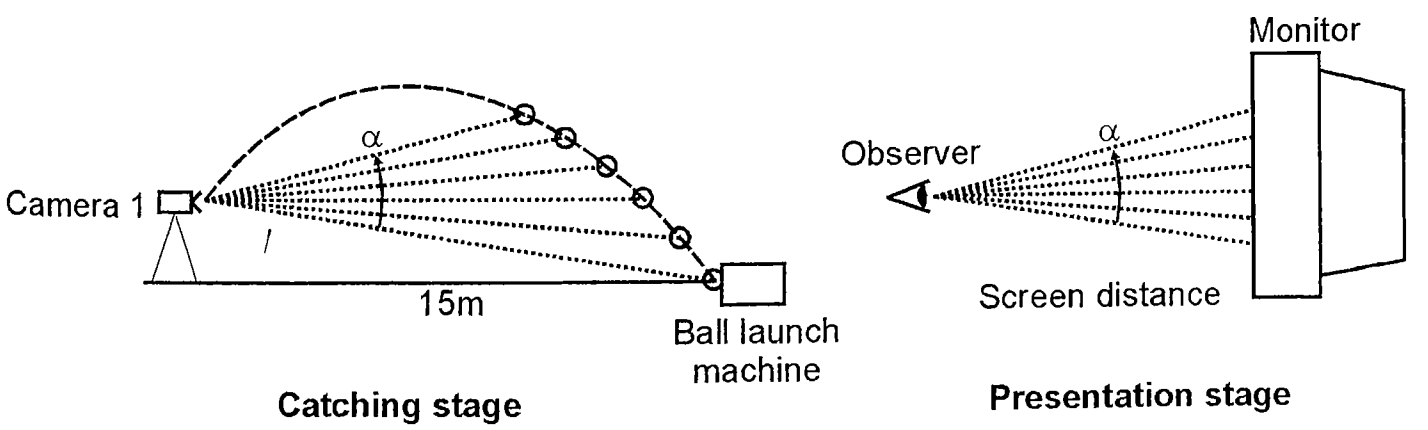


Fig. 8.3 Translating the real angle change to the presentation on the computer screen.

There were two steps involved in finding the screen distance. The first step was to find the variation in tan α experienced by the subject in the real situation. Camera 3 and camera 1 recorded examples of the three trajectories from the positions shown in figure 8.1. Camera 3 had a view similar to the left half of figure 8.3. Again, Vidi-Clik was used to record the position of the ball throughout its flight. The reference points used by Vidi-Clik to map the screen were the launch aperture of the ball launch machine (given the co-ordinates (0,0)) and the lens of camera 1 (given the co-ordinates (1500, 170)). Applying these reference co-ordinates meant that the co-ordinate map of the screen, calculated by Vidi-Clik, was approximately true. Therefore the change in α that would be experienced by a fielder stood at the start position could be calculated by recording the position of the ball as it tracked across the screen and comparing that to the position of the lens of camera 1. The second step was to measure the actual vertical movement (in cm) of the ball on the monitor screen in the recorded footage of the same trajectories recorded by camera 1. This information combined with the angular change assessed in step 1 allowed calculation of the screen distance. Predictably, there was slight variation in the calculated screen distance from frame to frame. A mean was taken of the calculations of screen distance and the value was found to be 48cm (SD = 3.9). A chin rest was provided to ensure that subjects remained at the correct screen distance throughout presentation of the video clips.

Subjects experienced the same relative change in image size watching the video clips as that they experienced when watching the real balls launched towards them. However, relative change in image size of the ball was unlikely to have provided a cue to interceptive behaviour. The diameter of a tennis ball is approximately 6.8cm.

For a subject stood at the start position, a ball at the point of release subtends a visual angle of 0.26°. In the first half second after launch of a ball that will land at his position, the approach of the ball causes its angular size to increase to 0.41°. However, at the same moment in time, the angular size of a ball projected on a 'long' or 'short' trajectory differs from that of a ball on an 'at' trajectory by less than 0.01°. It is unlikely that a fielder could determine the appropriate course of action from this difference.

8.2.4.3. Responses

After viewing a video clip, subjects were required to state whether they believed that in order to catch the ball in that particular trial they had to move forwards, move backwards, or stay in the same place. Subjects scored 1 for a correct response and 0 for an incorrect response (no feedback was given). They were also asked to supply a confidence rating on their response. Ratings were based on a 0 to 10 scale, where 0 indicated that their answer was a complete guess and 10 indicated that the subject was totally confident that their answer was correct.

8.3. Results

All the statistics from this section are shown in appendix A8.2.

8.3.1. Trajectory parameters

The trajectories used had the following initial values for $d^2(\tan \alpha)/dt^2$:

Short: -0.25

At: 0

Long: 0.73

8.3.2. Response times

Plots of the subjects' position against time for each catch were used to find the time at which each subject began to move in the correct direction time to catch the ball (where movement was necessary). Mean response times for novices and experts for 'short' and 'long' trials are shown in table 8.2.

Skill	Trial type	N	Mean RT(sec)	SD
Novice	Short	20	0.53	0.10
	Long	20	0.62	0.11
	Total	40	0.57	0.11
Expert	Short	40	0.51	0.11
	Long	40	0.65	0.12
	Total	80	0.58	0.13
Total	Short	60	0.52	0.10
	Long	60	0.64	0.12
	Total	120	0.58	0.13

Table 8.2.

Given the obscurity of the cue purported to control behaviour, the response times were remarkably rapid. Mann-Whitney tests were conducted to investigate the differences between the mean response times across groups. The overall difference between response times to 'short' and 'long' trials was significant ($Z = -5.428$, $p < 0.001$). However, the overall mean response times across skill groups did not significantly differ ($Z = -0.272$, $p > 0.75$), suggesting that skilled ball catchers are not able to detect and utilise the available cues to interceptive behaviour faster than unskilled catchers. The advantage that skilled fielders hold must come from more effective use of cues throughout the flight of the ball rather than in the initiation of movement.

8.3.3. Responses to presentation of video clips

As was expected, subjects were proficient at selecting the correct course of action to take, given equivalent visual information to that which they experienced

when they were catching balls for real. Table 8.3 shows the mean score for subjects across skill levels and trial types. The performance of both novices and experts for each trajectory type was well above the 33% that would be expected by chance.

Skill	Trial type	N	Mean score (/1)
Novice	Short	20	1.00
	At	20	0.60
	Long	20	0.95
	Total	60	0.85
Expert	Short	40	0.77
	At	40	0.58
	Long	40	0.95
	Total	120	0.77
Total	Short	60	0.85
	At	60	0.58
	Long	60	0.95
	Total	180	0.79

Table 8.3.

A Mann-Whitney test revealed that there was no significant difference between the overall performance of fielders in the novice and expert groups. However, further investigation of the novice/expert comparison revealed that the difference in performance for 'short' trials did reach significance ($Z = -2.3$, $p < 0.03$), with 'novice' subjects performing slightly better than the expert group. The mean performance for subjects in correctly detecting 'at' trajectories was poorer than for the two other trial types. The differences were significant in each comparison ('short' vs. 'at': $Z = -3.2$,

$p < 0.002$; 'at' vs. 'long': $Z = -4.7$, $p < 0.001$). The accuracy of subjects' response to 'short' and 'long' trials did not differ significantly.

As noted by Michaels & Oudejans (1992), it is logical that subjects should be poorer recognising 'at' trajectories. McLeod & Dienes (1996) suggested that humans use an interception strategy where the sign of $d^2(\tan \alpha)/dt^2$ is the input to a servo that controls running to catch the ball. In the experiment, $d^2(\tan \alpha)/dt^2$ for balls on 'at' trajectories will not provide the servo with a distinct signal. However, if subjects believed that $d^2(\tan \alpha)/dt^2$ had a slight positive or negative component when viewing the video clips they may have erroneously suggested that a fielder should move to catch the ball. This is not catastrophic for a fielder attempting to catch a ball on an 'at' trajectory in the real world. As soon as the fielder started to move in the incorrect direction, the sign of $d^2(\tan \alpha)/dt^2$ would provide a cue indicating that they should reverse their movement and return to their original position.

8.3.4. Confidence ratings of judgements

Table 8.4 shows the mean confidence scores for subjects in their classification of video clips.

Skill	Trial type	N	Mean conf. (/10)
Novice	Short	20	7.95
	At	20	5.80
	Long	20	7.85
	Total	60	7.20
Expert	Short	40	7.50
	At	40	6.75
	Long	40	7.48
	Total	120	7.24
Total	Short	60	7.65
	At	60	6.43
	Long	60	7.60
	Total	180	7.23

Table 8.4.

The mean confidence scores across skill levels are very similar, confirmed by a non-significant Mann-Whitney test ($Z = -0.17$, $p > 0.85$). However, like the accuracy scores, there is a significant difference in confidence scores across trajectories. Mann-Whitney tests showed subjects' confidence in their judgement of 'at' trajectories differed significantly from their (greater) confidence in classifying the each of the other trajectories ($p < 0.003$ in each case). A Kendall's τ correlation analysis was performed, comparing subjects' accuracy with their confidence. It revealed a

significant positive association between the accuracy of subjects' judgements and their confidence in that judgement ($\tau = 0.177$, $p < 0.01$). This is similar to the results of Michaels & Oudejans (1992) who found that high-certainty judgements in a similar experiment tended to be the most accurate.

8.3.5. Velocity ratios

Babler & Dannemiller (1993) performed an experiment in which subjects had to predict the landing location of stimuli on simulated trajectories ascending a computer screen. The velocity of the stimulus ascending the screen observed from a fixed position is equivalent to $d(\tan \alpha)/dt$. They used a velocity ratio to measure the acceleration of $\tan \alpha$ that was required for subjects to decide whether they thought a stimulus would land in front or behind them. Velocity ratio is defined as the ratio of the change in velocity to the velocity average: $VRatio = (VF - VI)/VAve$, where *VRatio* is the velocity ratio and *VF*, *VI*, and *VAve* are the final, initial and average angular velocities respectively. The group that received no feedback on their performance in Babler & Dannemiller's fourth experiment was most similar to that performed by subjects in this experiment. They had to decide whether a simulated projectile on free-falling approach would land in front, behind or at their position. Babler & Dannemiller found that subjects in this group required a change in velocity ratio of 0.34 to reach the threshold for correct 'long' responses (75% correct). For 'short' trajectories, they found that to reach the same threshold, subjects required a change in velocity ratio of –0.41.

Figure 8.4 shows the velocity ratio profile of the trajectories used in this experiment.

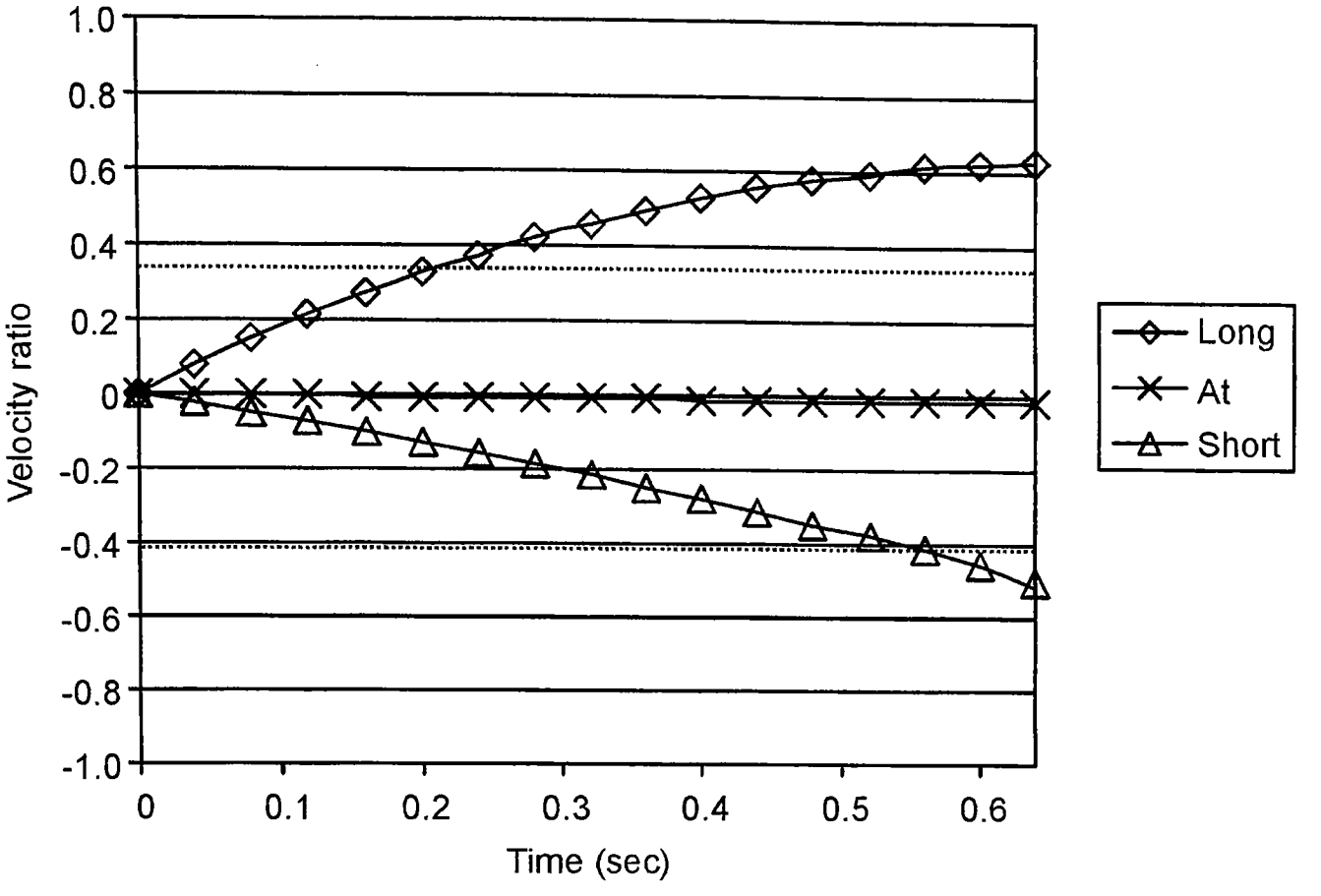


Fig. 8.4. Velocity ratios for the initial portion of trajectories used in this experiment (the dotted lines show the thresholds for correct responses found by Babler & Dannemiller (1993)).

Figure 8.4 suggests that the threshold of velocity ratio for the detection of 'long' trajectories is reached much earlier than that for the 'short' trajectories. This result is at odds with the response times of fielders in this experiment. It was found that the response time to 'short' trajectories was significantly shorter than that for 'long' trajectories. Furthermore, the mean response time for fielders to 'short' trajectories was 0.52sec. Figure 8.4 shows that the threshold of the velocity ratio for detection of a 'short' trajectory, as found by Babler & Dannemiller, was not reached until slightly after this time.

8.4. Discussion

Babler & Dannemiller (1993) suggested that the advantage held by skilled fielders could lie in greater sensitivity to the available cues to interceptive behaviour. Analysis of the response times of novices and experts suggested that expert fielders

have no advantage in the speed with which they are able to utilise these cues. In fact, none of the analyses presented could separate the performance of novice and expert fielders, failing to provide any cogent explanation for the difference in ability of the two groups. The superiority of skilled fielders must lie elsewhere.

It appears that subjects are satisfactorily able to distinguish trajectories presented on a monitor screen when the visual information is equivalent to that which would be experienced in the real world. As found by Michaels & Oudejans (1992), performance in judging each trajectory type was substantially better than chance. However, unlike the results of Michaels & Oudejans, there was a consistent tendency for subjects to perform significantly less well when classifying trajectories that would land at their position. This supports the hypothesis that it is harder to identify a $d^2(\tan \alpha)/dt^2$ of zero than when it has a positive or negative value. Babler & Dannemiller (1993) found that the addition of an 'At' response to the available 'Short' and 'Long' options used in a prior experiment made no difference to the performance of subjects in categorising 'Short' and 'Long' trajectories. This also suggests that 'At' trajectories do not provide a strong stimulus for perception of acceleration.

Interestingly, subjects were aware that they are poorer at recognising 'at' trajectories. Like Michaels & Oudejans (1992), a correlation between accuracy of judgement and confidence in that judgement was found. The zero-correlation criterion is not met, suggesting subjects are aware of the accuracy of their judgements. Compare this with the results of the experiments in chapter 7. Subjects watched real balls projected towards them on 'short', 'at', and 'long' trajectories. They were significantly poorer at describing the change in their angle of gaze for 'at' trajectories than the two other types, yet their confidence remained high across all trajectory types. Subjects therefore appear unaware that $d(\tan \alpha)/dt$ has a particular form for

those trajectories. Generally, subjects seem perfectly able to choose the correct course of action based on the visual information they have seen but do not know what it is about that information that has led them to their choice. Combining the evidence from chapter 7 with the results from the experiments in this chapter suggests that humans have difficulty deciding the correct course of action when they experience $d^2(\tan \alpha)/dt^2 = 0$ but can easily decide what to do when $d^2(\tan \alpha)/dt^2$ is above their detection threshold. Furthermore, this is perfectly compatible with human catching ability. Tresilian (1995) has shown that a simulated fielder can achieve interceptive performance equivalent to humans when it is sensitive to the sign of $d^2(\tan \alpha)/dt^2$. This strengthens the argument that the model of interception proposed by McLeod & Dienes (1996), based on a servo-mechanism that controls running to null $d^2(\tan \alpha)/dt^2$, is a valid interpretation of human interceptive behaviour.

Babler & Dannemiller (1993) suggested thresholds for detection of trajectory based on angular velocity ratios. Applying the thresholds Babler & Dannemiller found in their experiments to the trajectories used here showed that they did not fit with the response times of subjects. The velocity ratio threshold for 'long' trajectories was reached before that for 'short' trajectories. However, subjects' response times were more rapid for 'short' trajectories. It is conceivable that subjects can begin running forward faster than they can begin running backwards but the velocity ratio threshold for 'short' trajectories was not reached until slightly after the mean running response time for subjects to 'short' trajectories. When one considers that there must also be some neuromuscular delay, it seems that the velocity ratio thresholds found by Babler & Dannemiller (1993) do not apply to subjects in this experiment.

There are two differences in procedure that may explain the divergence of results from those Babler & Dannemiller (1993). Firstly, the response time of subjects

running to catch real projectiles launched towards them is being compared to the task of Babler & Dannemiller's subjects, who responded to an ascending stimulus on a simulated approaching trajectory presented on a computer screen. There are additional cues available to a subject performing the catching task since it is performed in three dimensions and it is a task with which subjects are more familiar. This may have affected subjects' ability to detect trajectory differences. Secondly, the launch position of the simulated trajectories used by Babler & Dannemiller was considerably further from subjects than that used in this experiment. The visual information supplied to subjects in their experiments gave the impression that they were between 35m and 45m away from the launch site whereas the fielder in this experiment was 15m from the launch site. This may have had a significant effect on the ability of the fielder to distinguish the three possible trajectories.

8.5. Experiment 2 – Reduced information

In experiment 1, the duration of the visual information presented to subjects watching video clips of the balls projected toward them was greater than that on which they based their decision. They were shown the information up until the point at which they began to move. However, neuromuscular delays and the accelerative requirement of moving the human body mean that the action decision must have occurred some time before movement began. In a third phase of the experiment, three example video clips of each trajectory were selected. Each was then was cropped by different amounts, reducing the available information upon which subjects had to base their decision of the appropriate action. A decrease in accuracy and confidence in their answers was predicted. The pattern of this decrease could indicate the true moment at which subjects had decided the correct course of action and allow further

investigation into the changes in visual information that elicit a particular interceptive behaviour.

Todd (1981) claimed that subjects performing landing judgements in condition C of his experiments (single pixel stimulus) relied on the height attained of the stimulus to make their decision and could not take advantage of the cue provided by its acceleration. However, Babler & Dannemiller (1993) found that image acceleration played a significant role in subjects' ability to distinguish trajectories that were simulated to land either in front or behind them. The work of Michaels & Oudejans (1992) found, after rigorous analysis of their simulation experiment, that the acceleration of the stimulus was the best predictor of response when subjects were asked to say whether or not the stimulus accelerated, also suggesting that humans *were* sensitive to acceleration. However, they also found that the best predictor of subjects' landing judgements tended to be the height attained by the stimulus. In this experiment, variation of the duration of the video clips removed the relationship between the final height the ball achieved on screen and its trajectory (whether 'short', 'at', or 'long'). The height on screen attained by the ball for the 'long' trajectory with the maximum number of frames removed was less than the height attained by the ball on the 'short' trajectory with the minimum number of frames removed. Therefore, the terminal height attained by the ball is no longer a cue to trajectory type. Finding that subjects were able to make accurate judgements under these conditions would suggest that they are able to use acceleration when it is the most accurate cue to the correct response.

8.6. Method

8.6.1. Experimental apparatus

Visual information was presented to subjects using the same apparatus as in the previous experiment.

8.6.2. Subjects

A new group of 15 university students aged 18-32. 9 were experienced at ball sports (8 male, 1 female) and 6 were inexperienced at ball sports (1 male, 5 female).

8.6.3. Production and presentation of video clips

In the previous section, subjects watched video footage until the point at which they began to move. The overall mean response time for 'short' trajectories was 0.52seconds (equivalent to 13 frames of video footage) and 0.64seconds (equivalent to 16 frames of video footage) for 'long' trajectories. The response time for 'at' trajectories was taken as the mean of the two other trajectory types giving 0.58seconds, which is approximately equivalent to 15 frames of footage (rounding up to the nearest frame). One example of the video footage from camera 1 of each trajectory type was selected. The mean response times represent the time at which subjects were able to discriminate between trajectories comfortably. Each clip was shortened to reduce the information presented to subjects. The clips were cut by 4 different amounts. Table 8.5 summarises the changes to the three video clips.

Reduction (frames)	Trajectory type					
	Short		At		Long	
	Frames	Time(sec)	Frames	Time(sec)	Frames	Time(sec)
-2	11	0.44	13	0.52	14	0.56
-4	9	0.36	11	0.44	12	0.48
-6	7	0.28	9	0.36	10	0.40
-8	5	0.20	7	0.28	8	0.32

Table 8.5.

Each clip was presented to subjects 3 times in a pseudo-random order. There were therefore 3 trajectories × 4 reductions × 3 presentations, yielding a total of 36 trials presented to each subject. The reduction in duration of the video clips shown to subjects meant that the change in velocity ratio would be far below the threshold that Babler & Dannemiller (1993) suggested for detection of a 'short' trajectory. However, even with the maximal reduction in duration the change velocity ratio was above Babler & Dannemiller's threshold for detection of 'long' trajectories. Finding a significant difference in subjects' ability to detect 'long' trajectories over 'short' trajectories would support Babler & Dannemiller's threshold system.

8.7. Results

Statistical analyses conducted in this section are shown in appendix A8.3. Questioning subjects after responding to the video clips, none realised that there were only 3 clips of varying lengths being used. There was no correlation between trial number and score or confidence as might be expected if subjects learnt how to perform the task as they viewed more trials.

8.7.1. Comparison of Novice and Expert fielders

Table 8.6 summarises the responses of novice and expert fielders.

Skill	Trial type	N	Mean score (/1)	Mean conf. (/10)
Novice	Short	72	0.76	6.60
	At	72	0.53	5.63
	Long	72	0.76	7.29
	Total	216	0.69	6.50
Expert	Short	108	0.78	6.56
	At	108	0.51	5.73
	Long	108	0.76	6.93
	Total	324	0.68	6.41
Total	Short	180	0.77	6.58
	At	180	0.52	5.69
	Long	180	0.76	7.07
	Total	540	0.68	6.45

Table 8.6.

As in the previous experiment, there is no significant difference between novice and expert subjects. A Mann-Whitney test confirmed that the difference across skill levels between the mean score and confidence ratings for each trajectory was non-significant. The apparent uniformity of responses across the two groups meant comparisons across skill level were not relevant in subsequent statistical tests.

8.7.2. Effect of reduction in frames viewed

8.7.2.1. Mean score

Performance is still remarkably high, despite the reduction in visual information made available to subjects. As before, subjects scored 1 for a correct discrimination of trajectory and 0 for in an incorrect response. Figure 8.5 shows how subjects' mean scores varied with the number of frames by which the video footage was reduced.

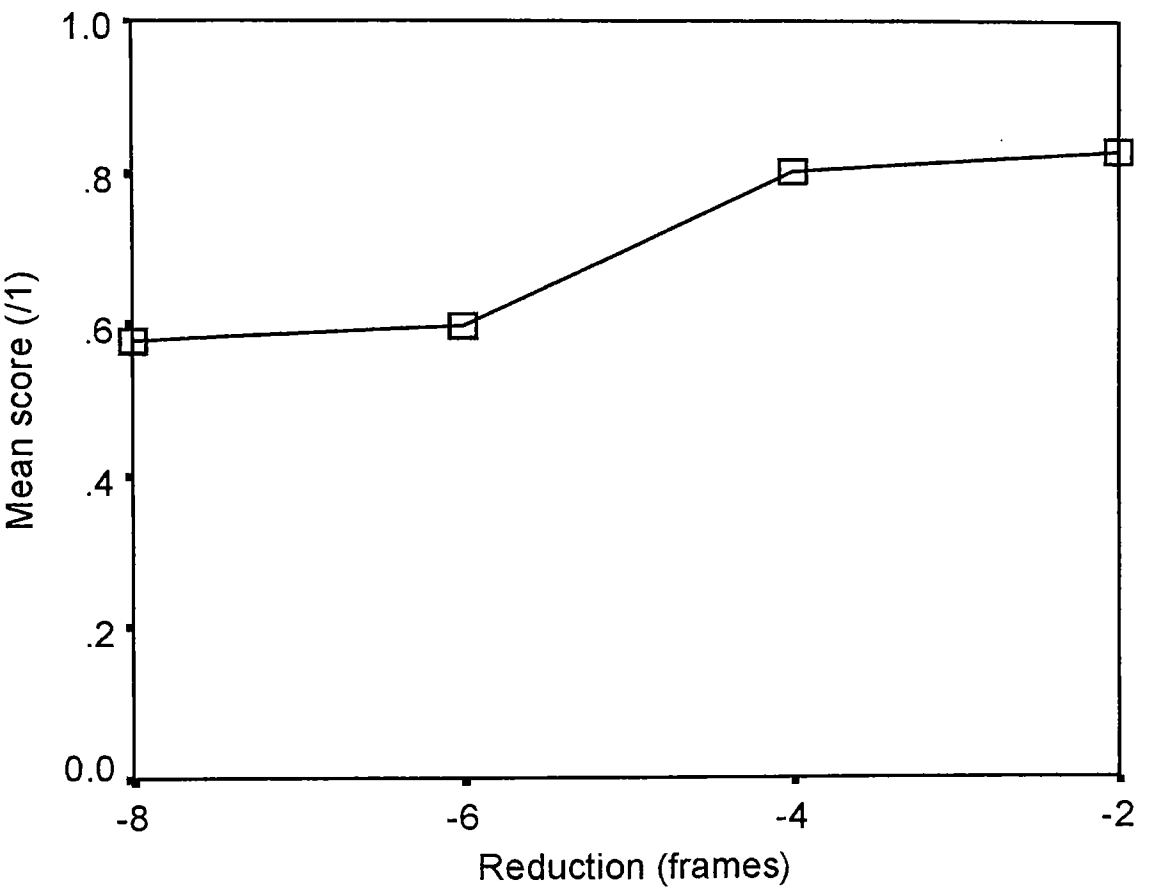


Fig. 8.5 Variation in mean score with increase in visual information presented.

There is a marked improvement in performance between the –6 and –4 frame reduction levels. However, even when subjects are presented with the minimal information (viewing 8 frames less than had been viewed previously), performance is still significantly better than 0.33, which would be expected by chance (based on Z approximation, $p < 0.001$). A Kendall's τ test of correlation showed that frame reduction showed a highly significant correlation with mean score ($\tau = 0.213$, $p < 0.001$). A linear regression model was fitted to frame reduction against mean score.

The fit of the model was highly significant ($F = 31.0$, $p < 0.001$). Using the regression model, it was calculated that performance would fall to chance (a mean score of 0.33) if 0.51seconds (12.8 frames) were removed from the footage. Recall from table 8.2 that subjects overall mean response time was 0.58seconds. This suggests that subjects are able to discriminate between trajectories within moments of the release of the ball. Since $d^2(\tan \alpha)/dt^2$ is a valid cue to the correct behaviour a similarly short time after ball release, its use in interception strategy is supported.

8.7.2.2. Confidence ratings

A Kendall's τ test of correlation showed that there was a highly significant association between subjects' accuracy of judgement and their confidence in the accuracy of that judgement ($\tau = 0.258$, $p < 0.001$). The result is much like the correlation found between mean score and confidence for the uncut video clips and strengthens the idea that subjects are aware when their responses are uncertain. Figure 8.6 shows how mean confidence ratings varied with frame reduction.

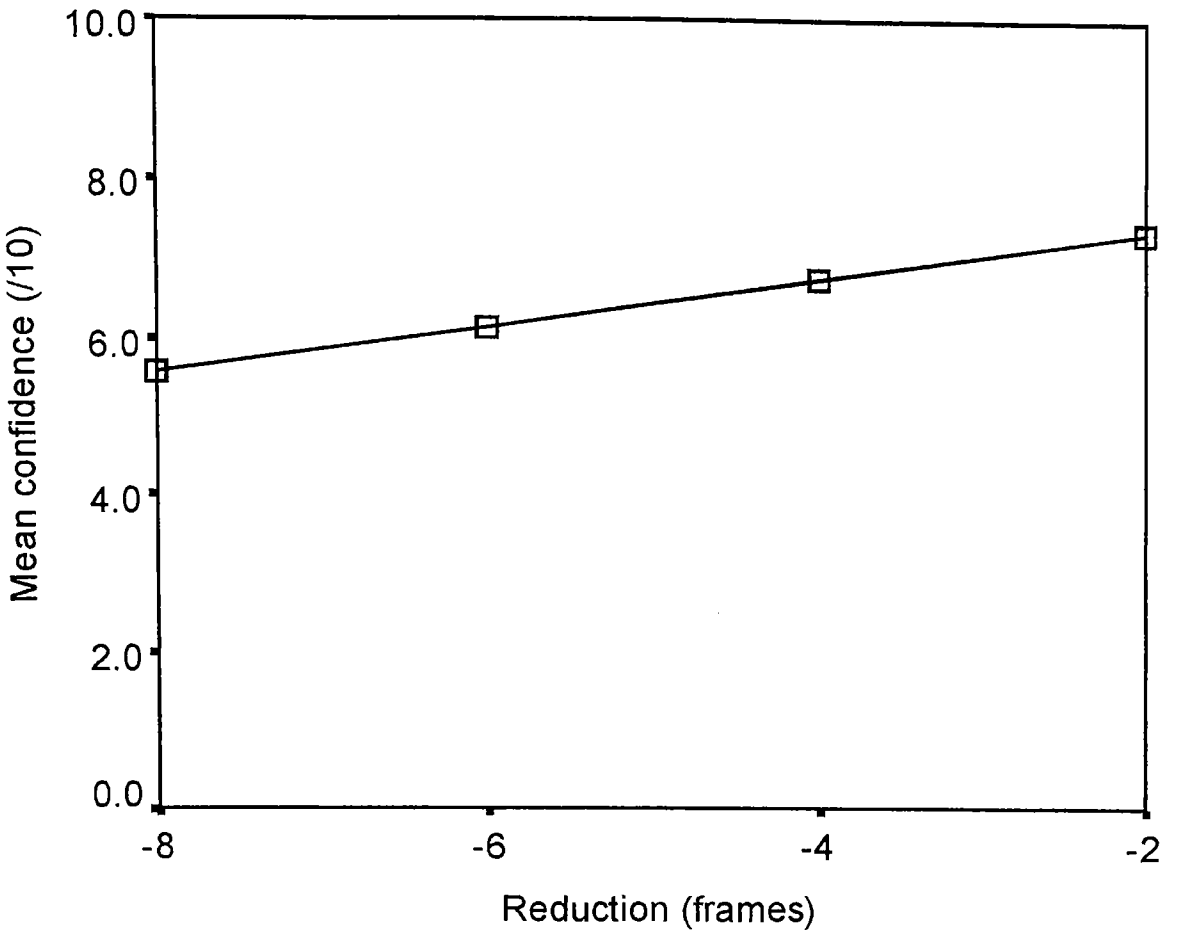


Fig. 8.6 Variation in mean confidence ratings with increase in visual information presented.

Predictably, there is a consistent increase in confidence as subjects received more information on which to base their decision. The correlation between the two variables was significant (Kendall's $\tau = 0.25$, $p < 0.001$). However, it is difficult to estimate the level of confidence that subjects would deem sufficient to act upon their judgement of the appropriate behaviour. Given the rapid response times of fielders moving to intercept projectiles, they must act on their judgement within milliseconds of ball release.

8.7.2.3. Performance separated by trial type

Figure 8.7 shows how subjects' performance at discriminating between trajectory types varied with frame reduction.

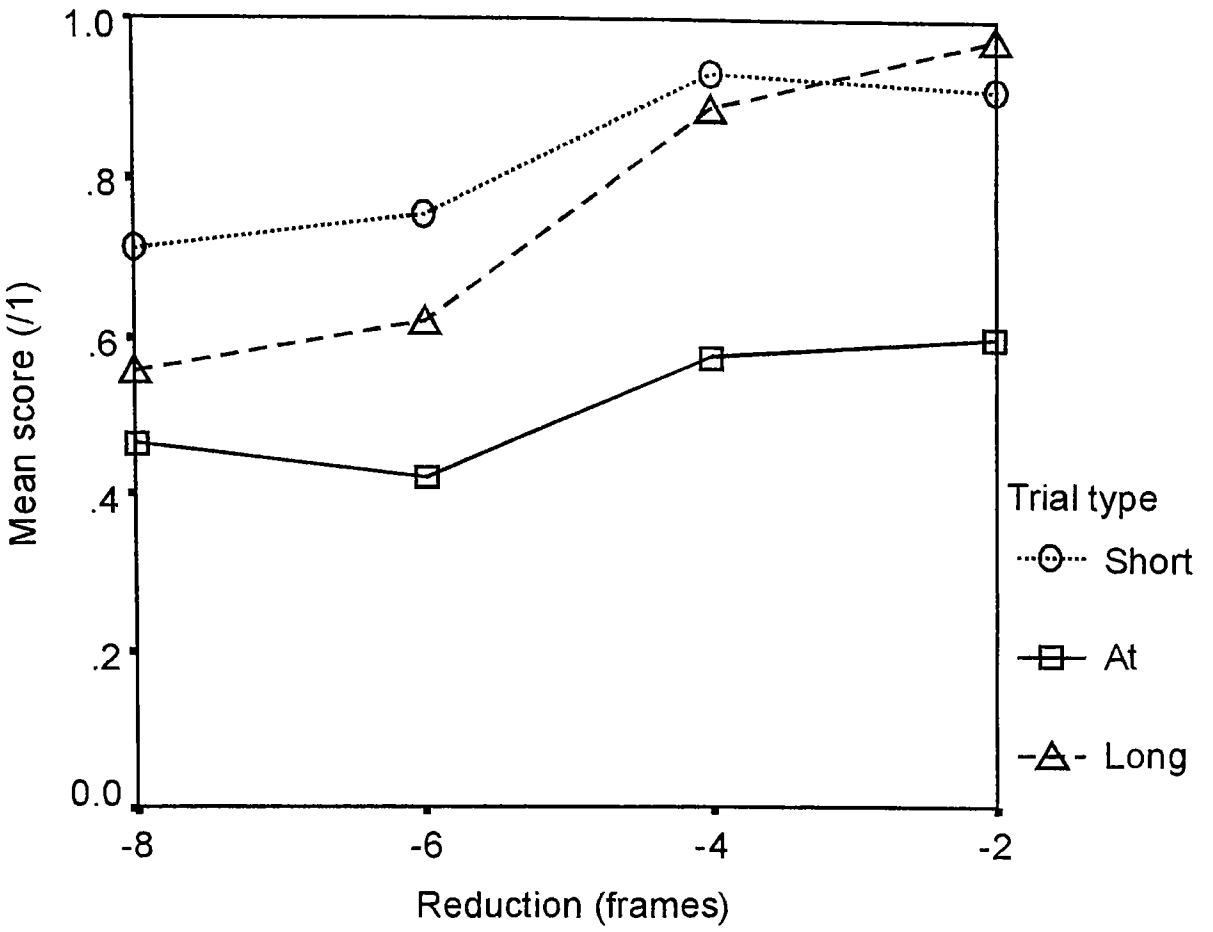


Fig. 8.7 Variation in mean score with increase in visual information presented separated by trial type.

Interestingly, the performance of subjects at correctly recognising 'short' and 'long' trajectories appears approximately similar. However, performance with 'at' trajectories appears qualitatively different. This was confirmed quantitatively by a test of correlation between mean score and frame reduction. A highly significant correlation with mean scores for 'short' and 'long' trajectories was found (Kendall's τ: $p < 0.003$ in each case). The correlation with mean scores for 'at' trajectories failed to reach significance – scores remained poor at all levels of frame reduction. The similarity in performance for 'short' and 'long' trajectories conflicts with the predictions based on Babler & Dannemiller's velocity ratio thresholds, suggesting whilst something akin to the change in angular velocity ratio may be the cue to interceptive behaviour, the thresholds that they found are not universal.

The poorer performance of subjects for 'at' trajectories suggests fielders find it easier to recognise when a trajectory is not going to land in their immediate vicinity.

That a subject receives a strong signal to move but does not receive a strong signal to stay in the same place supports the idea of an interception strategy based on a servo-mechanism that is sensitive to $d^2(\tan \alpha)/dt^2$.

8.8. Discussion

The usefulness of these experiments in illuminating where differences lie in the abilities of novice and expert fielders has been minimal. Babler & Dannemiller (1993) suggested that an expert fielder might show a faster reaction time to a given trajectory than a novice fielder due to greater sensitivity to optic acceleration. However, no difference was found between the performance of novice and expert fielders in any test and suggests that expert fielders do not possess greater sensitivity to optic acceleration. This negative result suggests that the difference lies elsewhere, possibly in the realm of muscular control. As shown, unskilled fielders are equally able at recognising the appropriate cues for controlling interceptive behaviour but perhaps they lack the necessary muscular co-ordination to engage accurately the instructions.

Varying the duration of the video clips presented to subjects confounded the relation between the final height attained by the ball in the each clip and the trajectory that the ball was following. However, subjects' performance at discriminating between trajectories remained remarkably high, despite reductions in the amount of visual information presented. This suggests that subjects cannot have been using the height attained by the ball as the primary cue on which to base their judgement and must have been using the valid cue provided by the optical acceleration of the ball. The result contradicts the work of Todd (1981) that suggested humans were unable to take advantage of accelerative cues. It also supports the work of Michaels & Oudejans (1992) and Babler & Dannemiller (1993) showing that it is possible for humans to take advantage of optical acceleration when making landing judgements. Michaels &

Oudejans suggested that the presence of a structured background might facilitate the detection of information about ball trajectory. The result of this experiment suggests that this is true. Also supported is the work of Rosengren, Pick, & von Hofsten (1988). They observed fielders catching luminous balls in dark and light conditions and found a significant facilitation of catching under light conditions (although the authors noted that performance under dark conditions was surprisingly good). Furthermore, Babler & Dannemiller (1993) included a perspective grid in their computer display in an experiment that was similar to Michaels & Oudejans (1992). The former found that their subjects could detect the acceleration of a simulated projectile, the latter found it was not the best predictor of performance. It is unclear how the presence of a structured background aids interception. It is proposed that the rate of change of tan α is the main cue to interceptive behaviour and this is fully specified in the absence of depth cues (explaining the 'surprisingly good' performance of catchers in the dark in Rosengren, Pick, & von Hofsten's experiment). It is possible that depth cues confer the catcher with a useful sense of realism and familiarity with the task that aids discrimination.

The evidence presented also suggests that subjects are able to correctly discriminate between trajectories that will cause projectiles to land in front or behind them within milliseconds of launch. It is at this point that the results diverge somewhat from those of Babler & Dannemiller (1993). They found that their subjects required greater exposure to change in angular acceleration than that which subjects received in this experiment before they could accurately recognise 'short' trajectories. In fact, subjects' performance distinguishing 'short' and 'long' trajectories in this experiment was virtually equivalent. Although both this study and that of Babler & Dannemiller (1993) support the use of a variant of image acceleration as the cue to

behaviour, the threshold levels of velocity ratio that they report are required for detection do not apply to the subjects in this experiment.

A linear regression model was fitted to the data comparing subjects' performance at discriminating between trajectories against the duration of visual information removed from the video-footage. A highly significant result was obtained. Extrapolation of the regression line revealed that discriminatory performance would be better than chance even if subjects viewed less than 100msec of a trajectory. This result provides evidence that explains why fielders can react so rapidly to intercept projectiles. Figure 8.8 shows how d(tan α)/dt varies in the initial portion of each of the three trajectories.

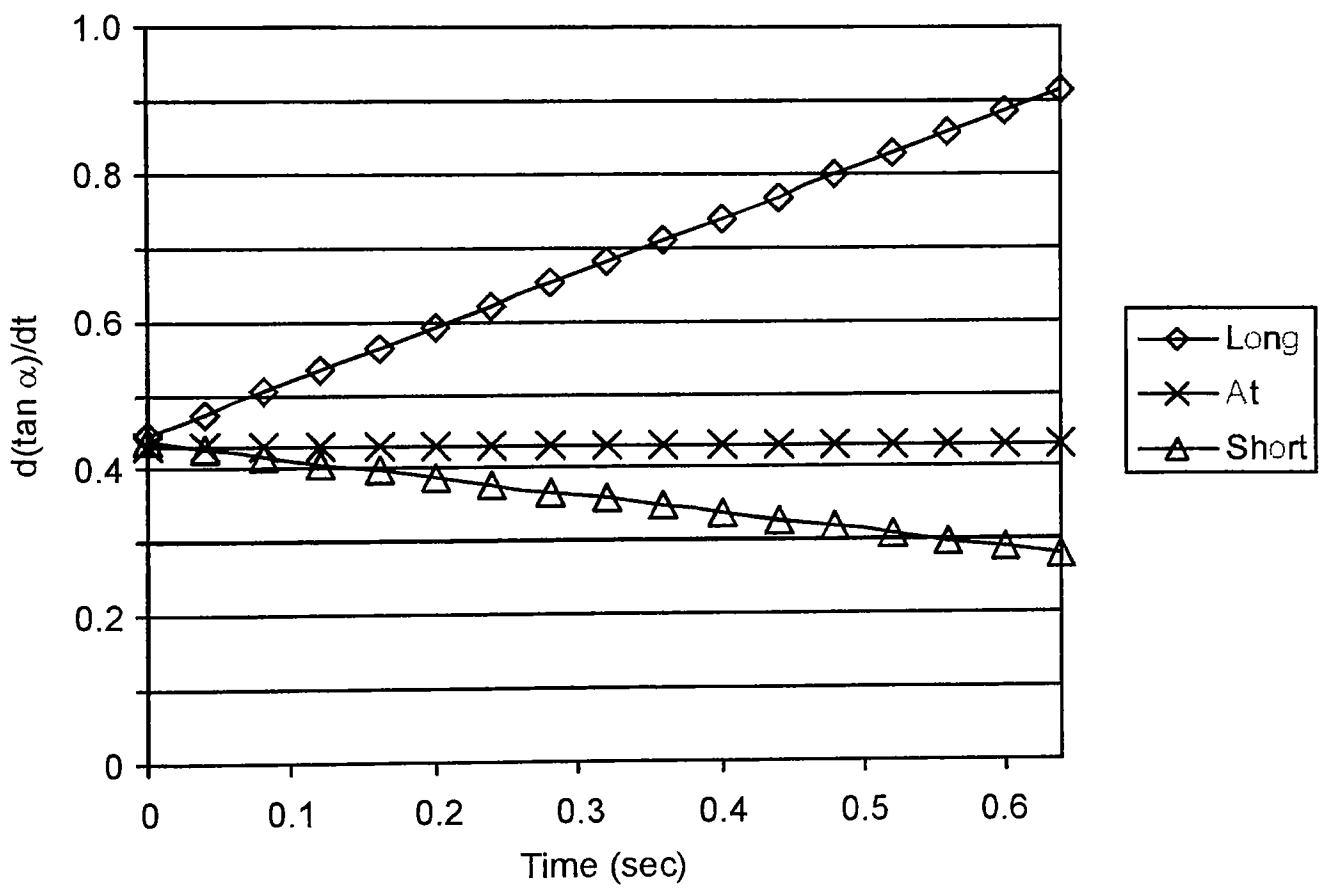


Fig. 8.8 d(tan α)/dt for the initial portion of trajectories used in this experiment.

If one believes that humans are sensitive to $d^2(\tan \alpha)/dt^2$ for discerning trajectories, their apparent ability to distinguish trajectories with extremely limited information is explained by the immediate divergence of the three lines in figure 8.8. Incidentally, figure 8.8 bears a striking resemblance to figure 8.4, and this is to be

expected given the similarity in the calculation of the y-axis values. The formulation used by Babler & Dannemiller (1993) could be used to illustrate the same point. However, the evidence produced in this experiment suggests that the thresholds they detected are not accurate.

Confidence in the accuracy of judgement heightens with increases in the amount of visual information to which subjects are exposed. It appears that trajectories that would not require a fielder to move in order to catch the ball are harder to recognise. This was used as evidence to support the use of an interception strategy based on a servo-mechanism that adjusts running behaviour based on $d^2(\tan \alpha)/dt^2$. Intuitively, it would seem that failing to recognise when you are in the right place to catch a ball is a highly unusual tactic to employ. However, this result is based on a simulation of a catching task where no movement is required. In the real situation, it makes sense that the signal to move should be easy to recognise because it is under these conditions that a rapid response is required. However, when little or no movement is required it is inconsequential whether this is recognised or not since the fielder is in approximately the right place. If the fielder makes the erroneous decision to move there will instantly be a signal to move back the other way provided by the $d^2(\tan \alpha)/dt^2$ servo so the fielder will never move far from the interception point. Using $d^2(\tan \alpha)/dt^2$ in this way is an efficient strategy for interception.

The evidence discussed thus far has been used to argue in favour of an interception strategy that uses detection of acceleration. However, there exists a flaw in the experiment that tempers this conclusion. In experiment 2, the duration of the video footage that subjects were shown was reduced and varied to undermine the correlation between the height attained by the ball up the screen. However, in both experiments there was nothing to prevent subjects using a strategy of trajectory

discrimination that relied on the velocity of ascent of the stimulus. This correlation could be removed by repeating the experiment using a variable launch angle.

Despite this fault, the results throughout this experiment have at least failed to contradict the hypothesis that fielders use an interception strategy that is based around detection of deviation in the motion of the projectile from constant $d(\tan \alpha)/dt$. This contradicts the work of Todd (1981) and extends the work of Michaels & Oudejans (1992) and Babler & Dannemiller (1993) to strengthen support for the use of optical acceleration as the basis for guiding interceptive behaviour.

9. When α must decrease

9.1. Introduction

Studies by authors such as Michaels & Oudejans (1992), McLeod & Dienes (1996) and chapters 3 and 4 in this thesis has shown that fielders running to catch a ball consistently produce locomotion toward the interception point that causes the tangent of their angle of elevation of gaze (tan α) to increase at a constant rate. This is logical behaviour for a fielder because, provided he can maintain constant d(tan α)/dt, he will arrive in the vicinity of the ball as it lands (see McLeod & Dienes (1996) for proof). The experiment presented in this chapter confronted subjects with an unusual situation in which it was impossible to hold d(tan α)/dt constant throughout the flight of a ball but it was possible to catch it. The aim of this experiment was to investigate fielders' interceptive behaviour under these exceptional circumstances.

The task required of subjects in the experiment was more challenging than those examined in other chapters. Subjects were required to catch balls that travel in the aligned plane and land behind their start position. However, unlike other experiments, the interception point could not be reached by simple backward motion in which the fielder continuously faces the direction of the launch point and takes a comfortable catch. In this experiment, the fielder must run facing away from the projection point so that they are sprinting forwards, away from the projection point. As the ball descends and passes over the head of the fielder, α (and therefore tan α) must decrease. This is among the most difficult variety of catch to take successfully. Investigating what happens to interceptive behaviour *in extremis* could reveal important details about how interception is achieved. It is predicted that the

interceptive behaviour displayed fielders will represent the performance of a strategy based on optical acceleration cancellation (OAC) operating at its extreme limit.

9.2. Method

Trials in this experiment were performed using the same subjects and set-up as experimental sessions 1 & 2 described in chapter 3. Consequently, this method section details where protocol differed from previous experiments. For full details, see the method section of that chapter (see also appendix 1) for information about estimating fielder and ball position).

9.2.1. Experimental apparatus

VHS video camera on tripod, tennis balls, tape measure.

9.2.2. Subjects

6 university graduates (5 male, 1 female) all experienced at ball sports.

9.2.3 Interception

9.2.3.1. Experimental set-up

At the top of the building (at a height of 14.75m) were the thrower and the video camera angled down to view the 'catching area' (see figure 9.1).

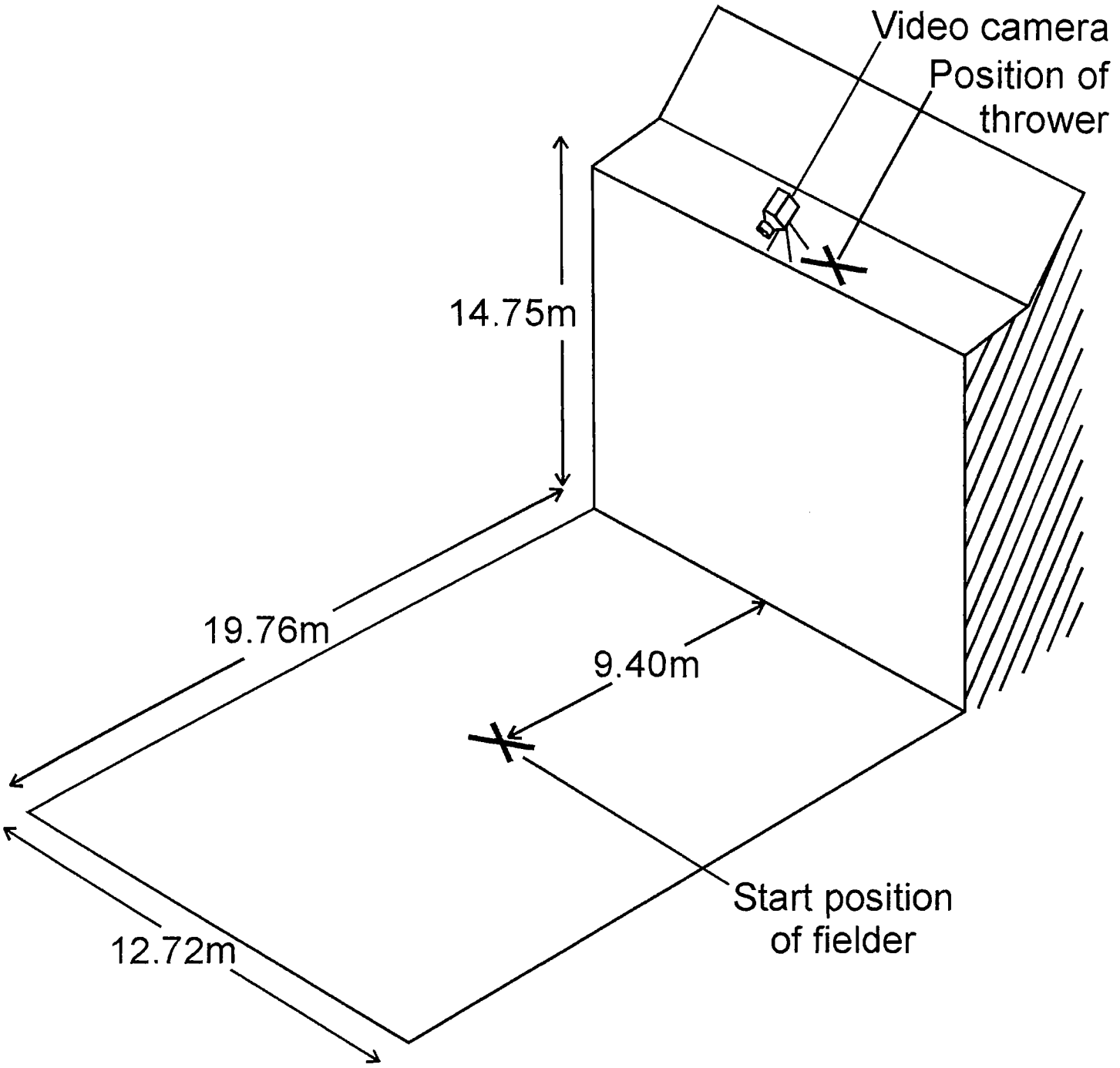


Fig. 9.1 Experimental set-up (approximate scale).

Trials began with subjects stood at the start position, at a distance of 9.40m away from the building. The camera shutter speed was set at its fastest level, 1/500th of a second, to minimise blur of the ball and fielder on the recorded video footage. The field of view of the camera covered the maximum possible distance that a fielder could run and successfully catch the ball under the conditions of the experiment.

9.2.3.2. Format of catching trials

Subjects each participated in 40 trials. A trial consisted of a ball being launched by the thrower to travel in the same vertical plane as the fielder and to land within the

field of view of the camera. Ball launch was indicated on the video footage using the hand-sweep method that was described in chapter 3. This identified the start of a trial for analysis. Balls were thrown by hand to fly directly over the head of the subject. Valid trials for analysis were those where a fielder ran facing in the same direction of travel as the ball and managed to make contact with the ball before it landed. A trial was considered invalid if either of these conditions were violated. Subjects began trials with their feet parallel to the plane of projection of the ball (in a 'side-on' orientation). Standing with this orientation gave fielders clear sight of the launch of the ball and facilitated the motion of turning and running away from the projection point, increasing the chances of recording a valid trial. Fielders chose whether to begin standing looking over their left or right shoulder depending on whichever felt most comfortable.

9.2.3.3. Recording of fielder movement

Fielders' movements were recorded using Vidi-Clik. The manipulations and assumptions used to convert Vidi-Clik co-ordinates to true positions in chapter 3 (and explained fully in appendix 1 were applied to the Vidi-Clik co-ordinate position of the fielder in this experiment. Movement recording began the frame after the hand-sweep had appeared on the video footage. In each subsequent frame, the position of the fielder was recorded by positioning the cursor at the top of the fielder's head and clicking the left mouse button. Recording ended when the fielder made contact with the ball. In this final frame, the cursor was also positioned over the ball to record its position. This gave X-Y co-ordinates for the fielder in each frame of footage and the ball in the final frame. These were converted into true positions using the appropriate transformation.

9.2.3.4. Ball position

The position of the ball throughout its trajectory was estimated using the iterative computer program that calculated the best fit to the trajectory for each trial. The program used the duration of flight, a gravitational constant, a drag factor (applying the assumptions used by Brancazio (1985)), and the start and end position of the ball to simulate trajectories. The accuracy of this method is explored in appendix A1.3.

9.3. Results

The 6 subjects received a total of 240 trials. Owing to the difficulty of the task, only 41 trials (17.1%) were valid.

9.3.1. Trajectories

9.3.1.1. Performance of trajectory estimation program

As in chapters 3 and 4 the performance was of the trajectory estimation program was assessed using the difference between the position of the ball as predicted by the program and the estimate of its true position using Vidi-Clik.

	N	Mean	Minimum	Maximum	SD
Error (cm)	41	0.46	0.07	1.17	0.32

Table 9.1.

9.3.1.2. Trajectory parameters

There was a characteristic (and unintentional) difference between trajectories in session 1 and those in session 2. Accordingly, the trajectory parameters for each session are presented separately in table 9.2. The first two columns indicate launch

properties whilst the third column ('Ball distance') refers to horizontal distance between the launch point and the interception point.

Session		Launch vel.(m/s)	Launch angle(°)	Ball distance(cm)
1	Mean	9.15	29.6	1565
(N=28)	SD	0.71	9.82	97.4
2	Mean	8.98	-3.97	1375
(N=13)	SD	0.40	3.54	41.7
Total	Mean	9.10	18.9	1504.6
(N=41)	SD	0.63	17.9	122.2

Table 9.2.

The interceptive behaviour of the fielder was qualitatively similar across the two sessions. However, table 9.2 shows that the fielders in session 1 were intercepting balls on a longer and higher trajectory than those in session 2.

9.3.2. A typical trial

Figure 9.2 illustrates the features of a typical trial. The main graph shows how the fielder moved to catch the ball. The circles represent the location of the ball, starting from the launch position at the top of the building on the left. The crosses indicate the position of the fielder. For clarity of the graph, positional information of ball and fielder was sampled every 0.12seconds (every third frame). The inset graph shows a trace of how tan α varied with time for that trial (using all data points).

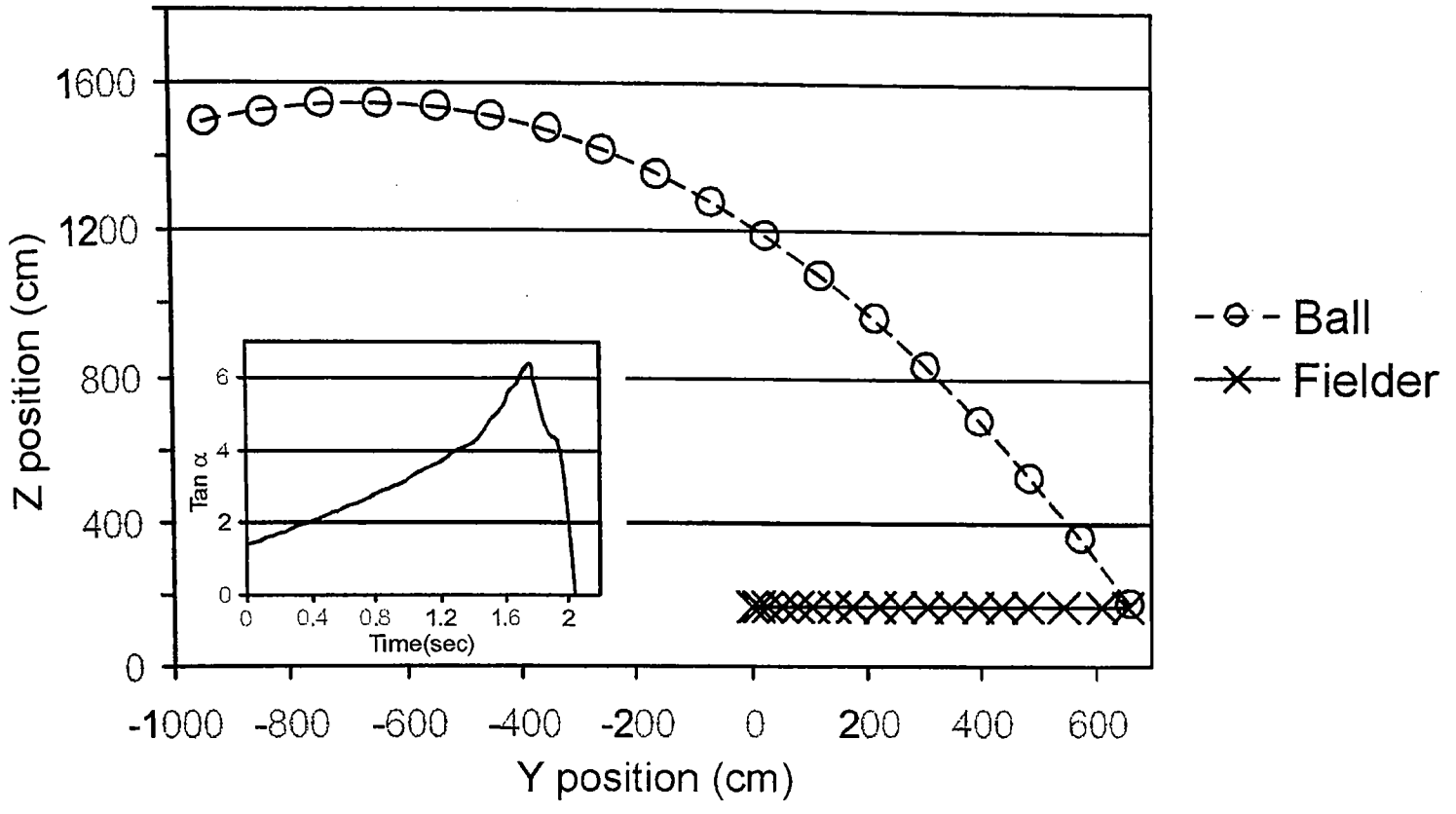


Fig. 9.2 The procession of a typical trial.

The graph of tan α vs. time reveals much about the relative position of fielder and ball over the course of the trial. Tan α rose at an approximately constant rate for the first two-thirds of the trial, then the rate increased and tan α peaked at approximately 1.7s. At 1.7s, the ball came past the fielder and tan α fell dramatically from that moment on.

9.3.3. Descent of tan α

As expected, given the nature of the task, tan α decreased at some point in all trials. Table 9.3 summarises the peak values of α in degrees and the time before the catch was made that the peak values were reached.

	N	Mean	Min.	Max.	SD
Peak value of α(deg)	41	80.2	72.3	89.5	3.9
Time before catch(sec)	41	0.40	0.08	0.88	0.21

Table 9.3.

9.3.3.1. Peak tan α and prehensive behaviour

The mean time before the catch at which tan α began to decrease was 0.40seconds. It would have been of interest to examine whether the point at which tan α began to decrease coincided with the onset of symmetrical hand movements in readiness to catch (prehensive behaviour). However, the fielder ran to catch the ball facing away from the camera so it was not possible to observe the frame in which prehensive behaviour began. It is possible to use data regarding onset of prehensive behaviour from previous experiments (chapters 3 and 4) for comparative purposes. Table 9.4 shows that the onset time of prehensive behaviour prior to catching found in the previous experiments shows a very similar pattern of results to that for the time of peak tan α in this experiment.

Time before catch(sec)	N	Min.	Max.	Mean	SD
Peak tan α	41	0.08	0.88	0.40	0.21
Prehensive behaviour onset	340	0.04	0.96	0.44	0.19

Table 9.4.

This suggests that fielders might control their movement so that tan α continues to increase until the moment at which they begin prehensive behaviour. From that point on, fielders' movements are guided by cues other than optical acceleration.

9.3.4. The increase to peak α

The typical peak value of α was around 80°. That this value is not 90° reflects the technique of fielders looking over their shoulder to track the ball. Fielders rarely chose the more awkward technique of tilting their head back between the shoulder blades and looking directly upwards whilst running forwards. In order to fixate the ball over the shoulder, the ball must be displaced from the sagittal plane of the fielder's body and this displacement prevents α reaching 90°.

9.3.4.1. Regression models of tan α vs. time

The task in this experiment caused tan α to decrease at some point during interception. The previous section revealed that tan α peaked before decreasing in the final moments before the catch. A multiple regression technique was used to investigate the increase in tan α from release of the ball until its peak. The peak value of tan α was taken as $(\tan \alpha)_t$, where $(\tan \alpha)_t$ is the first frame of a trial in which $(\tan \alpha)_t > (\tan \alpha)_{t+1}$ and t is the frame number. Linear and quadratic regression models were computed to fit the variation of tan α against time for each trial. Both models provided good fits to the data, illustrated by the typically high r^2 scores (see Table 9.5).

Model	N	Mean	Min.	Max.	SD
r^2(linear)	41	0.91	0.20	1.00	0.19
r^2(quadratic)	41	0.95	0.39	1.00	0.13

Table 9.5.

There were infrequent occasions when r^2 was poor for both the linear and quadratic models (N.B. the minimum values for r^2(linear) and r^2(quadratic) shown in table 9.5 were for the same trial). These poor fit statistics were observed for trials

where tan α increased approximately linearly for the majority of the trial before increasing dramatically as tan α reached a peak value as a result of α nearing 90°. These two distinct phases of tan α variation prevented both the linear and the quadratic regression models from producing a good fit.

Although the mean r^2 value for the linear regression is high, it is lower than the values found in the experiment conducted in chapter 4. In a simpler catching task, subjects tended to move so that tan α could be modelled using linear regression that gave an r^2 value of typically 0.98. F-tests were conducted to assess the significance of the improvement in fit observed by increasing the number of terms in the regression model. It was found that a quadratic model provided a significantly better fit to tan α vs. time in 40 of the 41 trials. Furthermore, in 39 of the 40 trials with significant curvature, the sign of the squared term in the quadratic model was positive, indicating that $d^2(\tan \alpha)/dt^2$ tended to be positive. Since fielders do not appear to be moving so that they cancel optic acceleration, it is possible that they are using an alternative cue under the more difficult circumstances presented in this experiment. That tan α should consistently increase at an increasing rate suggested the possibility that there was linear variation in α rather tan α in each trial. Consequently, an identical multiple regression analysis was performed on α vs. time up to the time of peak tan α (time of peak tan $\alpha \equiv$ time of peak α). The fit of the linear model was indeed better for α vs. time compared to tan α vs. time, indicated by a mean r^2 value for the linear models of 0.96 (cf. 0.91 for tan α vs. time). However, F-tests established that the quadratic model significantly improved the fit in 39 of the 41 trials, suggesting that α is also not increasing with perfect linearity. The sign of the squared term in the quadratic models was negative in 38 of the 39 significant models. Whilst tan α seems to increase at an

increasing rate, α appears to increase at a decreasing rate and is no more predictive of fielder behaviour than tan α.

9.3.4.2. Qualitative assessment of tan α vs. time

Plots of tan α vs. time were constructed for all trials. It appeared an initial steady increase in tan α was ubiquitous. However, after approximately 1second, the rate of increase of tan α could vary greatly across trials. This is illustrated in figure 9.3.

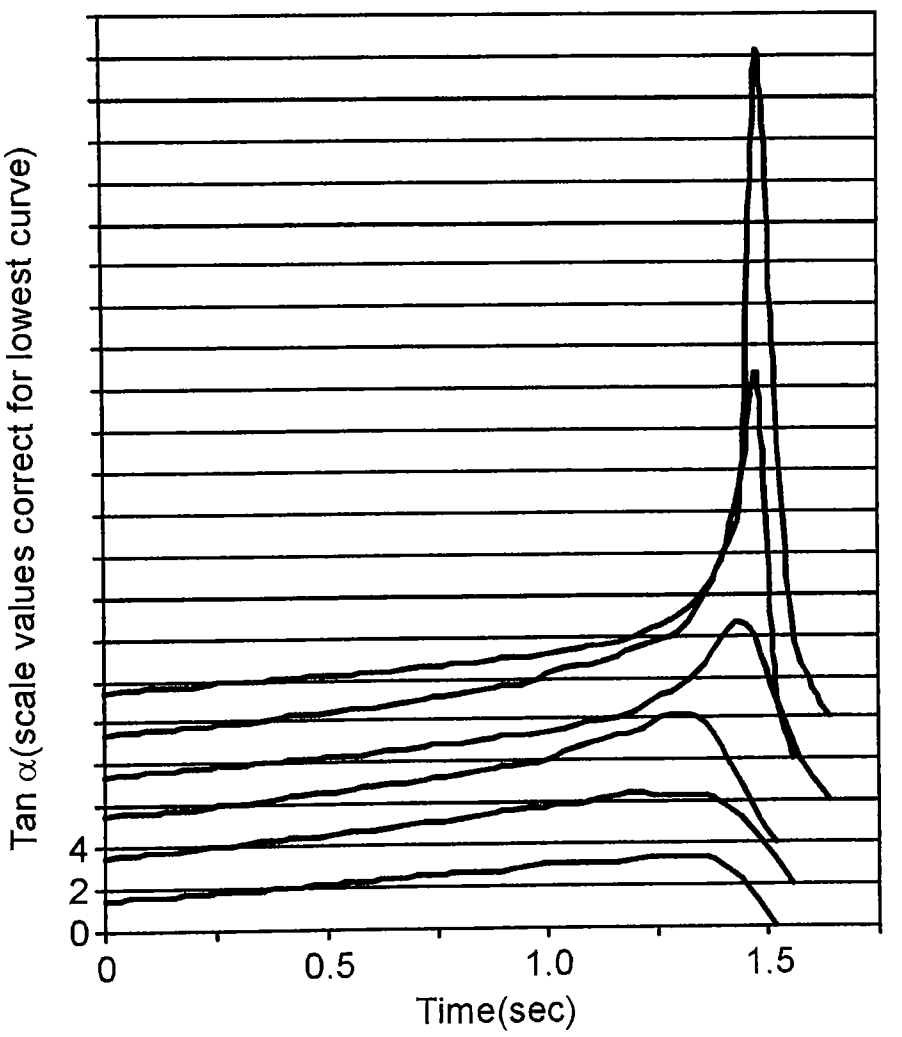


Fig. 9.3 A 'family' of curves showing tan α variation for 6 different trials. Data for each trace was sampled every 0.04 seconds (information from every analysed frame of video footage was used). Note that for clarity, each trace was slightly displaced in the Y-axis.

Figure 9.3 illustrates how tan α could continue to increase at a steady rate to a plateau and then decrease rapidly to 0. However, after 1second in another trial, tan α could increase at a rapidly increasing rate to a severe peak before collapsing to 0. The observation of variation in the rate of increase of tan α across trials led to the hypothesis that the peak value of tan α may be correlated with some measure of trial difficulty. More difficult trials allowed the fielder less margin to manoeuvre to a comfortable position to take the catch and the fielder must remain near to the plane of trajectory of the ball. This will cause tan α to accelerate to a sharp peak as the ball goes overhead. Less difficult trials allowed the fielder time to move outside the plane of trajectory of the ball to take the catch in a more comfortable side-on position. In this situation tan α will increase at a steadier rate. This measure of trial difficulty was estimated as the horizontal displacement (in the X-axis) of the ball relative to the fielder at the moment of peak tan α. The calculated values were normalised to ensure fair comparison of trials in which the ball passed left of the fielder's head with those that passed to its right and are shown in table 9.6.

	N	Mean	Min.	Max.	SD
Difference in X at peak tan α(cm)	41	36.0	1.26	75.5	17.8

Table 9.6.

The correlation between the peak value of tan α and the horizontal displacement of the fielder from the position of the ball at that peak value was calculated. It proved to be highly significant (Kendall's $\tau = -0.42$, $p < 0.001$). A significant negative correlation confirms that the greater the peak value of tan α, the smaller the displacement of the ball from the fielder in the X-axis. This result was somewhat expected since the horizontal displacement of the fielder from the plane of the ball has

a direct effect on the value of α. A further relationship was established between the linear regression models of tan α vs. time and the fielder's displacement relative to the ball in the X-axis. There is a highly significant positive correlation between displacement in X and r^2 for the linear model fit to tan α vs. time (Kendall's τ = 0.365, $p < 0.002$). It appears that tan α is more linear when the displacement between fielder and ball is larger. The correlations involving displacement in X (as a measure of difficulty) and tan α may be slightly misleading since this distance is directly related to the calculation of tan α. Therefore, an independent measure of trial difficulty was calculated. For each trial, the average speed required to reach the interception point was calculated, based on the assumption that a more difficult trial will require a greater average speed. Repeating the correlation calculations revealed that average speed showed no significant correlation with the peak value of tan α, displacement in X or r^2 for the linear regression model to tan α vs. time ($p > 0.1$ in each case. See appendix A9.1 for full details).

9.4. Discussion

9.4.1. Trial validity

The low return of valid trials from all ball launches illustrates the difficulty of the task. Only 17% of ball-launches yielded valid trials in this experiment. Compare this with the 59% valid trials observed in the similar task performed by the same subjects in chapter 3. Session 2 yielded fewer valid trials than session 1. The main (and unintentional) difference between the two sessions was the launch angle of the ball. In session 1, the ball was projected with a positive component of vertical velocity, giving a positive launch angle. By contrast, in session 2, balls were projected with minimal vertical velocity, giving a launch angle close to 0° (horizontal). Overall

launch velocity was similar across the two sessions with the result that the ball travelled a shorter distance and was in the air for a shorter duration in session 2. This provides a likely explanation for the discrepancy in the number of valid trials across the two sessions. The reduction in flight duration in session 2 gave fielders less time to reach the ball, making catches harder.

9.4.2. The fall of tan α

Previous work in this thesis (chapters 3 and 4) and elsewhere (Michaels & Oudejans (1992), McLeod & Dienes (1996)) has shown that fielders intercepting a projectile tend to run so that tan α increases at a constant rate until the final moments before interception. This experiment was conducted to investigate what would happen to interceptive behaviour in a situation where tan α must decrease for the fielder to catch the ball. It was found that the point at which tan α began to decrease was very late in the procession of a trial. Although the point at which prehensive behaviour began could not be recorded in this experiment, the point at which tan α began to decrease appeared conspicuously similar to the time of onset of prehensive behaviour found in previous experiments. This suggests that the fall of tan α may represent the onset of prehensive behaviour, at which point fielders use cues other than tan α to guide their subsequent interceptive behaviour. This supports a strategy where a fielder moves so that tan α increases until the final moments before a catch when other cues are exploited to guide the fielder's hand(s) to the ball.

9.4.3. The rise of tan α

Regression models were fitted to tan α vs. time up to the peak value of tan α. These showed that linear models fitted the data well (mean $r^2 = 0.91$). This lends supports to the proposal that a fielder runs to cancel optical acceleration until the final

moments before the catch. However, it was found that quadratic regression models were usually significantly better than their linear counterparts, suggesting curvature of tan α vs. time. Furthermore the quadratic regression models tended to have a positive squared term, indicating positive acceleration of tan α. This is an unsurprising result. The ball travels over the head of the fielder and this causes positive optical acceleration and provides a cue to the fielder that he must move further backwards to intercept the ball.

It would be unwise to utterly reject interception strategies based on optical acceleration cancellation (OAC) after discovering a tendency of fielders to observe of positive optical acceleration in this experiment. Remember these trials test the extremes of fielders' interceptive capabilities. It is not wholly incompatible with OAC models since it might be expected that at the boundaries of performance, a slight positive acceleration (or negative for running forward to catch) might be observed. The fielder may apply maximum effort attempting to cancel optical acceleration and, although he cannot maintain optical acceleration cancellation throughout the flight of the ball, he just manages to be in range of the ball to catch it. This is supported by the excellent fit observed for the linear regression models, suggesting that OAC may indeed be guiding performance.

The improvement in fit of the regression models to α vs. time reflects the more consistent change in α, in contrast to tan α, as α nears 90°. Above 80°, tangents of angles increase enormously as they approach ∞ at 90°. This had a distorting effect on tan α vs. time, reducing the quality of fit of the regression models. It is therefore unlikely that α was used as a cue to interceptive behaviour in preference to tan α.

9.4.4. Determinants of the rate of tan α increase

During this experiment the increase in tan α over time was shown to vary across a family of curves that illustrated the variation in the form of tan α vs. time from trial to trial. Tan α was consistently observed to begin increasing at a steady rate until about two-thirds of the way through a trial. Subsequently, tan α could continue increasing at a steady rate before reaching a plateau and then decreasing rapidly. Alternatively, it could increase at a greatly increasing rate up to a sharp peak before falling dramatically. Investigation was carried out as to what might underlie this variation in the form of tan α vs. time across trials.

The correlations found involving the displacement in the X-axis of the fielder from the ball were of interest because it is possible to regard this measurement as an estimate of trial difficulty. For less difficult trials, a fielder could move outside the plane of trajectory of the ball, track the ball over his shoulder and take a relatively comfortable catch to his side. In more difficult trials, the fielder had no time to move outside the ball's trajectory plane and had to track the ball with his head in a more extreme position, tilted back and looking upwards. As the ball passed overhead, an attempt at catching could be made, the fielder stretching his arms out in front of him. Clearly this estimate of trial difficulty is limited – if a fielder were to run orthogonal to the plane of trajectory of the ball then his displacement from that plane would be large at the peak value of tan α. However, it would prove an extremely difficult task to reach the interception point from that point onwards. Nevertheless, within the context of this experiment and assuming that fielders were making every effort to catch the ball, this estimate of trial difficulty appears valid.

The first correlation calculation showed that displacement in X was negatively correlated with the peak value of tan α. This is not an altogether surprising result

since the distance between fielder and ball in the X-axis is involved in the calculation of tan α. However, a related (but perhaps more pertinent) correlation was found between r^2 for the linear regression model of a trial and the displacement of the fielder in the X-axis from the ball at peak tan α. The correlation showed that tan α vs. time tended to be more linear when displacement in X was greater. This linked the difficulty of a trial to the form of tan α variation. It was hoped that an independent measure of trial difficulty, such as the speed required for the fielder to reach the interception point, would corroborate this result. However, attempts to find an independent measure that correlated with the displacement in the X-axis at peak tan α proved fruitless. Furthermore, the average speed required to reach the interception point is not necessarily a true measure of trial difficulty. It does not take into account the fact that human acceleration is non-linear so a greater average speed over the entire duration of a trial may not necessarily that it was more difficult.

This leaves a somewhat confounded argument. If there was a small displacement in X at peak tan α, a trial was regarded as difficult. If a trial was difficult, the fielder could not move outside the plane of the trajectory of the ball to make the catch more comfortable and so tan α increased at an increasing rate. Although unsatisfactory, evidence that displacement in X was linked to trial difficulty comes from the video footage of trials. When the ball travelled directly over the head of a fielder (their displacement in X was smaller), they seemed to run harder attempting to catch the ball. The issue of trial difficulty could be resolved by asking subjects to rate trial difficulty after each catch.

9.5. Conclusion

Fielders appear to run to catch a ball so that optical acceleration is cancelled as effectively as possible when the ball is projected so that it will fly over their heads. Fielders in this experiment tended to move outside of the plane of trajectory of the ball to track the ball in a more comfortable position, looking over their shoulder. Doing so ensured that tan α would increase at an approximately constant rate. The catch could then be taken to the fielder's side. In more extreme cases, the fielder could not move outside the trajectory plane of the ball and yet he still reaches the interception point. This is the most difficult type of catch and causes the rate of change of tan α to increase rapidly as the ball passes overhead. Tan α only begins to decrease in the final moments before the ball is caught. This is possibly linked to the switch to prehensive behaviour that engages alternative cues to guide action and interception.

In summation, this experiment was designed to investigate what happens when tan α must decrease but the results suggest that fielders tend to produce locomotion towards the interception point that causes tan α to increase until prehensive behaviour can be engaged. This suggests that even in exceptional circumstances, interceptive behaviour is guided by controlling the increase in tan α.

10. Conclusions and general discussion

10.1. The LOT strategy and alternatives

The aim of this thesis has been to extend knowledge of how humans, when watching a projectile, use the visual information that is available to them to guide their movements to intercept the target. The first three experimental chapters examined how interception is achieved by a fielder who must run in two dimensions to reach the target and showed that the widely cited Linear Optic Trajectory (LOT) strategy, proposed by McBeath, Shaffer, & Kaiser (1995), is not a convincing model of this behaviour. In the fourth experimental chapter, alternative models were tested and one was found to improve upon the LOT interception strategy but still did not appear to provide a definitive explanation of human interceptive behaviour.

10.1.1. Misconceptions about the OAC theory

In setting out their LOT model, McBeath, Shaffer, & Kaiser (1995) raised several criticisms of models of interception based on optic acceleration cancellation (OAC), advocated by e.g. Michaels & Oudejans (1992), McLeod & Dienes (1996). Chapman (1968) proposed the idea that a fielder might run so that he cancelled the optic acceleration of a projectile in order to get to the right place at the right time to catch it. His work was purely mathematical in approach, focussing on imaginary 'fielders' moving to catch in the vertical plane linking their position with the projection site and assuming parabolic projectile trajectories. Brancazio (1985) suggested that air resistance on the ball causes sufficient deviation of its trajectory from parabolic that Chapman's hypothesis was invalidated. However, studies by Michaels & Oudejans (1992) and McLeod & Dienes (1996) that examined the movement of real fielders demonstrated the robustness of cancellation of optic

acceleration as the cue to interceptive behaviour. McBeath, Shaffer, & Kaiser (1995) suggested that their LOT model was a more appropriate description of human interceptive performance. In their critique of models based on OAC, they appeared to demonstrate misconceptions about how a fielder cancelling optic acceleration would move to catch a ball when they were required to move in two dimensions to make a catch. Much of the evidence that McBeath, Shaffer, & Kaiser claim to support the LOT model over the OAC model derives from their belief that a fielder following an OAC strategy will run in a straight line towards the interception point when moving in two dimensions to make a catch. Interestingly, Tresilian (1995) also suggested that OAC models should yield straight-line paths. Tresilian argued that, to extend Chapman's model to account for interception in two dimensions, a second control action must be added that moves the fielder toward the vertical plane of the ball's motion. McBeath, Shaffer, & Kaiser (1995) stated that, using the OAC model, a fielder maintains horizontal alignment with the ball whilst simultaneously holding $d(\tan \alpha)/dt$ constant. This will indeed yield straight running paths if one assumes that the fielder utilises the cue provided by $d(\tan \alpha)/dt$ and that provided by the ball's movement out of alignment with the fielder at precisely the same time. This is certainly a questionable assumption. I contend that a model of interception can be based on OAC without the fielder necessarily having to run in a straight line. In support of this belief are the results of the experiments in chapters 3 and 4, in which fielders ran experiencing constant optic velocity and tended to follow characteristic curved paths. Whether running forwards or backwards to make a catch, fielders tended to show greater lateral acceleration in their initial movement, therefore producing concave running paths when running forward and convex running paths when running back, relative to the point of projection. Furthermore, regression

analysis of the curvature of running paths of fielders across blocks of trials showed that, even though fielders ran to the same interception point for each trial, their running path remained curved. One might expect that after a few trials the fielder merely learnt the location of the interception point and ran in a straight line to it but this did not occur and the fielder appeared to use the same strategy throughout, producing typically curved paths. This behaviour is consistent with an interception strategy where the cue to lateral movement is acted upon earlier than the cue to movement in depth. The depth movement cue is $d^2(\tan \alpha)/dt^2$ which presumably requires more processing time than the lateral cue – whether the ball has moved out of lateral alignment. It is therefore unsurprising that running paths tended show this curvature. This hypothesis is also entirely consistent with the running path data presented by McBeath, Shaffer, & Kaiser (1995).

A related misconception of the OAC model, upheld in McBeath, Shaffer, & Kaiser (1995), is that fielders run at constant speed to the interception point. It is true that in Chapman's mathematical analysis of fielder behaviour, he proposed that the interceptor would move at a steady rate toward the catch position whilst cancelling optic acceleration. In reality, this would present some problems to the fielder. Firstly, it is unclear how a fielder would determine the correct constant speed at which to run without knowing exactly when and where the ball was going to land and secondly, the fielder's acceleration is unaccounted for within this framework. However, McLeod & Dienes (1996) showed that fielders displayed different speed functions depending on how far they had to run to catch the ball but in each case they ran so that $d^2(\tan \alpha)/dt^2$ was zeroed. McLeod & Dienes suggested that Chapman's constant speed formulation was a special solution where fielders run so that $d(\tan \alpha)/dt$ is held at a particular constant value that yields constant running speed. They argued that a fielder may keep

any value of d(tan α)/dt constant since doing so will ensure that they reach interception point at the correct time. The particular value of d(tan α)/dt chosen will determine the speed function that the fielder follows but will not necessarily result in a constant running speed. McLeod & Dienes' less strict definition of Chapman's hypothesis appears to model fielder behaviour more accurately and contradicts McBeath, Shaffer, & Kaiser's suggestion that OAC necessarily results in constant running speed. It is the OAC model as defined by McLeod & Dienes that was compared to the LOT model in analyses within the thesis.

As a corollary to the argument about the shape of running paths using the OAC model, in chapter 5, evidence was produced that seemed to contradict the prediction made by McBeath, Shaffer, & Kaiser (1995) about the shape of running paths produced by the LOT model. They stated that running paths using the LOT strategy would curve outwards with a $\cap$-shaped speed function. In chapter 5, the optic trajectory of a simulated fielder on a constant-speed, straight-line approach to the interception point was analysed. It was found that the fielder experienced an optic trajectory that was more linear than those used by McBeath, Shaffer, & Kaiser (1995) to claim linearity of the optic trajectory of real fielders in their experiment. The suggestion was made that fielders approaching the interception point on a reasonably direct route will experience an optic trajectory that will be approximately linear. This approximate linearity explains the good fit that McBeath, Shaffer, & Kaiser (1995) reported for linear regression models to plots of the optic trajectory.

10.1.2. Failings of the LOT model

The experiments presented in chapters 3 and 4 required skilled fielders to make catches running in two dimensions to reach the interception point. Analysis of their movements revealed aspects of their interceptive behaviour that were inconsistent

with the LOT model. For the optic trajectory to be linear, the fielder must run to hold the angle of the optic trajectory, Ψ, constant. If Ψ (and therefore tan Ψ) is being held constant, tan α and tan β must vary in proportion with one another since tan Ψ is defined by the ratio (tan α)/(tan β). However, although tan α always increased at a constant or very near constant rate, the variation in tan β could change from trial to trial. There was certainly no clear tendency for tan β to change in proportion with tan α. McBeath, Shaffer, & Kaiser (1995) claimed that the cue fielders use to guide their running is curvature of the optic trajectory. This was examined by looking at the regression of tan α on tan β and determining its curvature in the time before the fielder reached a critical running speed. For motion in depth, the optic trajectory tended to curve downward and therefore only provided an accurate cue to motion in depth when the fielder had to move forwards to make a catch. Examination of tan α vs. time, the cue for OAC models, showed that it was a valid cue to interceptive behaviour in over 90% of trials. The fact that it was not a legitimate cue in 100% of trials when Chapman's mathematical analysis suggests it should be is of interest and is discussed later in section 10.8.7. Examining curvature of tan α on tan β as a cue to lateral movement showed that, again, the tendency was for the optic trajectory to curve downward. The initial cue to lateral movement for the LOT strategy must be the direction in which the optic trajectory sets off rather than its curvature. The curvature itself can only become relevant to lateral control once the fielder is running toward the interception point. However, this leads to another dilemma for the LOT model. The optic trajectory can vary in one dimension, it can curve up or down. However, a fielder catching a ball launched in an unaligned projection plane requires a cue to guide their motion in two dimensions. In chapter 5, the optic trajectory that would be experienced by a stationary and moving fielder was analysed to investigate

what cue it might provide. It was found that the optic trajectory uniquely specified the landing location of a projectile but its curvature did not provide a valid cue to the whereabouts of this location. A simulated fielder was forced to move at constant speed to various positions around the interception point. It was found that the optic trajectory would only curve upwards when the fielder's lateral movement would take him beyond the interception point. Although this suggests that curvature of the optic trajectory does provide a valid cue to lateral movement, it also explains why fielders in the experiments of chapters 3 and 4 tended to experience downward curvature of the optic trajectory. Fielders tend not to run at a speed that will take them beyond the interception point so the optic trajectory will tend to curve downwards. This tendency was also found in the simulation study in chapter 5. A reason for this consistent downward curvature was proposed. If a fielder is not running fast enough to reach a ball that will land in front of him, $d(\tan \alpha)/dt$ will decrease whereas $d(\tan \beta)/dt$ will continue to increase. If a fielder is not running fast enough to reach a ball that will land behind him, $d(\tan \alpha)/dt$ will increase but $d(\tan \beta)/dt$ will increase faster because β can increase to an obtuse angle whereas α cannot. In each case, $\tan \beta$ (the denominator in the ratio defining the optic trajectory) grows faster than $\tan \alpha$ (the numerator). Therefore, $\tan \Psi$ decreases and the optic trajectory curves down.

In their paper, McBeath, Shaffer, & Kaiser (1995) presented graphs of α against β to demonstrate the constancy of Ψ. In response to technical comments on their paper, they suggested that the ratio α/β was a better representation of the optic trajectory. However, since they claim that the optic trajectory angle, Ψ, derives from $\tan \Psi = (\tan \alpha)/(\tan \beta)$, they should have plotted $\tan \alpha$ against $\tan \beta$. To check that the failings of the LOT model reported in the presented experiments were not due to conducting analyses using the tangents of the visual angles rather than the angles

themselves, linearity of the ratio α/β was tested. Plots of α against β showed the same characteristic downward curvature displayed by plots of their tangents. Corroborating this result was the analysis that showed the plots of α against β in McBeath, Shaffer, & Kaiser (1995) and Shaffer & McBeath (2002) used to show linearity of the optic trajectory did in fact show significant curvature. A final blow to this derivation of the LOT model was that α/β tended to be linear in the initial stages of catch and grew increasingly non-linear as the fielder neared the interception point. This is the diametric opposite of what McBeath, Shaffer, & Kaiser (1995) would predict.

The LOT model is not an accurate model of human interceptive performance. McBeath, Shaffer, & Kaiser (1995) showed that it is a mathematical solution to the outfielder problem and found some empirical support for its use. Although the optic trajectory experienced by fielders appeared linear (regression showed typically high r^2 values for the fit of a linear model), more detailed analysis showed that a curvilinear regression model significantly improved fit to the optic trajectory. Their rejection of solutions based on OAC appears grounded in false assumptions about the behaviour that a fielder guided by OAC may exhibit. Combining the vertical visual angle, α, with the lateral visual angle, β, into the single stimulus represented by the optic trajectory appears an elegant solution to the outfielder problem. However, analyses suggest that fielders do not attempt to run so that the optic trajectory is linear and that its curvature does not always provide a valid cue to the correct course of action. Given these issues, alternative strategies were proposed that guided a simulated fielder to the interception point. The evidence that fielders run so that they null optic acceleration appears incontrovertible. Therefore the new strategies were all based upon the supposition that centred directly below the ball at any point during its flight there is a circle that delineates all the positions at which a fielder could stand to

observe constant d(tan α)/dt. This circle shrinks as the ball nears the ground, thus guiding the fielder nearer and nearer the ball. Since standard video equipment was used, the positional data for the ball and fielders movements was estimated at 0.04second intervals. At each interval, the radius of this circle can be calculated using the height of the ball above the fielder's eye. The proposed strategies move the simulated fielder to a particular point on the circle at each interval. They are therefore mathematical solutions to the outfielder problem. However, it is the difference between where on this ring that they place the fielder that determines how good they are at modelling the behaviour of real fielders.

10.2. Alternative strategies

Four different strategies were proposed and compared to the LOT strategy in their ability to model the behaviour of fielders catching balls launched on a variety of trajectories. The LOT strategy was first compared to a version of the constant δ strategy in chapter 3. The LOT strategy was found to be less effective than the constant δ strategy but neither seemed to fully capture how fielders moved to intercept the ball. Improvement in the modelling of both models and the proposal of new models came with the use of the constant d(tan α)/dt rings described above. The use of more refined coding also aided the development of more effective strategies. No explicit direction was included in the new programs to ensure that lateral motion began prior to motion in depth, as it was for the simulation of the constant δ strategy in chapter 3. Therefore production of running paths that curve in the appropriate direction was down to whether the strategy was an accurate reflection of human interceptive behaviour. The programs implementing the strategies were initially run with fixed values for maximum speed and acceleration of the simulated fielder and

initiated at exactly the same time for each trial. This yielded unsatisfactory performance so these values were varied from trial to trial to improve the fit of the running path taken by the simulated fielder to that taken by the real fielder. The validity of this optimisation process is considered in section 10.3. The performance of the strategies examined in chapter 6 in their pre-optimised and optimised forms is discussed here in reverse order of effectiveness.

10.2.1. Constant γ strategy

The poorest of the modelled strategies was unique in that the additional control variable to determine lateral movement was based on the horizontal angle between the direction of the ball from the fielder and the direction in which the fielder was running. This angle was termed γ. None of the other strategies used the direction of running as a determinant of their interceptive behaviour. The simulated fielder moved to hold γ constant and $d(\tan \alpha)/dt$ constant. The path taken by the simulated fielder rarely matched that taken by the real fielder. By holding γ and $d(\tan \alpha)/dt$ constant he could be sent in the incorrect direction in depth and then end up in a position where he was unable to keep $d(\tan \alpha)/dt$ constant and therefore could not reach the interception point. Although the real fielder often ran so that γ was constant in the final third of a trial, in the early stages of a trial he tended to move so that γ increased. Given the performance of the simulated fielder, this must be an essential feature of the real fielder's interceptive behaviour. The suggestion was made that the constant γ that was observed for the real fielder in the latter stages of a catch is the result of a different control strategy for lateral motion. Optimisation of parameters was attempted but did not significantly improve the strategy. The particularly poor

performance of the constant γ strategy led to its rejection as a possible model of human interceptive performance.

10.2.2. Conserved alignment strategy

In this strategy the fielder moves laterally to catch up with the ball whilst nulling $d^2(\tan \alpha)/dt^2$. He attempts to restore the alignment that existed between him and the ball at launch and therefore must initially move faster than the ball laterally before slowing to match its lateral velocity. This strategy was suggested because the rapid initial lateral movement of the fielder would produce running paths that curved in the typical manner. It was more considerably efficient than the constant γ strategy and usually got the fielder to the interception point in time to catch the ball. However, the paths taken by the simulated fielder tended to show excessive curvature. Like the constant γ strategy, for the simulated fielder to maintain constant $d(\tan \alpha)/dt$ he often had to move in the incorrect direction in depth. This is inefficient behaviour and would restrict the fielder's zone of successful performance. Optimisation of parameters significantly improved the fit of the strategy to that of the real fielder. Reducing the maximum speed and acceleration of the simulated fielder prevented him from gaining alignment with the ball too quickly, thus reducing the exaggerated curvature of the running paths. However, the conserved alignment strategy was still significantly poorer than the other strategies as a result of running paths that displayed excessive curvature. The outcome of the analysis was that real fielders do not use the original alignment that existed between them and the ball as a cue to their lateral movement when intercepting a ball in an unaligned plane.

10.2.3. Minimum energy strategy

At the outset, this appeared to be an appealing strategy. Evidence has consistently shown that fielders tend to move so that they experience constant d(tan α)/dt (Michaels & Oudejans (1992), McBeath, Shaffer, & Kaiser (1995)). The minimum energy strategy was an attempt to maximise the efficiency with which the fielder achieved constant d(tan α)/dt. As with all the other strategies, the shrinking ring of loci that produce constant d(tan α)/dt was used. At each time interval, the simulated fielder moved from his current position to the nearest position on the next ring (within the restrictions on his movement). It was believed that a 'minimum energy' running path would be the result of moving to the nearest position that cancelled optic acceleration throughout the flight of the ball. It seemed intuitive that a fielder would learn this minimum energy strategy to maximise his zone of successful performance if using constant optic velocity to guide his behaviour.

The performance of the strategy was reasonable but significantly poorer than the either the LOT or constant δ strategies. The simulated fielder often produced some highly unusual running paths that were unlike those followed by the real fielder. It was soon found that although the minimum energy strategy is efficient locally, i.e. moving from one ring to the next, it could produce running path that were inefficient overall because the simulated fielder followed paths that were much longer than those taken by the real fielder. In several trials, the simulated fielder moved to positions where he could not maintain constant d(tan α)/dt and therefore could not reach the interception point. This effect is shown in figure 6.16 in chapter 6. It appears that in order to maximise efficiency of getting to the interception point (which is after all the ultimate goal of a catching strategy), it pays for the fielder to expend slightly more energy nulling optic acceleration than is necessary in the early stages of a catch.

Interestingly, after optimisation of parameters the strategy performed well at producing changes in the lateral visual angles (β and δ). Although the strategy did not perform as well as the LOT strategy in placing the simulated fielder close to the position of the real fielder, it did significantly better in fitting tan β and tan δ to that experienced by the real fielder. It was suggested that since the minimum energy strategy placed no restriction on the lateral movement of the fielder, optimisation of parameters allowed a good fit to be achieved. The LOT strategy did not achieve such a good fit to tan β or tan δ because the position of the fielder is over-specified. The constant δ strategy is equally strict about the lateral position of the fielder but performed better than the LOT strategy (and matched the minimum energy strategy) in fitting tan β and tan δ. This, I believe, is due to the constant δ strategy approximating fielder behaviour better than either the LOT strategy or the minimum energy strategy. It therefore produces a better fit to the lateral visual angles than the LOT strategy and better fit to the running path than either strategy. Despite producing a good fit to the lateral visual angles, the tendency to produce highly irregular running paths invalidates the minimum energy strategy.

10.2.4. LOT strategy

The LOT strategy was included in the analysis to act as a benchmark to which other strategies could be compared. It was proposed by McBeath, Shaffer, & Kaiser (1995) and requires to the fielder to run so that they experience a linear optic trajectory. In doing so the fielder indirectly causes the tangents of the vertical optical angle (α) and the horizontal optical angle (β) to change in proportion with one another. It was initially modelled in chapter 3 and its performance suggested that it could produce a reasonable to fit to the running path of real fielders. The program

used to model the LOT strategy in chapter 6 was a development of this version. In modelling the LOT strategy, the fielder did not respond to curvature of the optic trajectory as prescribed by McBeath, Shaffer, & Kaiser (1995). The simulated fielder was simply guided so that he experienced constant d(tan α)/dt and constant d(tan β)/dt and consequently linearity of his optic trajectory. This implementation of the LOT strategy was consistently better than the three models described thus far and in pre-optimised state, its performance was comparable to that of the constant δ strategy. Using optimised parameters, its performance was significantly poorer than the constant δ strategy. Ostensibly, there was little wrong with the LOT strategy. The simulated fielder gets to the interception point and his running path usually curved in the correct manner. However, it was trials in which the fielder had ample time to reach the interception point that caused the LOT strategy to perform poorly. When catches were easy there was a greater tendency for the real fielder to move so that tan β, the tangent of the horizontal visual angle, decreased. If a fielder is to experience linearity of the optic trajectory, tan β must increase in proportion to tan α. Since d(tan α)/dt is constant, if the real fielder moves so that d(tan β)/dt is decreasing then he is not moving to experience a linear optic trajectory and the LOT model cannot match the real fielder's movements. The variation of the lateral visual angles (β and δ) was relatively unpredictable. There was a greater tendency for β and δ to decrease if a catch was easy, explained by the fielder getting into approaching the plane of projection of the ball. However, fielders often displayed different variation in β and δ for identical trajectories. Despite this variation in the lateral visual angles, the constant δ strategy consistently outperformed the LOT strategy, despite the similarity in their formulation. One must assume that the cue provided by δ is more robust than

that provided β and is likely to be closer to that used by the real fielder. The geometric construction of β is referent to the launch position of the ball. Although β is an indirect product of linearity of Ψ, I would question the validity of a strategy in which the position of the launch site is a vital component. The limitations of the LOT model in simulations and the volume of evidence produced opposing its use leads to the rejection of the LOT strategy as a valid model of human interceptive behaviour.

10.2.5. Constant δ strategy

Chapman (1968) and Dienes & McLeod (1993) suggested that a fielder intercepting a ball in an unaligned plane might move so that the ball was held at a constant lateral bearing relative to his position whilst ensuring constancy of d(tan α)/dt. Their research, however, focussed on interception in the aligned plane and the feasibility of such a strategy for interception in the unaligned plane was not tested. In the constant δ strategy the simulated fielder moves to hold constant the horizontal angle through which he has turned to fixate the ball. Alternatively, this can be seen as the fielder controlling his lateral motion to prevent horizontal movement of the ball on the retina. As such, this is an appealing strategy because if the fielder moves to prevent horizontal motion of the ball, the task becomes equivalent to that for interception in the aligned plane – the fielder must run so that the ball appears to ascend vertically with tan α increasing at a constant rate.

The initial tests of the strategy in chapter 3 suggested that it improved upon the LOT strategy. The program used to execute the strategy was developed further in chapter 6 and again its performance compared favourably with that of the LOT model. In fact, the constant δ strategy has consistently been the most proficient of the proposed strategies. After optimisation of parameters, it was significantly better than

all other strategies in the majority of performance tests. Most importantly, its error placement of the simulated fielder did not differ significantly from the error inherent in estimating the real fielder's true position suggesting it was a good interpretation of the strategy actually used by real fielders to achieve interception. There are grounds for claiming that the constant δ strategy is the definitive model to describe how a fielder runs to intercept a projectile. It is important to recognise however, that this impressive result was achieved using optimised parameters that allowed reduced limits on maximum speed and acceleration for the simulated fielder. The simulated fielder would sometimes be prevented from achieving constant δ by these lowered restrictions on motion and δ would show a steady increase. This greatly improved the model but some might question a 'constant δ' strategy that allowed fielders to show increases in δ. Furthermore, I believe the model could be improved still further if the simulated fielder was allowed to move so that δ could decrease. This often occurred when the real fielder had plenty of time to reach the interception point – the fielder would move into the plane of projection of the ball, possibly to attain a comfortable position to catch with his body behind the ball. Allowing δ to decrease for easy catches is even further removed from the idea of using *constant* δ to guide lateral movement. Therefore, I believe that fielders use an approximate version of the constant δ strategy. If the lateral velocity of the ball is small and the fielder can easily move to control δ then the fielder can choose to approach the interception point how he wishes. He may move into line with the plane of projection causing δ to decrease, he may move so that δ is constant, or he might allow δ to increase and take the catch so that the fielder's sagittal plane is orthogonal to the plane of projection. If the lateral velocity of the ball is high, the fielder will move so that δ is constant to ensure that

d(tan α)/dt is constant, thereby ensuring that he will be in the right place at the right time to catch the ball. If the fielder cannot move fast enough to keep δ constant, he will move laterally as fast as possible to minimise its increase. However, as with all trajectories, he will try to ensure that d(tan α)/dt is constant since this guarantees that he will reach the interception point at the right time. The evidence presented suggests that the fielder uses a strict strategy with regard to tan α, running to ensure that d(tan α)/dt is constant. This is logical because such a strategy is sufficient for interception. The strategy with regard to δ is less strict as there is no sufficient strategy that guarantees interception but, when necessary, the constant δ strategy is applied to maximise the likelihood that the fielder will be able to move so that d(tan α)/dt is constant.

An interesting possibility about the similarity between the LOT and constant δ strategies was noted in chapter 6. McBeath, Shaffer, & Kaiser (1995) reported empirical evidence that fielders tended to observe linear optic trajectories. However it is conceivable that the fielders in McBeath, Shaffer, & Kaiser's experiments were using a constant δ strategy. The trajectories used in their experiments were over much greater distances (around 50m) than those in presented in this thesis (around 15m). As a result, lateral movements of the fielder in McBeath, Shaffer, & Kaiser's experiment would have generated much smaller changes in the lateral visual angle, β. If the fielder were applying a constant δ strategy, β would tend to show a small and steady increase due to the fielder's movement away from the original vertical plane containing the fielder's start position and the ball launch position. Since for small angles $\beta \approx \tan \beta$, the fielder would show constant d(tan β)/dt. This combined with the ubiquitous feature of fielder behaviour, constant d(tan α)/dt, may have led McBeath,

Shaffer, & Kaiser to believe that the fielder used linearity of the optic trajectory. In the experiments presented here, the fielders' movements had a more significant effect on β, to such an extent that linearity of the optic trajectory of the fielder was not supported. It would be interesting to examine McBeath, Shaffer, & Kaiser's data to see if their fielders ran to hold δ constant.

Further support was garnered for fielders' ubiquitous use of constant $d(\tan \alpha)/dt$ to guide their interceptive behaviour from examining the difference in $\tan \alpha$ observed by the simulated and real fielders. For the optimised strategies, the error in fit to the tangents of the visual angles, $\tan \alpha$, $\tan \beta$, and $\tan \delta$, was calculated. The correlation between the error on each tangent and the average speed required to reach the interception point was assessed. The average speed required to reach the interception point can be regarded as a measure of a catch difficulty – the faster the fielder has to run to reach the interception point, the harder the catch. For the three most successful strategies, no correlation was found between error in $\tan \alpha$ and average speed, suggesting the fit to $\tan \alpha$ was as good for easy catches as it was for hard catches. The simulated fielder was guided to run so that $d(\tan \alpha)/dt$ was constant and since the fit to the $\tan \alpha$ variation of the real fielder was good, this feature of the simulations provides support for the use of OAC by the real fielder.

10.3. Optimisation

Optimisation of the parameters used in the models was used to improve their performance. Tresilian (1995) used a similar technique, varying parameters within the McRuer-Krendel operator that governed his interception simulations to adjust its transfer characteristics and improve the performance of the model. Of the strategies presented here, none was convincing using fixed parameters, so the time of strategy

initiation and the maximum running speed and acceleration of the fielder were systematically varied. Also the movement of the real fielder after the initiation of prehensive behaviour was removed from the analysis.

Varying the time of strategy initiation is an intuitive modification. It is likely that there was some variation in the reaction time of the real fielder and since the time of strategy initiation can make a critical difference to the path taken by the simulated fielder it seems valid to allow some variation in the initiation time. The rationale behind the removal of frames where the fielder was engaged in prehensive behaviour also seems perfectly valid. Prehensive behaviour represents the movements made by the fielder to cause hand to meet ball. The interceptive behaviour that is being modelled is intended to cause eye to meet ball. Whilst this is not the ultimate goal of a catching task, it is by using such a strategy that a fielder moves to the interception point at the appropriate time in order to make the catch. Since the interception strategies make no provision for prehensive behaviour it is reasonable to remove from analysis the frames after which prehensive behaviour began. The commencement of prehensive behaviour was assumed to be the frame in which the fielder changed the movement of his hands from those typical of running movements and brought them toward the eventual catch position.

Less intuitive is the variation in the limits on the simulated fielder's motion. By restricting the distance that the simulated fielder could move between each frame interval, limits were applied to the acceleration and speed that the simulated fielder could experience. Prior to optimisation, the limits were reasonably conservative. The maximum value used for running speed was $3.75ms^{-1}$ and that for acceleration was $3ms^{-2}$. The absolute maximum speed and acceleration of the real fielders used in the experiments is likely to be significantly greater. However, the fielder cannot run at his

absolute maximum velocity because he must prepare to make a catch. Furthermore, successful interception of the trajectories was feasible within these limits. Examining the performance envelope of the real fielder revealed that his maximal speed and acceleration did not exceed these values. Support for their use also comes from the observation that, using an appropriate strategy, the simulated fielder was able to reach the interception point in all trials within the proposed limits.

The optimisation process varied the maximum values of speed and acceleration by small decrements, in an attempt to improve the fit of the running path of the simulated fielder to that of the real fielder. Incrementing the maximum values would have been an invalid approach since the real fielder operated within the original limits and therefore so must any model of his behaviour. The rationale behind the reduction in limits on motion was to allow the simulated fielder to behave as the real fielder did – to approach the interception point more slowly, secure that the visual angles are under control. This led to several trials for each model in which the optimal maximum 'running' speed was less than $2ms^{-1}$ and trials in which the maximum acceleration value was a mere $1ms^{-2}$. Although these values seem almost unbelievably low, they maximise performance of the interception models and therefore must be considered relevant. I believe that this effect is a consequence of fielders' non-rigorous use of a lateral movement cue when they can reach the interception point with ease. For an easy catch, a fielder has time to approach the interception point however he chooses within the constraint that $d^2(\tan \alpha)/dt^2$ is held at zero. Consider a ball launched in an unaligned plane that will land a relatively short distance from a fielder. Since the interception point is easy to reach the fielder can comfortably maintain constant $d(\tan \alpha)/dt$. Once the fielder realises that a catch will be easy, he is not forced to apply a rigorous lateral control strategy to ensure that $d^2(\tan \alpha)/dt^2$ is cancelled. There are a

greater number of paths available to him that will null optic acceleration and therefore get him to the interception point in time to catch the ball, which is possibly why the catch seems easier. The fielder may choose to run to the interception point so that he doesn't reach the plane of projection and his hand-eye system is orthogonal to the plane of projection, i.e. he reaches 'in' to the catch the ball from the side of the projection plane. This would cause δ to increase and β to increase at an increasing rate. The only way for a strategy based on constant δ to model this behaviour is to limit the simulated fielder's maximum velocity so that constant δ is not possible to achieve, mimicking the manner in which the real fielder exerts control of δ whilst constantly ensuring that $d^2(\tan \alpha)/dt^2$ is kept at zero.

10.4. Catching and implicit knowledge

The discussion up to this point has concentrated on how a fielder achieves interception. The experiments presented in chapter 7 investigated the degree of awareness that fielders have of the basis of their interceptive behaviour. Subjects were asked to describe how their angle of gaze changed as they watched balls thrown towards them on a variety of trajectories. This was an attempt to discover whether the information that controls interceptive behaviour is stored implicitly, i.e. subjects were unaware of the information that directs their behaviour. Perceptual motor skills have rarely been used to study implicit knowledge, possibly because the information underlying such tasks is often unclear. The task of catching a ball was used to appraise implicit knowledge because the task is familiar to subjects and the basis of action is well understood thanks to studies such Chapman (1968), Michaels & Oudejans (1992), McLeod & Dienes (1996), and the research presented in this thesis. Shanks & St.John (1994) reviewed much of the work that reported evidence in favour

of the existence of separate implicit and explicit information systems and were not convinced that any of the studies had succeeded in establishing that distinct systems were employed. Shanks & St.John suggested that implicit knowledge could only be demonstrated if the test used to determine subjects' awareness of the relevant information satisfied the Sensitivity and Information criteria. These require the test to be sensitive to all of the conscious knowledge that is relevant to performance in the task and that the information to which the test is sensitive is responsible for behaviour in the task. As stated earlier, current research has identified that a fielder intercepting a ball launched in the aligned plane will run to ensure that the tangent of their angle of elevation of gaze will increase at a constant rate. To satisfy the Information criterion, it is clear that subjects' awareness of variation in the elevation of their gaze angle must be evaluated. The progression of the experiments undertaken in chapter 7 was designed to probe subjects' awareness of their gaze angle variation as extensively as possible to maximise the likelihood of recall, thus ensuring that the Sensitivity criterion was satisfied.

In the first experiment, subjects were asked simple questions about how they believed interception was achieved. For example, they were asked how would they know that they needed to move forward to catch a ball that would land in front of them. Subjects failed to mention angle of gaze and those that described a theory of how interception might be achieved based their hypothesis on information that would not be available to a fielder such as the peak of the ball's flight. In the second experiment, subjects were introduced to the concept of angle of gaze and how it can vary. They were asked to describe its variation if they imagined standing at a fixed position watching balls launched towards them on various trajectories. Subjects gave correct responses for balls that would land short of their position or those that would

fly over their head. However, there was a characteristic drop in the accuracy of subjects' responses when it came to describing the angle of gaze variation that they would experience for balls on trajectories that they did not have to move to catch – those that would give constant $d(\tan \alpha)/dt$. Furthermore, subjects tended to give equal confident ratings to all their judgements, whether right or wrong. This satisfies the zero-correlation criterion. Dienes & Altmann (1997) suggested that satisfying the zero-correlation criterion was characteristic of responses that would require access to implicit knowledge to answer correctly. Therefore, as a consequence of using an incorrect theory to generate their responses, subjects have no less confidence in their wrong answers than those that are right.

McLeod & Dienes (1996) found that fielders ran to catch so that $d(\tan \alpha)/dt$ was constant. It is conceivable that fielders are only able to make sense of α variation when they are acting naturally to intercept the ball rather than when they are observing trajectories from a stationary position. To investigate, subjects in the third experiment were asked about their angle of gaze whilst running to catch. Results mirrored those found in experiment 2. Subjects were able to answer accurately when describing α variation for balls that would land short or go over their head but were almost always inaccurate when asked about balls that they were able to run and catch. Experiment 4 gave subjects as many cues as possible to prompt recall of what happened to α. Balls were thrown toward subjects on a variety of trajectories. Immediately after each throw subjects were either asked to select a response from list of descriptions of possible α variation (amongst which was the correct answer) or describe what happened to their angle of gaze ('recognition' condition vs. 'free recall' condition). Even under these conditions subjects are significantly poorer at responding to trajectories that would give constant $d(\tan \alpha)/dt$. There was a

suggestion that the data gave tenuous support to Shanks & St.John's position as subjects in the recognition condition performed slightly but significantly better than subjects in the free recall condition for the critical 'ball caught at eye' condition. This suggested that subjects *could* recall their variation in α when the appropriate description must be selected from given alternatives. However, the subjects in the recognition condition were still significantly less accurate for this trajectory than the other trajectories they were required to consider. Furthermore, one might expect a slight improvement in the recognition condition as the subjects had a one-in-seven chance of getting the correct response. Since subjects appear unable to recognise or report the information that they used to guide interceptive behaviour, it was suggested that this information must be stored implicitly. Dienes & Berry (1997) defined features that they believe characterise implicit knowledge and the information a fielder uses to guide interceptive behaviour appears to match the proposed criteria. The information would be of little use in any other tasks, learning of it is based on repeated exposure rather than learning the underlying rules and the information is robust, showing little or no variation with I.Q. or frequency of occurrence.

If one presumes that information about α is used implicitly, then subjects must be using an alternative method of generating responses to the questions posed to them. Support for this assertion comes from subjects' consistent confidence in their responses whether correct or not. Dienes et al. (1995) argued that this suggests a common source for all judgements. A possible strategy was suggested based on the responses given by subjects in the experiments. It is conceivable that subjects might use knowledge of the appearance of a projectile trajectory from a side-on position as a basis for their interpretation of angle of gaze changes. The α variation is obvious for trajectories that will land short of or behind the fielder. However, for balls that would

intercept the eye the shape of the trajectory going up and then down could lead to the erroneous belief that angle of gaze must also go up and then down and this was the most common incorrect response given by subjects for this trajectory type.

An appealing account of why subjects are not aware of how they achieve interception comes from combining the work of Cleeremans (1997) and Maass & McLeod (1999). Cleeremans (1997) argued that implicit knowledge is encapsulated by the weights of connection in a connectionist network. Maass & McLeod (1999) constructed a simple connectionist network that received α of a projectile at successive time intervals as its input and generated an acceleration value for a simulated fielder as its output. The network produced motion of the simulated fielder that was very similar to movements made by real fielders in catching experiments conducted in McLeod & Dienes (1996). The network discovered the boundary that separated positive and negative values of $d^2(\tan \alpha)/dt^2$ and that if the fielder ran to maintain the value of α on this boundary the ball was intercepted. If one presumes that real fielders are using a real neural network to guide their interceptive behaviour then the determining rules are represented in the weights of connection in this network. The representation is non-conceptual and therefore cannot be freely expressed. This would account for the failure of subjects to state what happens to α when a ball approaches on trajectory that gives constant $d(\tan \alpha)/dt$ and their resultant reliance on an alternative theory to answer questions about α variation that produces incorrect answers for that type of trajectory. An alternative explanation for the inability to accurately describe their α variation can be found in the field of neuroscience. Milner et al. (1991) reported dissociation between a 'ventral stream' and a 'dorsal stream' of visual processing. They studied a visual form agnosic, MF, who was able to perform visual orientation tasks as well as normal controls without

being able to describe the information that she needed to perform the tasks. They argue that the evidence from studies of monkeys suggests that the damage that causes visual form agnosia is localised to the ventral visual processing stream. If the visual processing that is responsible for guiding interceptive behaviour were restricted to the dorsal processing stream then the catcher may not be aware of the information being processed. This hypothesis could be tested if there were a technique for imaging brain activity whilst a fielder was making a catch. Clearly, with current technology that is not possible. However, subjects could be presented with the visual information equivalent to that which they would experience before moving to catch and asked to decide which way they would have to run to catch the ball (much like the protocol of the experiments described in chapter 8). An imaging technique such as fMRI could be conducted whilst this visual information was being presented that might reveal the locality of the processing used to guide interception. If this were to be in the hypothesised 'dorsal stream' of visual processing, it would corroborate Milner's idea. Of course, this would require the imaging technique to have sufficient temporal resolution to detect where processing was occurring during presentation of the stimulus. Since fMRI has a resolution in the order of hundreds of milliseconds it may not be suitable for this task. Nevertheless, wherever the neural activity was located, it would be of interest to discover where this processing of which we are apparently unaware actually occurred.

Although the evidence presented in chapter 7 appears to contradict Shanks & St.John position, they may take issue with the fact that subjects were asked to recall what happened to α a few seconds after they had experienced that variation. It would be unworkable to ask a fielder to describe what was happening to α whilst the ball was in the air. However, in the strictest sense, implicit knowledge is that used without

concurrent awareness. I would contend that subjects were made aware of the pertinent information and told to attend to that information during the course of a trial. If they are unable to recall the information moments later it seems highly unlikely that they were aware of it whilst the ball was in flight. A supporter of Shanks & St.John (1994) position may also argue that fielders seem perfectly aware of the basis of action when action is necessary. However, it seems unusual that a fielder would report the sensation of incorrect information (saying that his angle of gaze goes up then down when it really increases all the time) when it is that information upon which his actions are based.

10.5. The signal to move

Initially, the aim of the experiment presented in chapter 8 was to validate simulation studies such as those conducted my Todd (1981), Michaels & Oudejans (1992), and Babler & Dannemiller (1993). They used computer presentations to display a stimulus ascending the screen. The target experienced a simulated gravitational force and thus had optical properties equivalent to those of a projectile launched from some distance ahead of an observer aligned with the plane of projection. Their work drew conclusions about subjects' ability to detect the acceleration of the target. Todd found no evidence that humans were able to take advantage of acceleration, Michaels & Oudejans found inconclusive evidence to the contrary. Babler & Dannemiller found that sensitivity to acceleration was sufficient for judging the relative landing location of a projectile. Each study thus made logical inferences about the validity of interception strategies based on detection of optical acceleration. The experiment in chapter 8 was conducted in the hope that the variation in the evidence for suitability of optical acceleration as a cue to behaviour could be

resolved. The results proved to be of interest but were confounded by a flaw in the experimental protocol.

Subjects were filmed catching balls launched that would land behind, at, or in front of their position. Immediately adjacent to their start position was a second camera situated at eye-level that recorded almost exactly the same visual information that the subject viewed until the moment they began to move. They were then replayed this video footage using a set-up that reproduced the visual angle changes that they experienced when catching the ball. It was expected that subjects would be accurate in deciding whether the ball would 'land' in behind, at, or in front of them. This was the case for 'short' and 'long' trajectories but performance was significantly poorer for 'at' trajectories. An explanation for the pattern of results was suggested. McLeod & Dienes (1996) argued that optic acceleration is the input to a servo that determines running behaviour. If the fielder is in the right place to make the catch there is no optic acceleration. Consequently, the servo gives no output and the decision about the appropriate behaviour is unclear. This, at first, appears inefficient, leaving the fielder without a definite course of action to follow. However, if, for example, the fielder makes an erroneous forward movement, he would immediately observe positive optic acceleration of the projectile. This would provide the servo with an input and its resultant output would instruct the fielder that he must move backwards to correct his error. Acceleration detection has sufficient sensitivity for correction of wrong movements before the fielder strays too far from the interception point.

Links were made between the results of this experiment and that presented in chapter 8, designed to show the existence of implicit knowledge. That experiment showed that subjects were accurate describing what would happen to α for balls that

would land behind or in front of them but were inaccurate at describing their α variation for balls that would intercept their eye if they did not catch it. Furthermore, their confidence in the accuracy of their judgements was not correlated with the actual accuracy of their judgements and therefore the zero-correlation criterion was met. Dienes & Altmann (1997) suggested that this reveals a lack of metaknowledge about the information under test (in this case, that which underlies how interception is achieved) and that the knowledge is therefore below a subjective threshold of consciousness. In the chapter 8 experiment, subjects were also accurate for recognising trajectories that would land behind or in front of them but significantly less accurate recognising trajectories that would intercept their eye. However, in this experiment the accuracy of subjects' judgements showed a significant positive correlation with their confidence in the accuracy of their judgements, suggesting that subjects are aware that it is harder to recognise a trajectory that will intercept the eye. This is of interest because it suggests where, during processing of the available information, that subjects first become conscious of their interceptive behaviour. Subjects appear unaware of the variation in α but are aware of the correct behaviour to intercept projectiles with different optic accelerations. Consequently, it seems subjects are unaware of the input to the servo that controls interceptive behaviour (optic acceleration) but are aware of its output (the appropriate behaviour for interception).

The results of this experiment produced one negative result that confirmed evidence from previous studies. It was found that expert fielders did not react significantly faster to the launch of the balls than novice fielders in the catching phase of the experiment, nor were they any more accurate at distinguishing the three trajectory types. This supports studies such as McLeod & Jenkins (1991) that show no

'expert' advantage in their perceptual abilities. The advantage held by expert fielders is therefore likely to lie in their co-ordination of movement rather than their perception and processing of the visual information.

An extension of the experiment reduced the duration of the video clips to see how much change in optic velocity was required before accurate judgements of trajectory type could be produced. A video clip showing an example of each trajectory type was selected and each had up to 8 frames (0.32seconds) of footage removed. The clips were then presented in random order. The removal of frames also eliminated the direct relationship between the height attained by the ball on screen and the appropriate response. There was a slight fall in accuracy corresponding with the reduction in information and again, performance was significantly poorer for trajectories that would not require movement to catch. However, subjects remained surprisingly accurate, even with the minimal information presented. Linear regression of accuracy vs. number of frames removed revealed that subjects' performance would only fall to chance level (33% correct) if they viewed less than a tenth of a second of the flight of the ball. This was used to support use of $d^2(\tan \alpha)/dt^2$ as it provides a valid cue moments after ball launch. Such rapid judgements would allow the fielder to begin moving toward the interception point quickly, maximising the efficiency of their interceptive behaviour. These claims rely on the assumption that subjects' accuracy will continue to decrease linearly with the duration of visual information that they are allowed to view. Although there was a significant linear fit to the regression of the data, there may be a sudden drop in performance if further frames were removed from the video clips presented. This could be investigated using the simulation system suggested in 10.8.4. The overall conclusion to this experiment is that a subject watching optic information presented on 2-D screen, that reproduces the

changes in optic acceleration that would be experienced if the trajectories were presented for real, can determine the appropriate course of action were he required to catch the ball.

The flaw that undermines the conclusion was that subjects could have been using the ascent velocity of the ball to come to the same trajectory judgement as that they would make using acceleration. This could be resolved by using trajectories with a variable launch angle. Although this defect precludes determining with any certainty that subjects use optic acceleration to guide interceptive behaviour it is nevertheless true to say that subjects' behaviour was entirely consistent with the use of $d^2(\tan \alpha)/dt^2$ as the relevant cue.

10.6. Difficult catches and $d(\tan \alpha)/dt$

The experiment presented in chapter 9 was designed to examine the interceptive behaviour of fielders at the limit of their ability to catch. Balls were launched over the head of fielders so that in order for them to make the catch they had to turn and run in the same direction as the flight of the ball. It has been shown that fielders tend to move so that they experience constant $d(\tan \alpha)/dt$ (e.g. McLeod & Dienes (1996)). This ensures that α increases throughout the flight of the ball and remains between 0° and 90°. However, this was an unusual situation for fielders because the trajectories they faced in this experiment caused them to observe a decrease in α as the ball passed over their head. The time at which α decreased in trials was found to be very late, apparently coinciding with the time at which fielders usually change their behaviour to prepare to make a catch. It was suggested that fielders attempted to maintain constant $d(\tan \alpha)/dt$ for as long as possible and that the fall of $\tan \alpha$ represents the onset of prehensive behaviour. The results largely fitted with this

suggestion. However, tan α vs. time tended to show curvature upwards. This is predictable for trials in which the ball is going to pass over the head of the fielder because when α approaches 90°, tan α will increase rapidly. The fielder at this point can no longer keep d(tan α)/dt constant. However, there tended to be a considerable period of linearity prior to this rapid increase in tan α.

On occasions, fielders moved outside the plane of projection of the ball. When they did this, the regression of tan α vs. time tended to be more linear. This would suggest that the catch was easier. In support of this assertion was the video footage of fielders' movements which seemed to show that they moved out of the projection plane when less energy was required to reach the interception point. However, despite this apparent link with trial difficulty there was no correlation between the average speed required to reach the interception point and this tendency for the fielder to move outside the plane of projection. Nor could a correlation be found with any other measure of trial difficulty. It was suggested that the link between the trial difficulty, tan α variation, and fielders' movements outside the plane of projection could be resolved by asking fielders to rate trial difficulty. This may show that although there was no measurable correlation, it is only when the fielder considers a catch easy that they move outside of the projection plane.

The results of the experiment were consistent with use of constant d(tan α)/dt as the guide to interceptive behaviour. However, it is being used at the absolute limit of its capability, hence the tendency for d(tan α)/dt to show positive curvature. It is likely that the d(tan α)/dt would show negative curvature for trajectories that would land short of the fielder and the fielder has to move at his maximum rate forwards. This is somewhat similar to the variation in δ. If the fielder had to move a long way laterally to reach the interception point, δ was observed to increase when for more

typical trials the fielder would hold δ constant. Likewise, for more usual trials the fielder will hold $d(\tan \alpha)/dt$ but in these extreme cases slight variation in $d(\tan \alpha)/dt$ is observed. That fielders seem to run so that $d(\tan \alpha)/dt$ remains constant for the majority of the flight and the tendency of α to fall only when the fielder is preparing to make the catch indicates the robustness of $d(\tan \alpha)/dt$ as a cue to interceptive behaviour.

10.7. Overview

The results of the experiments recorded within this thesis have suggested several ideas about how humans achieve interception. In this section these ideas are drawn together and described over the course of a fielder intercepting a projectile in an unaligned plane. Chapter 8 suggested that moments after launch of the projectile, the fielder will have detected the optic acceleration of the ball and the servo-mechanism based on $d^2(\tan \alpha)/dt^2$ will have decided whether the must run forwards or backwards to make the catch. If the fielder were in the right place to make the catch, the servo would provide no output. Any movement the fielder subsequently made would evoke optic acceleration, supplying the servo with an input. Its output would guide the fielder to correct his inappropriate movement. Chapter 6 suggested that the fielder would register the movement of the ball outside of the aligned vertical plane, thereby determining the lateral direction of movement. The fielder would then begin moving, attempting to null $d^2(\tan \alpha)/dt^2$ and to hold δ constant. In doing so, the fielder would prevent the ball from moving across his retina and therefore his visual experience would be equivalent to watching a ball in the aligned projection plane. It seems logical that a child would learn to catch in three steps. At first, the child would detect that catchable trajectories have constant $d(\tan \alpha)/dt$. He would then learn that if

he moves to reproduce constant d(tan α)/dt for trajectories offset from his position in the aligned plane, he will be in the right place at the right time to catch the ball. The third step in learning to catch would be learning to intercept balls in the unaligned plane by moving so that the visual experience is equivalent to that provided by all other trajectories that have been catchable previously, which translates into the constant δ strategy. If it seems unlikely that fielders would be able to compute anything like tan α, it is worth considering that a simple neural network constructed by Maass & McLeod (1999) discovered the boundary of optical acceleration in learning to catch based on the ratio of α_t to α_{t-1}. The network learnt the appropriate running contingency dependent on dα/dt relative to the current size of α. The result is that although the simulated movement of the fielder causes him to experience constant d(tan α)/dt, his running is controlled using an algorithm based on α that produces constant d(tan α)/dt. It is not inconceivable that fielders could use a real neural network that uses successive variation in α as its input to generate a running strategy that appears to cause them null $d^2(\tan \alpha)/dt^2$ because it must provide accurate predictive information about the interception point. In addition, the failure of subjects in chapter 7 to demonstrate awareness of the variation in α suggested that interception strategy might indeed be under the control of a neural network. If the basis of action is characterised by the weights of connections in a network, it is non-conceptual and therefore not available to consciousness, causing subjects to give responses using an alternative theory about how performance was achieved.

Chapters 3 and 4 suggested that the fielder would not necessarily run so that either of the ratios, tan α/tan β or α/β, were constant, thereby contradicting the work of McBeath, Shaffer, & Kaiser (1995). They also showed that the fielder's running path was likely to be convex relative to the projection point if he had to run

backwards and concave if he had to run forwards. Chapter 5 showed that he could not use curvature of the optic trajectory as a valid cue to interceptive behaviour. If the fielder does not need to make a large amount of lateral movement, he may move into line with the projection plane of the ball so that δ is reduced. Alternatively, he may allow δ to increase if he decides to take to catch at a position orthogonal to the plane of projection. If the catch required a large amount of lateral movement, he is much more likely to run so that δ is constant to maximise his chances of being able to hold $d(\tan \alpha)/dt$ constant. Chapter 7 suggested that the fielder will be unaware of how α is changing throughout the flight of this ball (but will be able to accurately derive this information if the ball is not coming straight to him). This could be because interception strategy is under the control of a neural network, like the one developed by the Maass & McLeod (1999), or because the processing responsible for interceptive behaviour is localised to the 'ventral stream' of visual processing, hypothesised by Milner et al. (1991). If the trajectory were similar to those used in chapter 9, such that the fielder had to turn and run backwards in the same direction as the flight of the ball, results suggested that he would run to ensure that $d(\tan \alpha)/dt$ was constant for as long as possible before making a final lunge for the ball. The final moments prior to making the catch would not be guided by a strategy designed to cause eye to meet ball but would be guided by another strategy intended to guide the fielder's hands to meet the ball.

10.8. Modifications to procedure and further study

10.8.1. Improving current interception strategies

The interception strategies presented in chapter 6 were relatively simple in terms of the input they received and the output they generated. The inputs were the

tangents of the relevant vertical and horizontal visual angles of the target from the fielder's point of view. These were used to calculate where the strategy would send the fielder. If this position caused the movement of the fielder to exceed limits on acceleration and speed, the magnitude of his movement toward the prescribed point was reduced so that the limits were not exceeded. The rationale behind examining relatively simple models of interceptive behaviour was that if these models could not produce faithful reproductions of human performance, it was unlikely that models with more restrictive assumptions would.

Tresilian (1995) used the McRuer-Krendel operator as a transfer function in modelling interceptive behaviour. The McRuer-Krendel operator is an equation that acts as a proportional controller in single input/single output tasks and was found to accurately describe human performance in experiments where subjects were required to act like a servo-control mechanism in order to null a visual error signal (McRuer & Krendel (1959)). Studies such as Michaels & Oudejans (1992) and Dienes & McLeod (1993) have suggested that fielders moderate their running in order to null optic acceleration so Tresilian considered the transfer characteristics of the McRuer-Krendel operator to be appropriate for modelling interception. However, he failed to find a suitable configuration of his interception model that produced human-like interceptive ability. Tresilian's failure appears to be attributable to his overly conservative interpretation of how the Chapman (1968) theory would work for a fielder running in two dimensions. Tresilian's view is that the signal provided by $d^2(\tan \alpha)/dt^2$ directs the fielder's acceleration only in the vertical plane linking the fielder and the ball. The interception strategies proposed in chapter 6 did not impose such a constraint on fielder movement but caused the fielder to continually move to a position on the ring of possible locations that would hold $d(\tan \alpha)/dt$ constant. The

exact position on the ring of positions was determined by an additional control parameter. For the most effective strategy, the additional control parameter was the angle δ (the horizontal angle through which the fielder has had to turn in order to fixate the ball) and the fielder ran to hold that angle constant. It would be interesting to study the effect of the McRuer-Krendel operator on the performance of the proposed strategies. It is likely that the addition of this transfer function would yield improvements over Tresilian's model and would increase the validity of the constant δ strategy.

10.8.2. Failure to reach the interception point

The experiment presented in chapter 9 examined fielder behaviour catching balls that were on the verge of being uncatchable. In the process of giving fielders trajectories that they were just able to catch, there were also a large number of trajectories that they were unable to catch. Often for these trajectories, fielders had decided that they could not reach the ball before it had landed and did not keep running with maximal effort throughout the ball's flight. An interesting study would give fielders a variety of trajectories that they were unable to catch (along with some that were catchable) and investigate at what point the fielder stopped accelerating or, if they had reached maximum velocity, the point at which they began to decelerate. The variation in $\tan \alpha$ and $d^2(\tan \alpha)/dt^2$ at this critical point could be studied. Examining the differences between catchable and uncatchable trajectories may reveal human ability to resolve differences in $d^2(\tan \alpha)/dt^2$. The results of the experiments in chapter 8 gave an indication as to the change in $d^2(\tan \alpha)/dt^2$ that observers had to view before they could decide in which direction they had to run in order to catch the

ball. The results of this proposed experiment could show how a fielder determines whether a ball is catchable or not.

10.8.3. Non-ballistic trajectories

Studies of catching have concentrated on how a fielder moves to catch a real ball or how a fielder responds to stimuli that simulated to follow a ballistic trajectory. Few studies have examined how interceptive behaviour changes when the fielder is required to intercept a non-ballistic trajectory. One example is Savelsbergh et al. (1991, 1993) who examined how subjects timed their catching action for a ball that decreased in size as it swung towards them on rotating arm. Another is Todd (1981) who simulated the ascent of projectile that could experience a different gravitational force from trial to trial and assessed subjects' predictions of landing site. However, neither of these studies examined how fielders' movement changed in response to deviation of the target from a normal projectile trajectory. Tresilian (1995) examined such a paradigm. He looked at the difference in movement of a fielder running to catch a tennis ball and a similarly sized sponge ball. The relative contribution of air resistance caused the flight characteristics of the sponge ball to differ greatly from that of the tennis ball. Tresilian found evidence that human fielders use an error-correcting strategy rather than a predictive strategy for interception, although his claims that a predictive strategy should necessarily generate straight paths are not altogether certain (see chapter 1). However, it would be interesting to study how fielders behave when trying to catch projectiles capable of generating their own lift e.g. a Frisbee. If a fielder ran to catch a Frisbee so that $d(\tan \alpha)/dt$ were held constant then they would be in the right place at the right time but given the extra time available to the fielder to reach the interception point, they may vary the way in which $\tan \alpha$ changes. An alternative technique for studying interceptive behaviour in the

face of deviation from ballistic trajectories would be to examine how balls are caught when they are launched so that they bounce against a wall before reaching the fielder. The collision would reduce the kinetic energy of the projectile as well as diverting its trajectory. The fielder must make some kind of prediction about the future trajectory of the ball after it rebounds from the wall. Another experiment could use a bowling machine, as used for cricket, which can apply spin to balls at launch so that they curve laterally in the air. The curved trajectory would cause the fielder to adjust his normal interception strategy to compensate for the lateral velocity of the ball. The changes in the fielders' behaviour in response to such deviations may confirm that fielders tend to use a particular strategy for interception or expose characteristics of interception strategy as yet undiscovered.

10.8.4. Estimates of ball and fielder position

Appendix A1 details how estimation of the position of the ball and the fielder was achieved. Estimates of error suggested that imperfections in the approximations would not have significantly affected the results or the analyses performed. Indeed, it was found consistently throughout the experiments that subjects were keeping $d(\tan \alpha)/dt$ constant, reproducing the results of previous studies, suggesting that accuracy was sufficient to validate the conclusions drawn. However, I believe that greater confidence in the experimental results and more definitive conclusions could be gained by improving the techniques used to estimate positions. Restrictions of budget and availability limited the equipment that could be used in the experiments presented. Consequently, position estimation of ball and fielder was a somewhat crude and laborious affair. The movements of the fielder were filmed with a standard video camera, recording at 25 frames per second and with a shutter speed of $1/500^{th}$ of a second. The video footage was fed into a computer program, Vidi-Clik, using a

video-editing suite and the position of the fielder was recorded in each frame by moving the computer cursor to the top of the fielder's head. Accuracy of cursor placement could have been improved by giving fielders a suitably designed hat to give a consistent reference point. Vidi-Clik works by applying a grid to the computer screen based on the X-Y co-ordinates of two reference points, supplied by the user. The X-Y co-ordinates of the fielder were therefore correct in terms of the Vidi-Clik grid but the camera angle at which the fielder movements were viewed and lens distortion meant that these co-ordinates were not accurate representations of the fielders' true position. To compensate, calibration equations were calculated using the position of an experimenter stood at a variety of known measured positions so that applying these equations converted Vidi-Clik co-ordinates to approximately true co-ordinates. The position of the ball was recorded in the frame where the fielder made contact with the ball and its position converted to true co-ordinates using the same conversion equations. The number of frames between ball launch and this frame gave an estimate of the trajectory time to the nearest 0.04sec. For each trial, the duration of ball flight and its start and end co-ordinates were the parameters used to calculate an estimate of its position in each frame of the trial using the modelling techniques applied by Brancazio (1985). The precision of the ball position estimate is dependent on the accuracy of the parameter estimates. The estimate of ball launch time was particularly uncertain when a hand sweep in front of the camera was used to indicate ball launch.

Ball trajectory could be computed with much greater accuracy using a technology similar to the 'Hawk-Eye' system used to track the ball in Channel 4 cricket coverage. The Hawk-Eye system uses mathematical modelling similar to that used for missile tracking. Six high-speed digital cameras are placed at strategic points

around the cricket ground, each viewing the pitch from a different angle. The cameras record ball position 150 times a second from the moment that it is released from the bowler's hand until it is hit by the batsman, it strikes the batsman's pad, or it passes the batsman and hits or misses the stumps. Within seconds of delivery the software uses the information from the six camera angles to compute the trajectory of the ball and can even predict its future path (if it had not struck the bat/batsman) to an accuracy of ±5mm. Implementing the system in a catching experiment would vastly improve accuracy in the measurement of ball position and the timing of launch and interception. Improving estimates of ball position would allow greater accuracy in the estimates of visual angles experienced by fielders. The Hawk-Eye system allows reconstruction of any trajectory in a virtual environment. A reconstruction can be viewed from any angle, allowing a representation of what the batsman saw to be simulated. Trajectories experienced by fielders could be reconstructed for presentation on computer screen in a similar manner to the protocol of the experiment in chapter 8. The somewhat precarious placement of a camera adjacent to the start position of the fielder, as was necessary in that experiment, would be unnecessary. The duration of a reconstructed trajectory presented to a subject could be varied more precisely to improve the estimate of the change in visual information that was required for subjects to judge the appropriate behaviour for interception. In chapter 8, it was found that subjects were significantly poorer at recognising 'at' trajectories. This was attributed to the use of a servo-mechanism for determining interceptive behaviour that cannot provide a signal when it experiences $d^2(\tan \alpha)/dt^2 = 0$. To further investigate, it would be useful to accurately vary trajectories to see how subjects' trajectory recognition improves as the ball landing position moves further away from the fielder. Using an accurate and realistic ball trajectory simulator would

render this task trivial – it would be simple to present subjects with an array of trajectories where the only accurate cue to the correct behaviour was the acceleration of tan α. The system would represent a vast improvement on the laborious method of recording and re-recording VHS video clips (with the associated loss of video quality inherent to that process) to the correct duration.

A more general solution would be to use a motion capture system. An example is the 'Vicon' system produced by Oxford Metrics. The Vicon system uses an array of high-resolution cameras that detect the infrared light from reflective markers and these can sample information at up to 240Hz; nearly ten times the temporal resolution of the VHS system. The software can interpret the information from up to 12 cameras and 50 markers. All relevant co-ordinate information could be captured accurately and in real-time by using reflective markers attached around the fielder's head and at the fielder's joints and by constructing a ball from the reflective material. The system would greatly improve the accuracy of positional estimates of ball and fielder and would alleviate the need for conversion equations and programs for trajectory estimation. Information from the markers placed on the fielder's joints would also allow detailed analysis into how fielder behaviour changes throughout a catch. One could study the initial movements made by a fielder after ball launch, before they set off toward the interception point. It is suggested that these movements are important in ensuring the validity of the movement cues experienced (see 10.8.7). I believe the greater temporal and spatial resolution of the motion capture system combined with information about the movements of the fielder's limbs would illuminate the true significance of these movements. The motion capture system would also allow investigation into the moderation of fielder behaviour as they changed strategy from one intended to make eye meet ball to one intended to make hand meet ball. These

movements were not considered within the thesis but the time at which the fielder begins preparation to make the catch could have a significant bearing upon his running strategy. By preparation for the catch, I refer to the cessation of the swinging action of the arms of the fielder when running and their symmetrical movement upward bringing the hands together to a catching position near the face. This was termed prehensive behaviour. There might exist a tangible relationship between variation in δ and the timing of the strategy change from interceptive to prehensive behaviour. For a catch where the fielder can reach the interception point with ease, he may get into line with the plane of projection of the ball, causing δ to decrease and he may also begin preparation for the catch at an earlier point in the flight of the ball. Similarly, for a more difficult catch, the fielder may find that δ is increasing and he can only make a one-handed lunge for the ball at the last possible moment. If one could factor the initial movements and prehensive behaviour into an interception strategy, it would represent a complete description of how a fielder makes a catch. One could also study how visual angle changes are implemented by the head-eye system by studying the contribution of the head angles to the overall angles. Like Hawk-Eye, using the Vicon system would greatly improve the accuracy in measurements of timing. There would be no need for intricate (or otherwise) mechanisms for signalling ball release.

Improvements in accuracy gained by implementing either or both of the Hawk-Eye or the Vicon systems would have generated greater confidence in the results of analyses. The additional information that they would have provided would have allowed further study of human interceptive behaviour. In the absence of either of these extremely expensive systems, the use of digital video rather than videotape-

based recording systems would have simplified analysis and editing of recorded footage.

10.8.5. Analysis software

The calculations of trajectory and simulated fielder movements were programmed using Visual Basic running in Microsoft Excel. This provided a convenient and user-friendly interface for programming and simple, powerful graphing tools. However, when optimising the parameters for the interception strategies the programs took an inordinately long time to run e.g. 26 hours to run the optimised Conserved alignment strategy on 20 trials. This was frustrating and prohibitive of progress. It appears that the MATLAB software could have fulfilled all calculation and graphing requirements, run programs much faster, and offers more powerful analysis tools. This would have allowed more in depth analyses and perhaps more strategy variants to be studied.

10.8.6. A control for response time

Chapter 8 examined the response times of experts and novices running to catch balls launched in the aligned vertical plane. The response times, measured as the time taken for the fielder to begin moving in the correct direction to catch the ball, were remarkably short (between 0.5 and 0.7sec) but not implausibly so. The response times of experts and novices did not differ, whether they were required to run forwards or backward to catch. A useful control statistic would have been to measure how quickly subjects could begin to run in each direction triggered by the stimulus of the ball emerging from the launch machine, without requiring the subject to catch the ball. The discrepancy between response times to run and response times to catch would have provided an insight into how fast it takes to process the visual information to

decide in which direction to run. Discovering this 'processing time' would have allowed the duration of visual information viewed by subjects to be varied more accurately around that value to characterise precisely when subjects made the decision to run in a particular direction.

10.8.7. Movement reversals

The experiments in chapters 3 and 4 examined the movements of fielders running two dimensions to catch projectiles launched in an unaligned plane. Fielders were often observed to make a small movement forwards of about half a pace almost immediately after the ball was launched, irrespective of whether they had to move forwards or backwards to catch the ball. If the interception point was behind his start position, the fielder had to reverse his direction of running to get to there. This behaviour was called a reversal. If the interception point was ahead of the fielder, even though he his initial step was in the correct direction, he usually retarded his forward velocity before continuing toward the interception point. This behaviour was called a hesitation. Reversals and hesitations were referred to as 'movement reversals'. The initial forward movement was assumed to be a simple 'priming' movement, akin to the bouncing movements made by a tennis player waiting to receive a serve. McLeod & Dienes (1996) also observed this behaviour displayed by one of the fielders in their experiments. They presumed that this was a reflection of the typical behaviour of cricket fielders to walk toward the batsman as the ball is being bowled. However, it was found that this movement might have more significance with regard to interceptive behaviour. For trials in the experiment conducted in chapter 3, the value of tan α experienced by the fielder was plotted against time up to the point at which the fielder had reached a critical velocity of his motion in depth. The curvature of this plot was assessed using regression analysis.

The curvature of tan α vs. time gives the sign of $d^2(\tan \alpha)/dt^2$, which is the cue to depth movement according to OAC models (positive and the should move backwards, negative and the fielder should move forwards). In the majority of cases (94%), the curvature of tan α was a valid cue to the correct depth movement that a fielder should make. However, in a few cases the curvature of tan α vs. time was an invalid cue to depth motion. In all cases where tan α vs. time gave an invalid cue the fielder had <u>not</u> made a movement reversal. It was suggested that although it is not always necessary and not always in the appropriate direction to achieve interception, the initial movement somehow validates tan α vs. time as a cue to depth motion. It is unclear why this might be true mathematically and it is possible that the effect is due to the unusual set-up of the experiment in chapter 3. Movement reversals were not studied in chapter 4 where the catching task was more familiar to subjects but the effect can still be observed to a lesser extent. This reduction may also be due to the interception point being in virtually the same place in each trial. Examination of how holding different values of $d(\tan \alpha)/dt$ constant affects the position of the rings of points that have the correct value of tan α over the course of a trial may yield some insight as to why this initial movement is made. It is possible that these initial movements are not a residual effect of the tendency of fielders to walk towards the batsman but that this tendency to walk in is now encouraged in cricket fielders because, unbeknown to them, it makes their catching more efficient.

11. Appendices

Appendix 1. Calculating the position of fielder and ball

This chapter investigates the methods used to calculate the position of the fielder and the ball in the experiments of chapter 3 and 4 and the error associated with those calculations. The experimental protocol in these two chapters covers the majority of the work involved in other experiments in this thesis.

A1.1. Recording fielder movements

Fielder movements were recorded by means of a video camera placed high above the area in which trials took place (see figures 3.2 and 4.1 in the appropriate chapters). This camera position allowed appraisal of fielders' lateral and depth movements rather than the single dimension recording of fielders' running in the other experiments presented and those of McLeod & Dienes (1996). Although this method enhanced the possibilities for investigation of human interception strategy, it presented problems in acquiring data suitable for analysis. Complicating factors include the distortion to the co-ordinate positions of the (approximately) rectangular catching area caused by its trapezoidal representation in the images captured by the video camera due to the angle at which the camera views the scene. Similarly, the lens of the camera caused aberrant distortion at the periphery of the image.

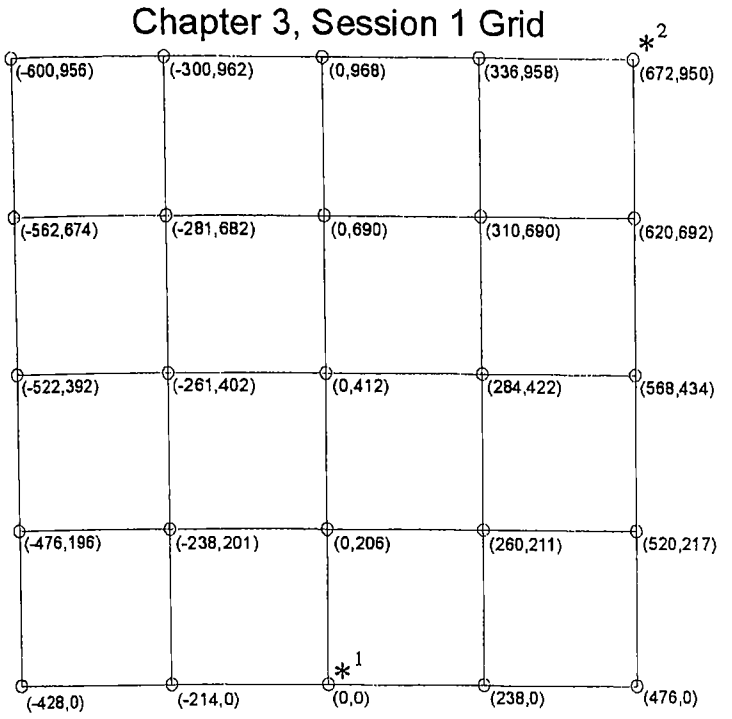
A1.1.1. Use of Vidi-Clik

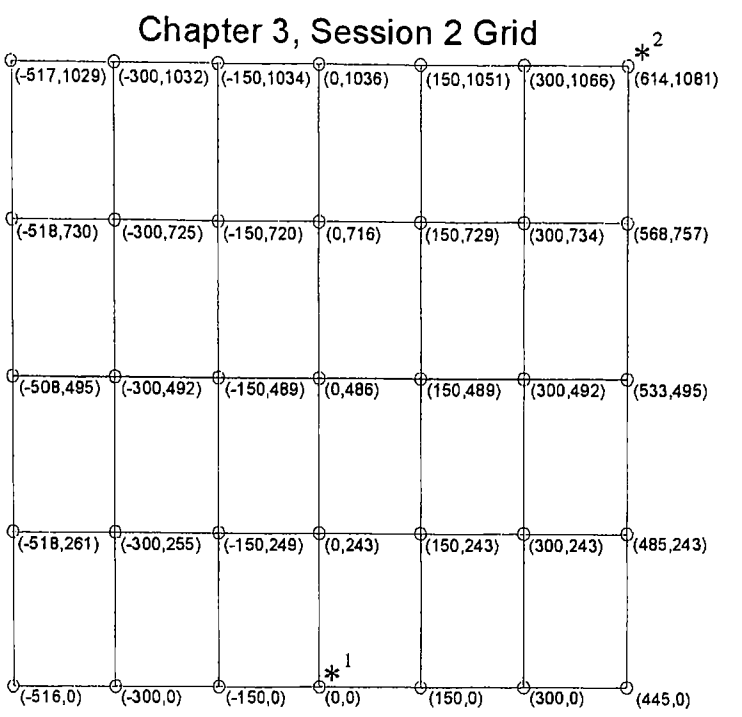
Appraisal of a fielder's position in each recorded frame of a trial was achieved using the computer program, Vidi-Clik. Vidi-Clik allows video-footage to be played through a computer and by designating the X-Y co-ordinates of two reference points on the screen, Vidi-Clik maps the entire screen relative to these points. For the experiments

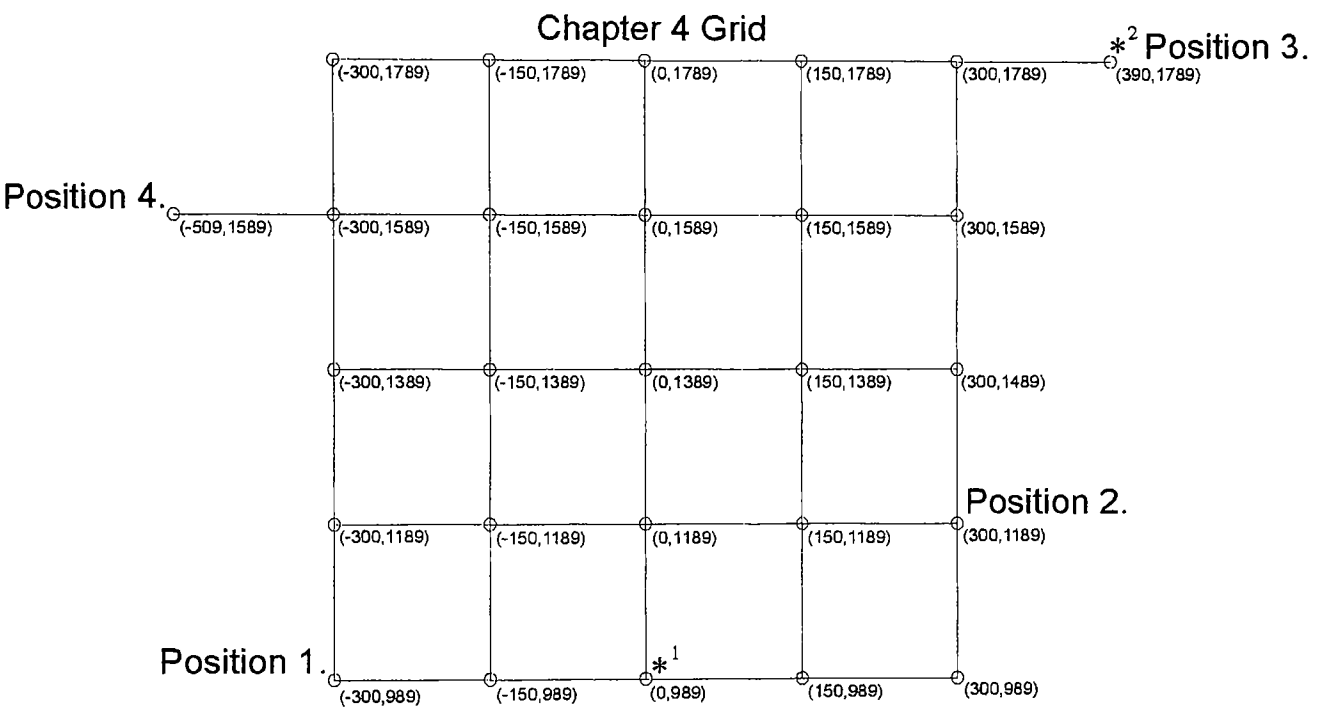
presented, the first reference point given was the measured position of an experimenter stood at the front-centre of the catching area, whilst the second was the measured position of an experimenter stood in the far right corner of the catching area. These were, respectively, the point nearest to the camera and the point furthest from the camera in the reference grid. A fielder's X-Y co-ordinate in each frame of video footage would then be recorded in Vidi-Clik by using the computer's mouse to position the cursor at the top of the fielder's head and clicking the mouse button.

A1.1.2. Conversion equations

The aforementioned distortions to the images recorded using the video camera meant that the Vidi-Clik co-ordinates of a fielder's position in each frame of a trial were not veridical. To rectify this situation an equation was generated that produced an estimate of the fielders' true position using Vidi-Clik co-ordinates. A separate equation was required for X co-ordinates and Y co-ordinates. Furthermore, different equations were used for each recording session to allow for slight differences in experimental set-up. Equations were produced on the assumption that any point of an image viewed in Vidi-Clik would deviate from its true position by an amount related to its distance in X and Y from the reference points (which have identical Vidi-Clik and measured positions). The equations were therefore in terms of the X and Y co-ordinate given by Vidi-Clik. To calibrate the equations used to convert Vidi-Clik co-ordinates into true positions, the Vidi-Clik co-ordinates of known positions would be required. The Vidi-Clik co-ordinates of the top of the head of an experimenter stood at measured positions forming a grid across the catching area were recorded. The grids used are shown in figure A1.1.







*1 First reference point for Vidi-Clik
*2 Second reference point for Vidi-Clik

Fig. A1.1. The grids used to calibrate the equations for converting Vidi-Clik co-ordinates to true positions. For the experimental sessions in chapter 3, the co-ordinates shown are the measured positions of each grid point relative to the bottom-centre point (0,0), whereas for the experiment in chapter 4, the positions are relative to the front of the ball firing machine.

A1.1.3. Parameters for the conversion equations

The parameters of the equations were then calculated using the curve-fitting function of the computer program, Sigma-Plot. The input to an equation would be either the X or Y co-ordinates of the experimenter's head at each position of the grid. The program then uses an iterative technique, feeding an equation with combinations of parameters, attempting to minimise the discrepancy between the output of the equation and the associated target values (in this case, the measured positions of each grid point). The conversion equations for the three different sessions are shown below with the associated parameters. In each case:

x_v represents the x co-ordinate as recorded using Vidi-Clik

y_v represents the y co-ordinate as recorded using Vidi-Clik

x_t represents the true x co-ordinate

y_t represents the true y co-ordinate

For the session 1 of the experiment in chapter 3:

Equation for conversion of x co-ordinates

$$x_t = x_v(ay_v^2 + by_v + c) + dy_v + e$$

where

$$a = 2.0310\times10^{-7}$$

$$b = 1.2542\times10^{-4}$$

$$c = 0.6931$$

$$d = 4.0247\times10^{-3}$$

$$e = -3.9421$$

Equation for conversion of y co-ordinates

$$y_t = ay_v^2 + by_v + cx_v^2 + dx_v + e(x_vy_v)^2 + f(x_vy_v) + g$$

where

$$a = 4.8421\times10^{-4}$$

$$b = 0.5163$$

$$c = -1.0815\times10^{-5}$$

$$d = -0.0308$$

$$e = 1.0345\times10^{-10}$$

$$f = -2.8246\times10^{-5}$$

$$g = 7.5916$$

The equations for session 2 of the experiment in 3 and those for the experiment in chapter 4 are the same, differing only in the parameters used.

Conversion of x co-ordinates

$$x_t = x_v(ay_v^2 + by_v + c) + dy_v + e$$

where

Parameter	Session 2, Chapter 3	Chapter 4
a =	1.0889×10^{-7}	1.0240×10^{-7}
b =	1.5353×10^{-4}	1.4011×10^{-5}
c =	0.6190	0.7293
d =	0.0340	0.0572
e =	3.7942	62.1311

Table A1.1.

Conversion of y co-ordinates

$$y_t = ay_v^{-2} + by_v^2 + cy_v + dx_v^2 + ex_v + f(x_v y_v)^2 + g(x_v y_v) + h$$

where

Parameter	Session 2, Chapter 3	Chapter 4
a =	-144.0047	7.8586×10^{7}
b =	3.1696×10^{-4}	2.2752×10^{-4}
c =	0.5860	0.3229
d =	-4.9851×10^{-6}	-1.6743×10^{-6}
e =	-0.0305	-5.5599×10^{-3}
f =	7.2692×10^{-12}	7.2692×10^{-12}
g =	-2.6182×10^{-5}	1.0929×10^{-4}
h =	12.6613	353.0779

Table A1.2.

Although the values of some of the parameters are minuscule (suggesting they are insignificant), they were significant in improving the accuracy of the conversion equations.

A1.1.4. Accuracy of the conversion equations

The estimates of position generated using the equations were, on average, within 5cm of the true position, with the discrepancy never greater than 15cm. Accuracy was poorest at the extremes of the viewed image, where lens distortion had its greatest effect. Given the variety of other factors that could generate error in position estimate, it appears the performance of the equations in correctly converting Vidi-Clik co-ordinates to true positions is satisfactory.

One source of error in position estimate was the variation in the consistency with which the pointer was placed at the top of fielders' heads in each frame of film. To account for this, the estimates of X and Y co-ordinates were smoothed using a Hanning window. Each co-ordinate was recalculated as half of itself plus a quarter of each of the adjacent co-ordinates (with the exception of the co-ordinates in the first and last frames which were untouched). A further source of error was the natural head movements made in the course of a fielder's running. The area within the field of view of the camera was calibrated such that the conversion equations were accurate for a surface at head height. If a fielder's head moves below that surface then a discrepancy between his estimated and true positions would arise. It seemed wise to get an estimate of the extent of the variation introduced by these factors. This was achieved by recording the position of an experimenter as he ran in a straight line from a central start position towards targets placed at the extremes of the field of view of the camera. The divergence between his calculated position and the known positions of these lines would allow an estimate of the cumulative error caused by the equations, inaccuracies in positioning the cursor and movements of the head below the calibrated surface. Figure A1.2 shows how the calculated position of the experimenter differed from the known position of the line along which he ran.

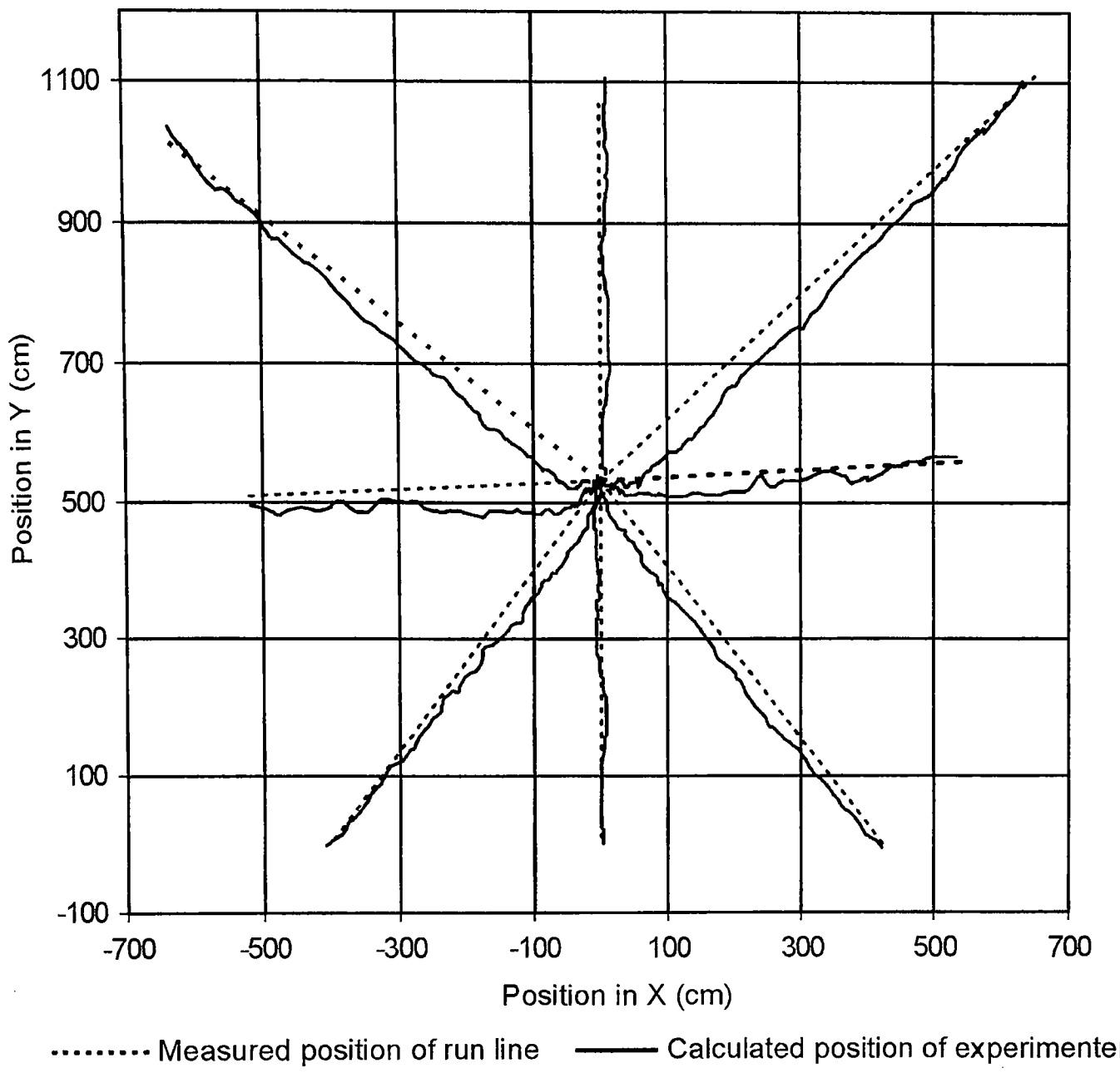


Fig. A1.2. Comparison of calculated and true positions within the view of the camera (experimenter began each run from the centre).

As is evident from figure A1.2, deviation from the expected position is greatest at the beginning of each run as the experimenter lowered his head to shift his body weight forward and gain momentum. Table A1.3 shows the average distance between the calculated position of the experimenter and the appropriate position on the line. N refers to the number of frames of video film (each lasting 0.04sec) over which the run took place.

Run	N	Mean	Minimum	Maximum	SD
Down	57	3.6	.0	8.4	2.2
Up	46	7.4	.0	13.0	4.1
Right	57	15.5	.0	30.1	9.8
Left	58	24.4	.0	45.6	12.8
Bottom-right	58	16.7	.0	26.9	6.9
Bottom-left	58	12.6	.0	29.8	7.6
Top-right	70	22.6	.0	42.0	11.6
Top-left	61	20.9	.0	38.4	10.7
Total	465	15.9	.0	45.6	11.3

Table A1.3.

The mean overall difference between the expected position of the experimenter and the estimate of his position calculated using the conversion equations is 15.9cm. This error seems acceptable since the fielder's calculated position is used relative to the calculated position of the projectile for calculations of visual angles and the distances between the fielder and the projectile are greater than 1m for the majority of a trial. Moreover, the error is largest when the fielder starts to run at the beginning of a trial, when a large distance separates fielder and ball. The error introduced into angles by the error in position was therefore minimal.

A1.2. Signalling the start of a trial for analysis

A significant difference in the protocol of the experiments in chapter 3 and that in chapter 4 is the method used to indicate the release of the target projectile, to signal the start of a trial.

A1.2.1. Signalling trial commencement in chapter 3

In the experiment described in chapter 3, the ball was thrown from the roof of a three storey building next to the catching area. This set-up was conceived to create an unfamiliar situation for fielders. The launch site was directly adjacent to the position of the video camera viewing the movements of subjects trying to catch the ball. Balls were thrown by one experimenter whilst a second experimenter signalled the start of a trial for analysis by sweeping his hand in front of the video camera, attempting to coincide the passing of his hand in front of the camera lens with release of the ball. Fielder movements were coded using Vidi-Clik and involved marking the position of the fielder in each frame of a trial. The appearance of the hand of the experimenter signalled that the fielder's position should be recorded in each subsequent frame until the fielder made contact with the ball. The hand sweep was only visible on the video footage in one frame of film giving a clear indication of the commencement of a trial. Accuracy of the signal was dependent on the skill of the experimenter in timing the sweep of his hand to coincide with ball release.

A1.2.2. Signalling trial commencement in chapter 4

For the experiment in chapter 4, a more sophisticated method of signalling ball release was exploited. In order to launch the ball with consistent launch characteristics, a ball firing machine was used and this was positioned at ground level. The video camera was again sited atop a three-storey building. The difference in position of camera and launch sites meant timing a hand sweep in front of the camera would be less reliable. The solution was to set up a signal that was triggered by the release of the ball from the firing machine and that would be visible to the video camera. An infrared emitter and sensor were affixed to the ball-firing machine so that the beam crossed the aperture through

which the ball emerged. When a ball was fired it broke the infrared beam, triggering a bright red light that was within the field of view of the camera (see figure A1.3).

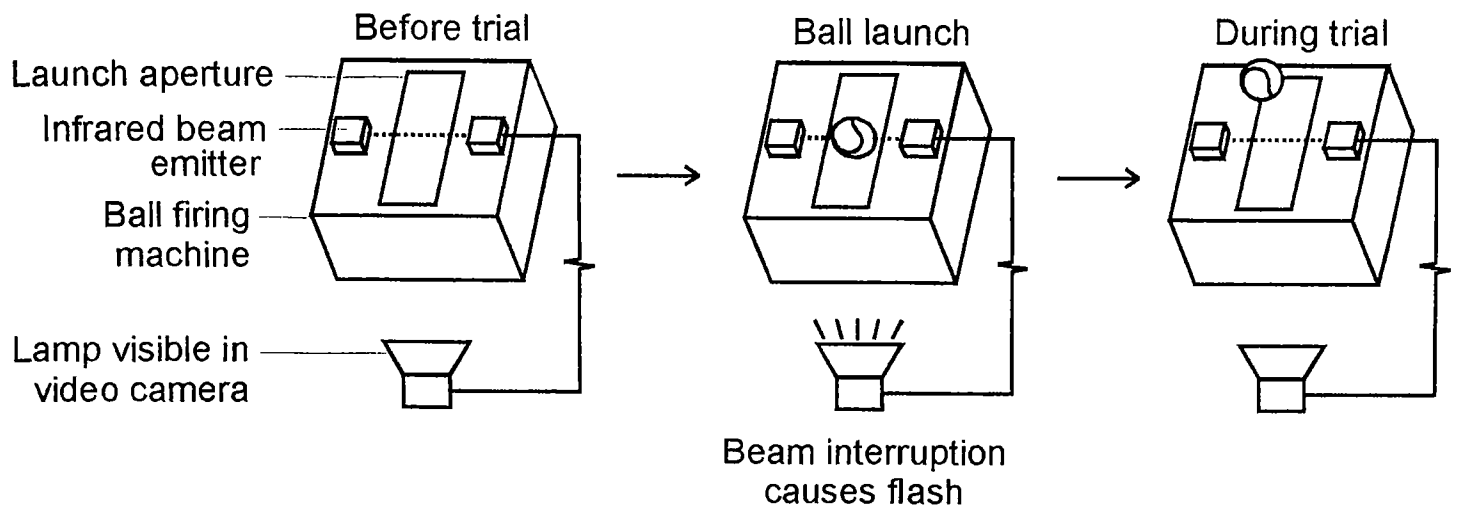


Fig. A1.3. Signalling ball release in the experiment presented in chapter 4.

The flash of the lamp was short enough to only appear in one frame of video footage and its appearance indicated that the fielder's position should be recorded in all subsequent frames until the fielder made contact with the ball.

A1.2.3. Comparison of the two techniques

The use of the infrared mechanism was clearly more accurate at signalling release of the ball than the method involving a hand sweep in front of the camera. Comparing the time that a fielder took to move 30cm in each experiment would provide a rough test of the consistency of the two signalling methods based on the assumption that fielders started to move at the same time in each experiment. The mean time to 30cm for subjects in trials using each of the ball release signals is shown in table A1.4 (mean time given in seconds).

Signal	N	Mean	SD
Hand	165	.36	.12
Light	175	.54	.10
Total	340	.45	.15

Table A1.4.

The mean time to 30cm is 0.18 seconds slower when the light is used to signal ball release and the standard deviations of the two signalling methods are reasonably similar. This suggests that the experimenter swept his hand in front of the camera consistently 0.18 seconds after the ball had been released. So although the hand sweep method was not truly accurate, it was consistent.

A1.3. Calculating ball trajectories

The movement of the fielders was recorded using Vidi-Clik to mark their position in each frame. This could technique could not be used for recording the position of the ball because the ball was not visible in each frame of video footage. Furthermore, its movement was in three dimensions so extrapolating the movement of the ball from its two-dimensional image would have been overly complicated. To find the position of the ball, a different system was required. A program was written that calculated an estimate of the ball's position in each frame using known information: the duration of the flight of the ball and the position of the ball at the start and at the end of its flight. The program simulated the force of gravity and an aerodynamic force proportional to the drag coefficient of the ball and the square of its velocity and used an iterative technique to find the launch velocity and angle that best fitted the known facts.

A1.3.1. Accuracy of ball trajectory calculations

The trajectory estimation program was successful in getting the ball to the correct final position (mean difference between final position of ball using Vidi-Clik and using trajectory estimation program: 1.35cm (N = 340)). However, this does not give any indication of how well the program did at fitting the estimate of the trajectory to the true trajectory. This was evaluated using a different experimental set up, shown in figure A1.4.

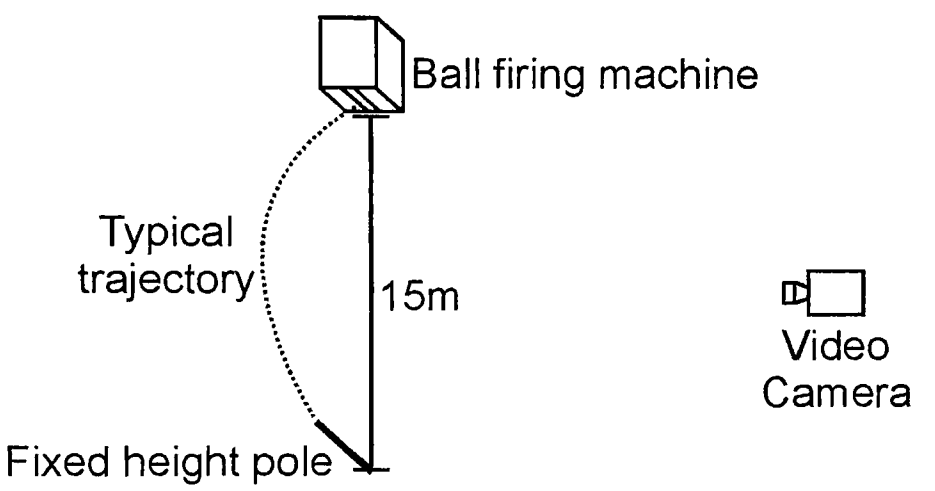


Fig. A1.4. Set-up for assessment of trajectory fit.

The camera views the entire flight of the ball from the launching machine to a pole, 2m high and 15m from the launch machine. This set-up allowed the position of the ball in each frame to be recorded using Vidi-Clik. The Vidi-Clik screen was calibrated using the measured positions of the base of the launch machine (0,0) and the top of the pole (1500cm, 200cm) so that the Vidi-Clik co-ordinates of the ball in flight were a close approximation of the true position. Three flights with different launch characteristics were analysed. The duration of each flight and the start and end position of the ball were known in each case. These could be fed into the trajectory estimation program to give an estimate of the position of the ball in each frame of a flight. This estimate could be compared to the true position found using Vidi-Clik. Table A1.5 summarises this

comparison. The first three rows summarise the difference (in centimetres) between the estimated and true position (N represents the number of frames analysed). The second three rows show the difference in α (in degrees) that would be experienced by a person stood where the pole is i.e. 15m from the launch machine. N is 5 fewer in this instance since the standard protocol of not analysing the final five frames was followed.

	N	Mean	Minimum	Maximum	SD
Trial 1	42	6.41cm	0.00cm	19.31cm	4.8689
Trial 2	38	6.60cm	0.00cm	19.40cm	4.1870
Trial 3	37	7.90cm	0.00cm	19.86cm	4.8518
α diff (1)	37	.26°	0.00°	2.78°	.4764
α diff (2)	33	.47°	0.00°	2.21°	.5635
α diff (3)	32	.49°	0.00°	2.65°	.6585

Table A1.5.

The mean difference in position in each case is approximately the width of a tennis ball and can probably be accounted for by slight errors in positioning the mouse pointer correctly over the ball when recording its position using Vidi-Clik. This equates to a mean error in α of less than 1°. Figure A1.5 illustrates the fit of the computed trajectory estimate. The circles show the true position of the ball as found using Vidi-Clik; the dashed line shows the trajectory estimate.

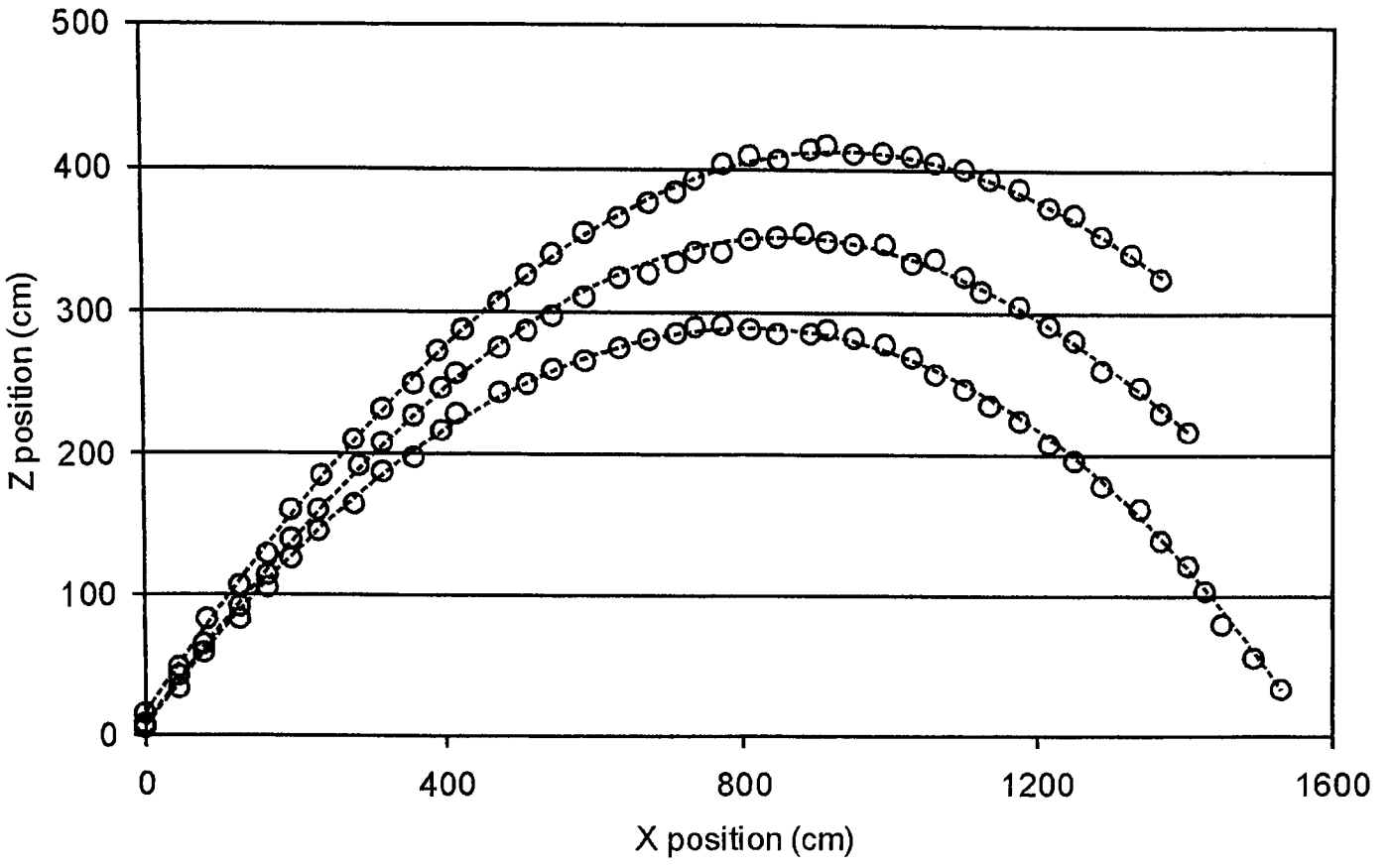


Fig. A1.5. Comparison of true and estimated trajectories.

Figure A1.5 indicates the quality of the fit and suggests that the computed trajectory estimate might even be nearer to the true trajectory than that found using Vidi-Clik, as it corrects the inherent error in positioning the cursor over the ball on the computer screen.

A1.4. Conclusion

The sources of error presented in this chapter do not present sufficient inaccuracy to significantly affect the calculation of visual angles between fielder and ball. Work in further chapters relies (to a lesser extent) on similar protocols as those examined here. The evidence collected in this section suggests that the techniques used are not detrimental to the analyses performed.

Appendix 3.1. Program to calculate best fit launch parameters

The program shown in this appendix shows how the best launch parameters were discovered using an iterative process. Once they had been found it was trivial to implement the program to calculate the trajectory of the ball given these launch parameters. Explanatory remarks are written in an italic font.

```
Sub calculate_launch_params()
Startup:
  For trials = 1 To 165
        Sets the number of trials.
Generalconstants:
  radcon = 3.14159 / 180
        Degrees-radians conversion factor.
  K = 0.00007
        Air resistance constant.
  dt = 0.04
        Time increment per frame.
  gravity = 981
        Gravity 981cm/s/s.
  ballheight = 1475
        Height of camera above ground.
  fixeddist = 940
        Distance from back wall to front of grid.
ltvalues:
  vmetball = 2
        Initial ball velocity.
      maxballang = 50
      maxballvel = 20
        Limits of ball launch characteristics (-50° to +50° and 2ms-1 to 20ms-1).
  astep0 = 2
  astep1 = 0.1
  astep2 = 0.01
        Angle interval for each revision stage.
  vstep0 = 2
  vstep1 = 0.1
  vstep2 = 0.01
```

Velocity interval for each revision stage.

angrange1 = astep0 / 2

angrange2 = astep1 / 2

Range of values to cover reassessed in successive revision stages.

velrange1 = vstep0 / 2

velrange2 = vstep1 / 2

Range of angle and velocity values to cover reassessed in successive revision stages.

lang = -maxballang

Initial launch angle.

smallesterror = 10000

Initial error value between endpoint of real and computed trajectories..

skip = 0

A flag for calculation revisions.

Getdata:

celltrial = trials + 1

subjects = Cells(celltrial, 1)

trialno = Cells(celltrial, 2)

Finds subject and trial number in question.

finframe = Cells(celltrial, 5)

Specifies number of frames in catch.

launchxpos = Cells(celltrial, 8)

launchypos = Cells(celltrial, 9)

Correction for fielder not standing in exactly the same position for each trial.

finxpos = Cells(celltrial, 10)

finypos = Cells(celltrial, 11)

catchheightcm = Cells(celltrial, 12)

Position of ball at point of catch.

Ballknowns:

ballxdistance = finxpos - launchxpos

ballydistance = finypos - launchypos + fixeddist

balldistance = (ballxdistance ^ 2 + ballydistance ^ 2) ^ 0.5

Determines distance ball travelled in XY plane.

tanlaunchdirection = ballxdistance / ballydistance

launchdirectionrad = Atn(tanlaunchdirection)

launchdirectiondeg = launchdirectionrad / radcon

Determines lateral angle of ball launch.

Spinon:

GoTo Newangle

Setlowerangle:

```
If skip = 0 Then
        lang = -maxballang
        GoTo Newangle
  End If
  If skip = 1 Then
        lang = bestang - angrange1
        GoTo Newangle
  End If
  If skip = 2 Then
        lang = bestang - angrange2
        GoTo Newangle
  End If
        Sets new ranges for iterative process.
Newangle:
  rad = lang * radcon
        Launch angle converted to radians.
Maths:
  x = 0: z = ballheight
  vball = vmetball * 100
  vx = vball * Cos(rad)
  vz = vball * Sin(rad)
        Defining velocities in appropriate units and directions.
For tframes1 = 1 To finframe
        Sets total number of frames for duration of flight.
  vint = (vx ^ 2 + vz ^ 2) ^ 0.5
  xdd = -K * vball * vx
  zdd = -K * vball * vz - (gravity)
  vdot = (vx * xdd + vz * zdd) / vint
  xddd = -K * (vdot * vx + vint * xdd)
  zddd = -K * (vdot * vz + vint * zdd)
  dvx = xdd * dt + 0.5 * xddd * dt ^ 2
  dvz = zdd * dt + 0.5 * zddd * dt ^ 2
  dx = vx * dt + 0.5 * xdd * dt ^ 2 + (1 / 6) * xddd * dt ^ 3
  dz = vz * dt + 0.5 * zdd * dt ^ 2 + (1 / 6) * zddd * dt ^ 3
        Calculating next positional increments using maths from Brancazio (1985).
Reevaluation:
  x = x + dx
  z = z + dz
  vx = vx + dvx
  vz = vz + dvz
```

Finds new ball position and velocity.

Next tframes1

Moves to next frame of trial.

Comparison:

predballdist = x

predxyerror = Abs(x - balldistance)

predzerror = Abs(z - catchheightcm)

totalerror = (predxyerror ^ 2 + predzerror ^ 2) ^ 0.5

Calculates distance of computed endpoint from true endpoint.

Info:

If totalerror < smallesterror Then

smallesterror = totalerror

bestvel = vmetball

bestang = lang

End If

If current parameters minimise error their values are recorded.

Skips:

If skip = 1 Then GoTo Nextang1

If skip = 2 Then GoTo Nextang2

Nextang0:

lang = lang + astep0

If lang > maxballang Then GoTo Nextvel0

GoTo Newangle

Increments launch angle value and recalculates trajectory.

Nextvel0:

vmetball = vmetball + vstep0

If vmetball > maxballvel Then GoTo Refine1

GoTo Setlowerangle

Increments launch velocity and returns to initial launch angle.

Refine1:

skip = 1

bestang0 = bestang

bestvel0 = bestvel

vmetball = bestvel - velrange1

GoTo Setlowerangle

Uses best parameters found so far and narrows parameter range and increments.

Nextang1:

lang = lang + astep1

If lang > (bestang0 + angrange1) Then GoTo Nextvel1

```
  GoTo Newangle
        Increments launch angle and recalculates trajectory.
Nextvel1:
  vmetball = vmetball + vstep1
If vmetball > (bestvel0 + velrange1) Then GoTo Refine2
  GoTo Setlowerangle
        Increments launch velocity and returns to best angle minus set range.
Refine2:
  skip = 2
  bestang1 = bestang
  bestvel1 = bestvel
  vmetball = bestvel - velrange2
  GoTo Setlowerangle
        Uses best parameters found so far and further narrows parameter range and
        increments.
Nextang2:
  lang = lang + astep2
  If lang > (bestang1 + angrange2) Then GoTo Nextvel2
  GoTo Newangle
        Increments launch angle and recalculates trajectory.
Nextvel2:
  vmetball = vmetball + vstep2
If vmetball > (bestvel1 + velrange2) Then GoTo Finpathcalc
  GoTo Setlowerangle
        Increments launch velocity and returns to best angle minus set range.
Finpathcalc:
  bestangrad = bestang * radcon
  Cells(celltrial, 12).FormulaR1C1 = smallesterror
  Cells(celltrial, 13).FormulaR1C1 = bestvel
  Cells(celltrial, 14).FormulaR1C1 = bestangrad
        Displays best parameters for that trial on a worksheet.
  Next trials
        Moves to next trial.
End Sub
```

Appendix 3.2. Multiple regression

On the following page is an example of the multiple regression tests carried out on the X-Y positional data in chapters 3 & 4. The example uses the first trial by subject 1 from position 1 from the experiment in chapter 4. The independent variable is 'S1X', the X position data for that trial. The dependent variable is 'S1Y', the Y position data for that trial. The first half of the analysis relates to the linear regression, the second half to the quadratic.

The F-test to determine whether the improvement in fit was conducted as follows:

- The value of F was calculated as

$$F = \frac{SS_Q - SS_L}{MS_Q}$$

where:

SS_Q is the sum of squares for the regression of the quadratic fit to the data.

SS_L is the sum of squares for the regression of the linear fit to the data.

MS_Q is the mean squares for the residuals of the quadratic fit to the data.

- The degrees of freedom for the numerator, df_n, was calculated as

$$df_n = df_Q - df_L$$

This was always 1 because a quadratic model (with two degrees of freedom) was being compared with a linear model (with one degree of freedom).

- The degrees of freedom for the denominator, df_d, was determined as the degrees of freedom for the residuals of the quadratic fit to the data. The value of this depended on the duration of the trial being analysed.

MODEL: MOD_1.

Dependent variable: S1Y Method: LINEAR

Listwise Deletion of Missing Data

Multiple R	0.99700
R Square	0.99401
Adjusted R Square	0.99392
Standard Error	10.88345

Analysis of Variance:

	DF	Sum of Squares	Mean Square	
Regression	1^{+}	1199999.1^{*}	1199999.1	($^{+}$: df_L; *:SS_L)
Residuals	61	7225.4	118.4	

F = 10130.88679 Signif F = 0.0000

---------- Variables in the Equation ----------

Variable	B	SE B	Beta	T	Sig T
S1X	1.235970	0.012280	0.997003	100.652	0.0000
(Constant)	1330.009537	1.842325		721.919	0.0000

Dependent variable: S1Y Method: QUADRATIC

Listwise Deletion of Missing Data

Multiple R	0.99779
R Square	0.99558
Adjusted R Square	0.99544
Standard Error	9.42526

Analysis of Variance:

	DF	Sum of Squares	Mean Square	
Regression	2^{+}	1201894.4^{*}	600947.20	($^{+}$: df_Q; *: SS_Q)
Residuals	60^{+}	5330.1	88.84^{*}	($^{+}$: df_d; *: MS_Q)

F = 6764.72145 Signif F = 0.0000

---------- Variables in the Equation ----------

Variable	B	SE B	Beta	T	Sig T
S1X	1.361446	0.029173	1.098219	46.669	0.0000
S1X**2	0.000571	0.000124	0.108695	4.619	0.0000
(Constant)	1329.721337	1.596704		832.791	0.0000

If the F value for the comparison of the two regression models was significant at the 0.05 level, the quadratic model was considered more appropriate. The sign of the quadratic component of the regression gives the direction of curvature of the quadratic model. Consequently, this reveals the curvature of the running path of the fielder.

Appendix 3.3. Programs to implement the LOT and constant δ strategies.

The code for both strategies was contained within a single program written in VisualBasic for use in MS Excel. The initial preparatory steps are explained and then the actual code used to model each strategy is shown with explanatory remarks written in an italic font (the original code was 210 lines).

- Program sets the number of trials.
- Selects which trial on which the program is to run.
- Sets-up the worksheet for the trial being analysed.
- States the value of the constants to be used (K (the air resistance constant), dt (time increment between frames), g (gravity), distances used in the set-up (e.g. initial height of ball above the ground), degrees-radians conversion factor).
- States the limits on fielder motion (running speed and acceleration) and the frame in which the strategy is applied.
- States the initial position of the simulated fielder.
- Defines the loop in which the simulated fielder's position will be calculated for each frame of the trial.
- Finds X-Y-Z position of the ball for that frame (pre-calculated).
- Begins subroutine to model the LOT strategy

```
LOT:
Psirelpositions:
  psixrelpos = xpos - psixperson
  psiyrelpos = psiyperson - ypos
        Position of ball relative to fielder.
PsiXYofperson:
  psitanpersonyang = zposrel / (psixrelpos ^ 2 + psiyrelpos ^ 2) ^ 0.5
        Calculates tan α for the simulated fielder.
  If tframes2 = psimoveframe - 1 Then
        origpsitanpersonyang = zposrel / (psixrelpos ^ 2 + psiyrelpos ^ 2) ^ 0.5
        psitanydiff = psitanpersonyang - oldpsitanpersonyang
        Interval through which tan α increases with each frame.
        psitanxangreltoball = psixrelpos / psiyrelpos
        psitanxangreltohome = -(psixperson / (psiyperson + fixeddist))
        Defines two components of tan β.
```

```
        psitanxang = psitanxangreltoball + psitanxangreltohome
        Calculates tan β.
        psiconstant = psitanpersonyang / psitanxang
        Defines tan Ψ.
        pospropor = psitanxangreltoball / psitanxang
        Proportion of psi made up by direction of fielder.
    End If
    If tframes2 < psimoveframe Then GoTo Psidirection
Psidefnposition:
    psitantargetyang = oldpsitanpersonyang + psitanydiff
        Increments tan α so that d(tan α)/dt is constant.
    psitantargetxang = (psitantargetyang / psiconstant) * pospropor
        Finds value of (component of) tan β that causes it to change in proportion with
        tan α.
    ball = Atn(psitantargetxang) / radcon
    If tframes2 > psimoveframe - 1 Then
        psixperson = xpos - psiyrelpos * psitantargetxang
        psiyperson = ypos + (zposrel / psitantargetyang) * Cos(psitantargetxang)
    End If
        Calculates new X-Y position of fielder using new values of tan α and tan β.
Psidirection:
    psixmov = psixperson - oldpsixperson
    psiymov = psiyperson - oldpsiyperson
    psidistance = (psixmov ^ 2 + psiymov ^ 2) ^ 0.5
        Distance moved in each direction and overall.
    If psixmov = 0 Or psiymov = 0 Then GoTo Psirightangle
    psitandirection = psixmov / psiymov
    psidirection = Atn(psitandirection) / radcon
    If psixmov > 0 And psiymov > 0 Then psidirection = -180 + psidirection
    If psixmov < 0 And psiymov > 0 Then psidirection = 180 + psidirection
        Finds direction in which simulated fielder moved.
    GoTo Psivelacc
Psirightangle:
    If psiymov = 0 And psixmov < 0 Then psidirection = 90
    If psiymov = 0 And psixmov > 0 Then psidirection = -90
    If psixmov = 0 And psiymov > 0 Then psidirection = 180
    If psixmov = 0 And psiymov < 0 Then psidirection = 0
    If psixmov = 0 And psiymov = 0 Then psidirection = 0
        Direction fielder faces if movement is in one dimension only.
Psivelacc:
```

```
  psivelocity = psidistance / 0.04
  psiacceleration = (psivelocity - oldpsivelocity) * 0.04
        Velocity and acceleration for that frame.
Psiacclimit:
  If Abs(psiacceleration) <= maxacc And psivelocity <= maxvel Then GoTo OACstart
        If simulated fielder movement within limits goto Constant δ model.
  If Abs(psiacceleration) > maxacc Then newpsiacceleration = maxacc
  If psiacceleration < 0 Then psivelocity = oldpsivelocity - maxacc
  If psiacceleration > 0 Then psivelocity = oldpsivelocity + maxacc
        If acceleration limit exceeded use maximum.
  If psivelocity < maxvel Then GoTo Psireassessposition
        Continue if velocity limit not exceeded.
Psivellimit:
  If psivelocity > maxvel Then psivelocity = maxvel
        If velocity limit exceeded use maximum.
Psireassessposition:
  psixdistmax = -psivelocity * Sin(psidirection * radcon)
  psiydistmax = -psivelocity * Cos(psidirection * radcon)
        Distance one would move at maxvel in each direction.
  newpsixdist = psixdistmax * 0.04
  newpsiydist = psiydistmax * 0.04
        Distance that would be achieved in one frame.
  psixperson = oldpsixperson + newpsixdist
  psiyperson = oldpsiyperson + newpsiydist
        New positions based on those distances.
Psireassessangles:
  psitanxangreltoball = (xpos - psixperson) / (psiyperson - ypos)
  psitanxangreltohome = -(psixperson / (psiyperson + fixeddist))
  psitanxang = psitanxangreltoball + psitanxangreltohome
  pospropor = psitanxangreltoball / psitanxang
  psiconstant = psitantargetyang / psitanxang
  psitanpersonyang = zposrel / ((xpos - psixperson) ^ 2 + (psiyperson - ypos) ^ 2) ^ 0.5
  psitanydiff = psitanpersonyang – oldpsitanpersonyang
        Works out visual angle tangents based on fielders reassessed position.
```

- Begins subroutine modelling the constant δ strategy.

```
OAC:
Xofperson:
  If tframes2 = 9 Then tantargetxang = (xpos - xperson) / (yperson - ypos)
```

Recognition of horizontal displacement after 9 frames.

If tframes2 > moveframe Then xperson = xpos - (yperson - ypos) * tantargetxang

After set frame number movement to maintain tan δ.

Yofperson:

If tframes2 = moveframe - 2 Then tanpersonyang1 = zposrel / ((xpos - xperson) ^ 2 + (yperson - ypos) ^ 2) ^ 0.5

If tframes2 = moveframe - 1 Then tanpersonyang2 = zposrel / ((xpos - xperson) ^ 2 + (yperson - ypos) ^ 2) ^ 0.5

Recognition of d2(tan a)/dt2 by 9th frame.

tanydiff = tanpersonyang2 - tanpersonyang1

Rate of change of tan α.

If tframes2 < moveframe Then GoTo Drection

Skips movement before recognition of α.

tantargetyang = tanpersonyang2 + Int(tframes2 - 9) * tanydiff

Ensures constant d(tan α)/dt..

If tframes2 > moveframe - 1 Then yperson = ypos + (zposrel / tantargetyang) * Cos(tantargetxang)

After 9th frame y position calculated using known values.

Drection:

xmov = xperson - oldxperson

ymov = yperson - oldyperson

distance = (xmov ^ 2 + ymov ^ 2) ^ 0.5

Calculates distance moved from old to new frame.

If ymov = 0 Then GoTo Rightangle

If xmov = 0 Then GoTo Rightangle

To prevent overflow in tandirection calculation.

tandirection = xmov / ymov

Tan of direction of movement.

direction = Atn(tandirection) / radcon

If ymov > 0 And xmov > 0 Then direction = -180 + direction

If ymov > 0 And xmov < 0 Then direction = 180 + direction

Direction of movement (degrees).

GoTo Velacc

Rightangle:

If ymov = 0 And xmov < 0 Then direction = 90

If ymov = 0 And xmov > 0 Then direction = -90

If xmov = 0 And ymov > 0 Then direction = 180

If xmov = 0 And ymov < 0 Then direction = 0

If xmov = 0 And ymov = 0 Then direction = 0

Direction if no movement in one dimension only.

```
Velacc:
  velocity = distance / 0.04
        Velocity calculation for each frame.
  acceleration = (velocity - oldvelocity) * 0.04
        Acceleration calculation for each frame.
Acclimit:
  If acceleration < maxacc And velocity < maxvel Then GoTo Reflexsteps
        If max accleration/velocity not exceeded then proceed.
  If acceleration > maxacc Then acceleration = maxacc
        If acceleration too great use maximum.
  velocity = oldvelocity + acceleration
  If velocity < maxvel Then GoTo Reflexsteps
Vellimit:
  If velocity > maxvel Then velocity = maxvel
        If velocity too great use maximum.
Reassessperson:
  xdistmaxvel = -velocity * Sin(direction * radcon)
  ydistmaxvel = -velocity * Cos(direction * radcon)
  newxdist = xdistmaxvel * 0.04
  newydist = ydistmaxvel * 0.04
  xperson = oldxperson + newxdist
  yperson = oldyperson + newydist
        Position recalculated using new values of velocity.
  tantargetxang = (xpos - xperson) / (yperson - ypos)
        Recalculates tan δ (to be held constant).
```

- If frame number has not exceeded initial movements phase then a 'reflex' forward movement is applied to the simulated fielder.
- X-Y position of simulated fielders written in the appropriate row and column of the worksheet (separate for LOT and constant δ strategy).
- Values of visual angle tangents and motion recorded for use in next frame
- Begins next frame.
- If at the end of a trial moves to next trial
- If at end of trials program ends.

Appendix 3.4. Examples of visual angle tangents experienced by real and simulated fielders

Each row of graphs in the figure refers to a single trial from the experiment described in chapter 3. They show variation in tan α and δ against time (tan α vs. time on the left and δ vs. time on the right) for a ball being caught by a real fielder, a fielder following a linear optic trajectory and a fielder using the constant δ strategy.

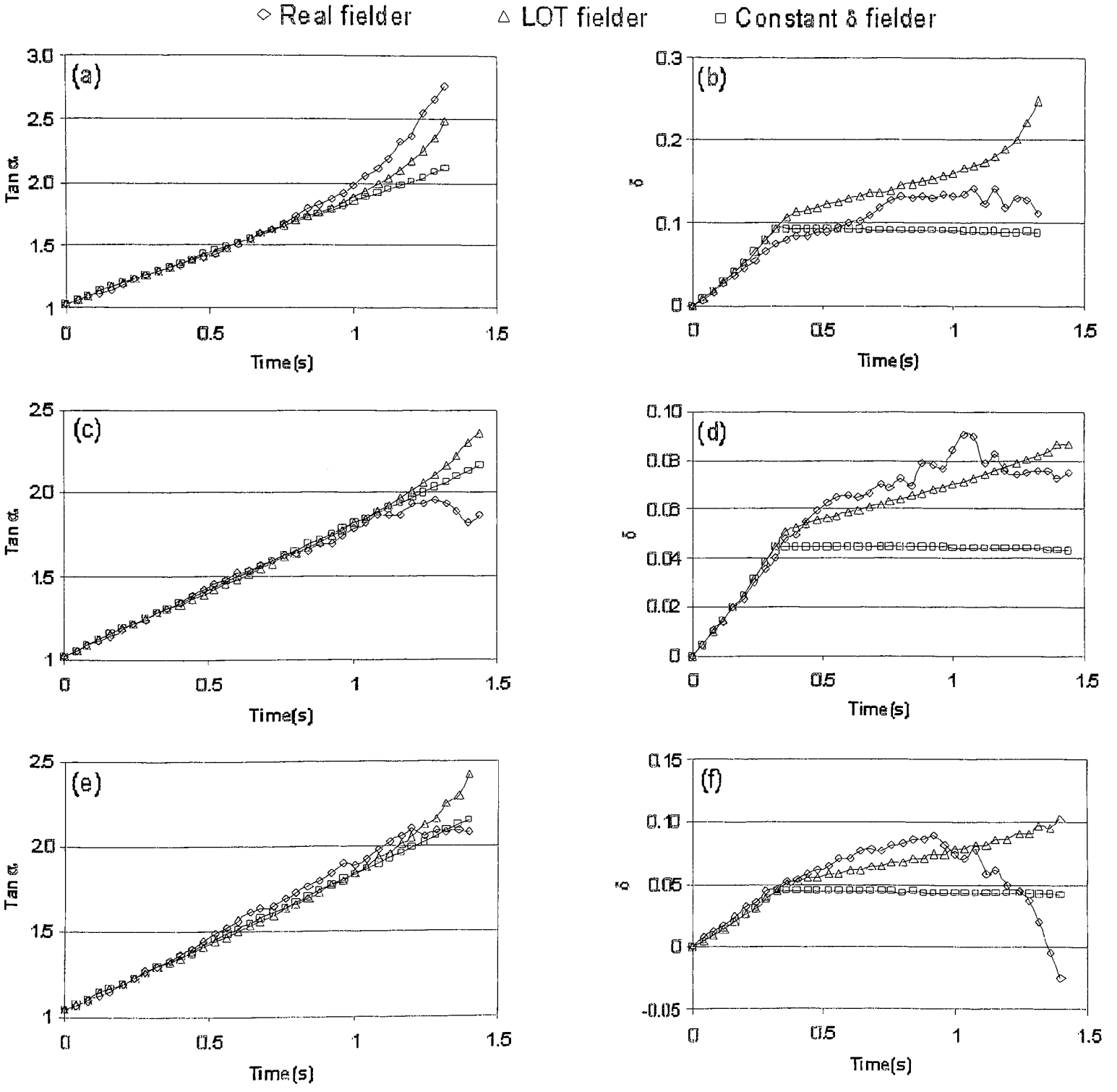


Fig. A3.2. Variation in vertical and lateral visual angle tangents for three different trials.

Graphs (a), (c), and (e) show that d(tan α)/dt was consistently constant as expected. In graph (b), the constant δ strategy produces a reasonably good fit to δ. In graph (d), it is the LOT model that gives a good fit and in graph (f), neither model gives a satisfactory fit to tan δ.

Appendix 4.1. Correlation between trial number and linearity of tan β vs. time

In chapter 4, the interception point was in the same place for each trial. It was suggested that subjects might have begun using the LOT model to guide their behaviour but become less dependent on it as they learnt the catching location. If this were the case, tan β vs. time would have begun linear and got less linear has subjects deviated from the LOT model. To test this hypothesis correlations were calculated between the number of trials completed and r^2 for the fit of a linear regression model to tan β vs. time. The results are shown in the tables below.

Descriptive Statistics

Subject		N	Minimum	Maximum	Mean	Std. Deviation
1.00	r2 lin	40	.04	1.00	.8101	.2480
	Valid N (listwise)	40				
2.00	r2 lin	39	.21	1.00	.9164	.1437
	Valid N (listwise)	39				
3.00	r2 lin	40	.01	1.00	.8516	.2385
	Valid N (listwise)	40				
4.00	r2 lin	28	.01	.99	.6250	.3376
	Valid N (listwise)	28				
5.00	r2 lin	28	.00	.98	.5510	.3270
	Valid N (listwise)	28				

Table A4.1 Summary values for r^2 of linear fit to tan β vs. time for each subject.

Correlations

Subject				Trial
1.00	Kendall's tau_b	r2 lin	Correlation Coefficient	.054
			Sig. (2-tailed)	.625
			N	40
2.00	Kendall's tau_b	r2 lin	Correlation Coefficient	.075
			Sig. (2-tailed)	.505
			N	39
3.00	Kendall's tau_b	r2 lin	Correlation Coefficient	.081
			Sig. (2-tailed)	.463
			N	40
4.00	Kendall's tau_b	r2 lin	Correlation Coefficient	.207
			Sig. (2-tailed)	.123
			N	28
5.00	Kendall's tau_b	r2 lin	Correlation Coefficient	.101
			Sig. (2-tailed)	.453
			N	28

Table A4.2 Correlation between r^2 and trial number.

Appendix 4.2. α vs. β for all other subjects

The following graphs show α vs. β for all trials completed by each subject.

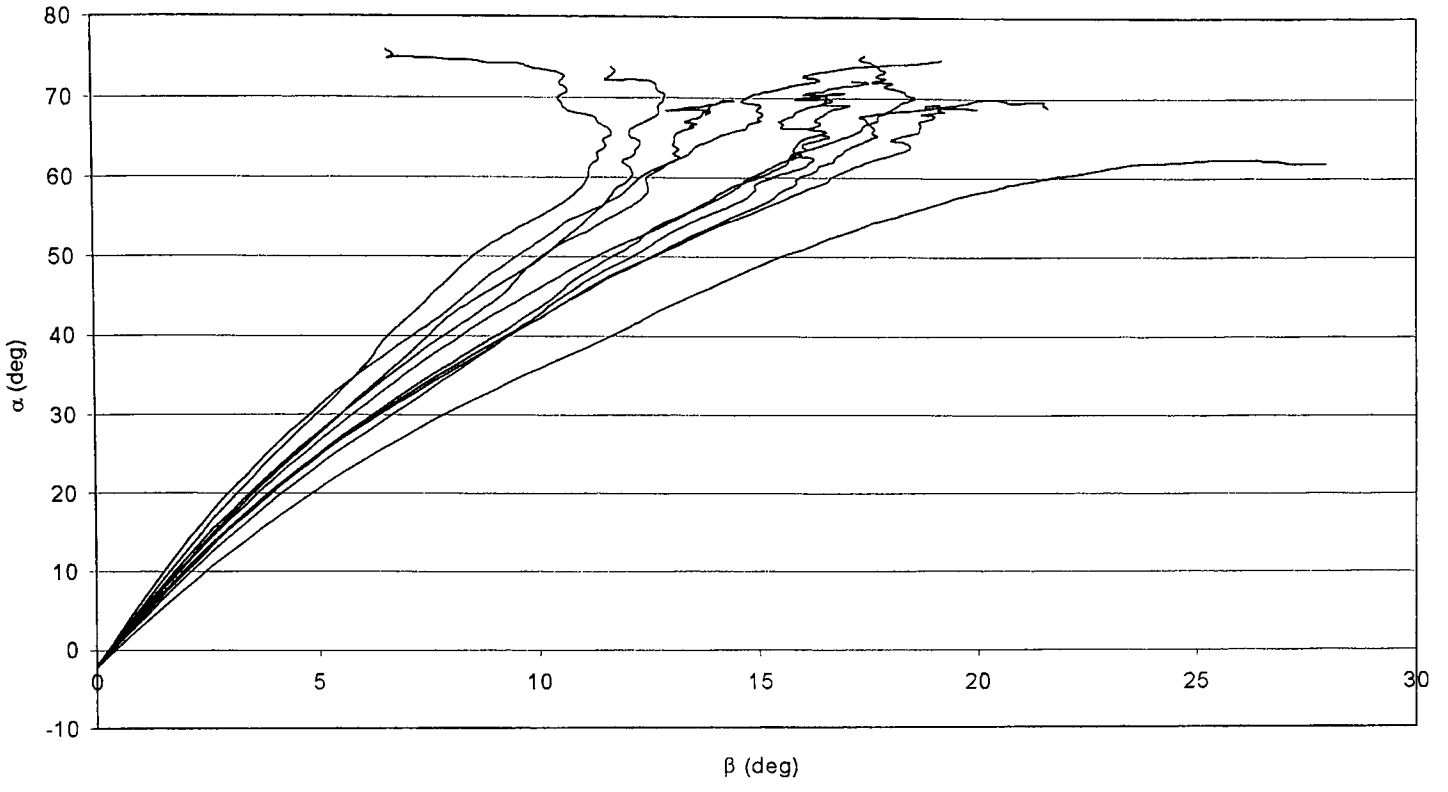


Fig. A4.1. Subject 1 from position 1

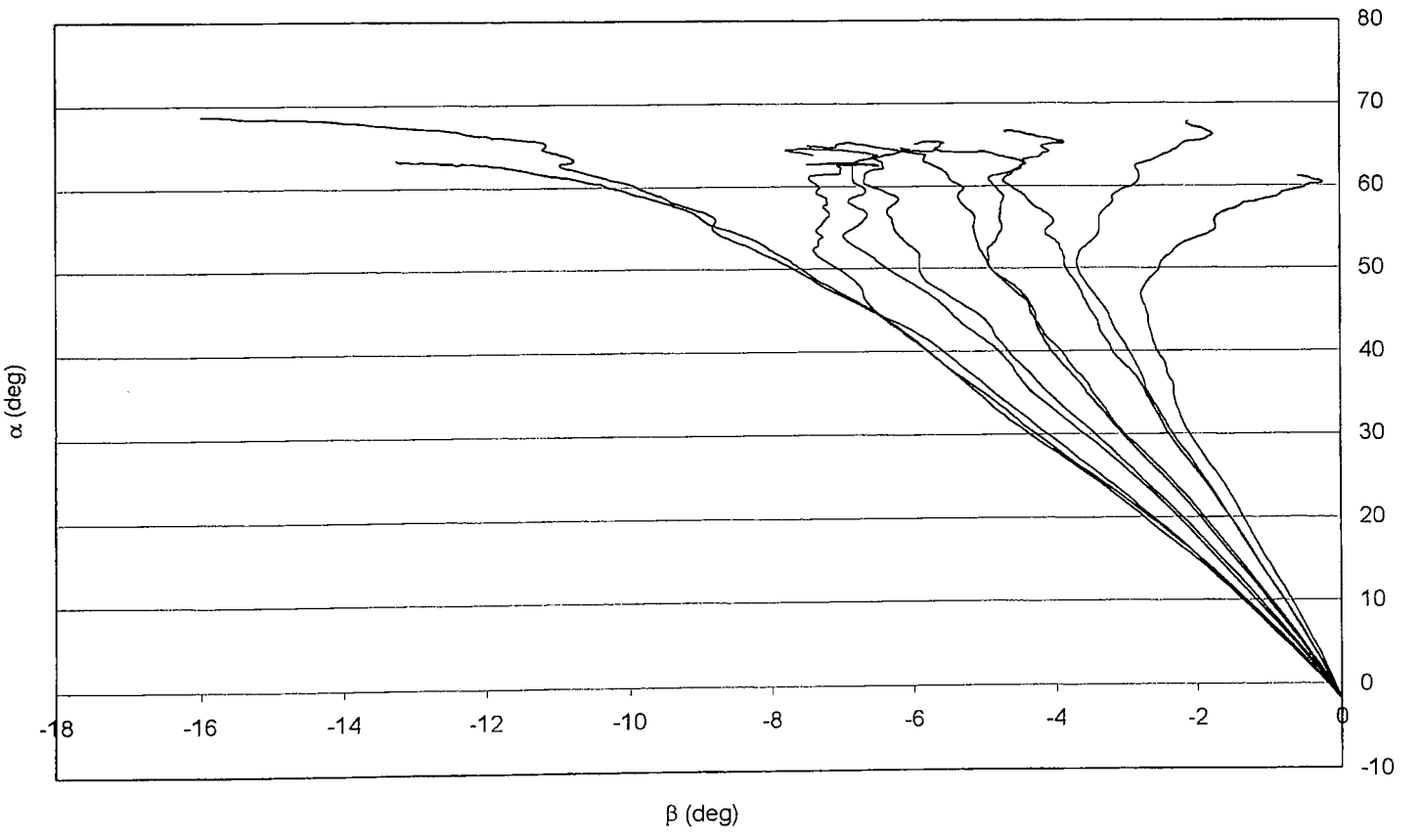


Fig. A4.2. Subject 1 from position 2

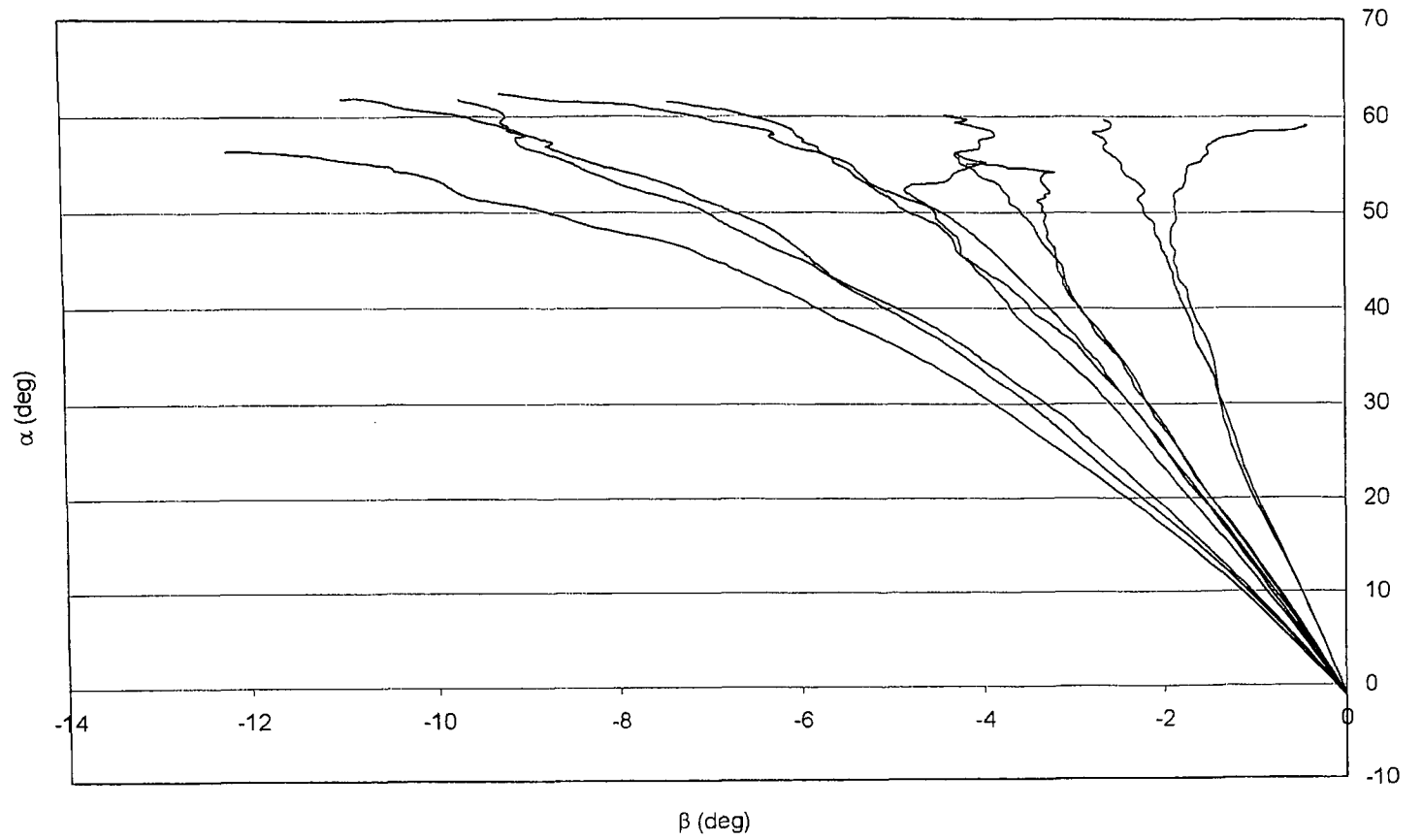


Fig. A4.3. Subject 1 from position 3.

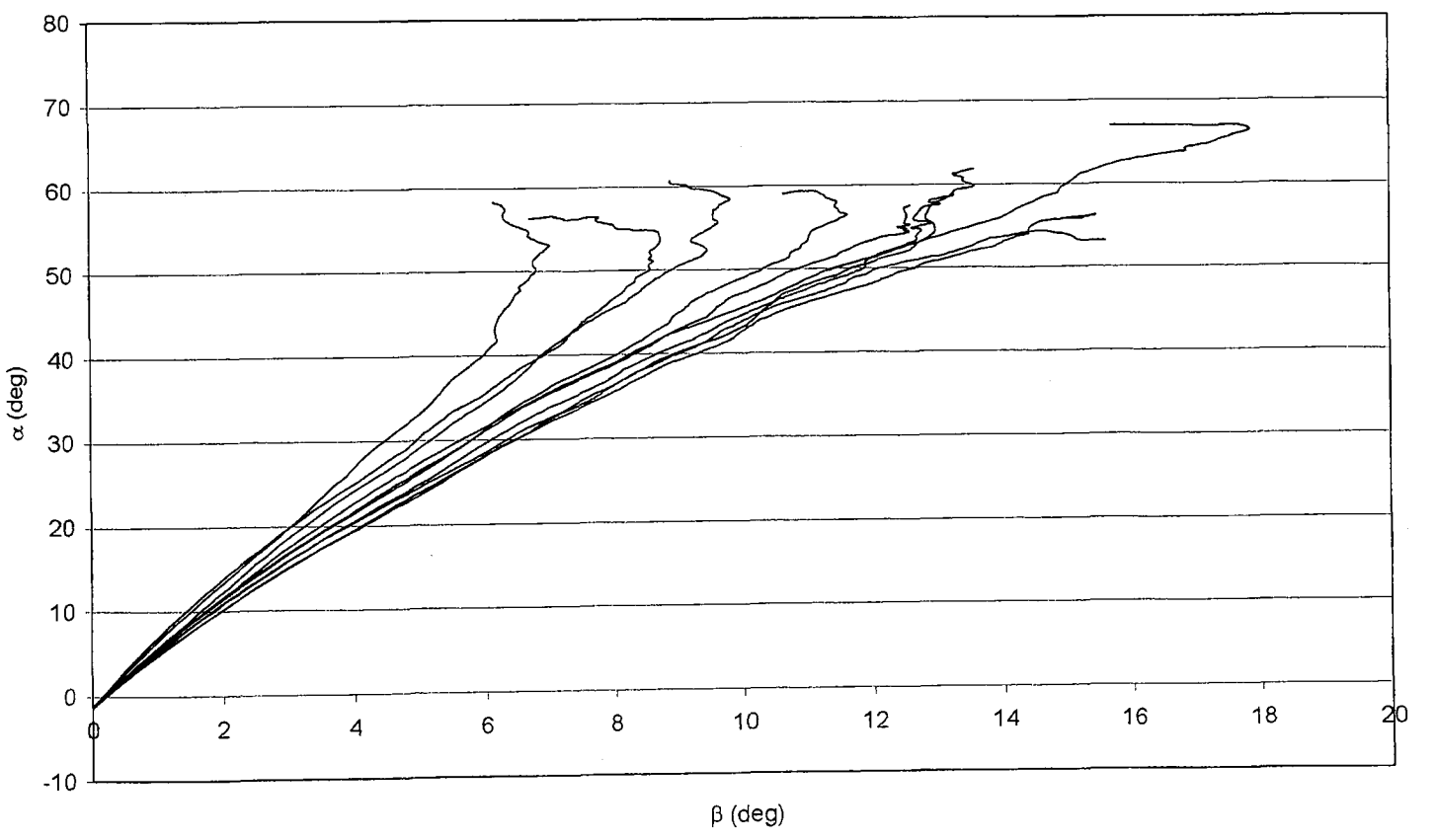


Fig. A4.4. Subject 1 from position 4.

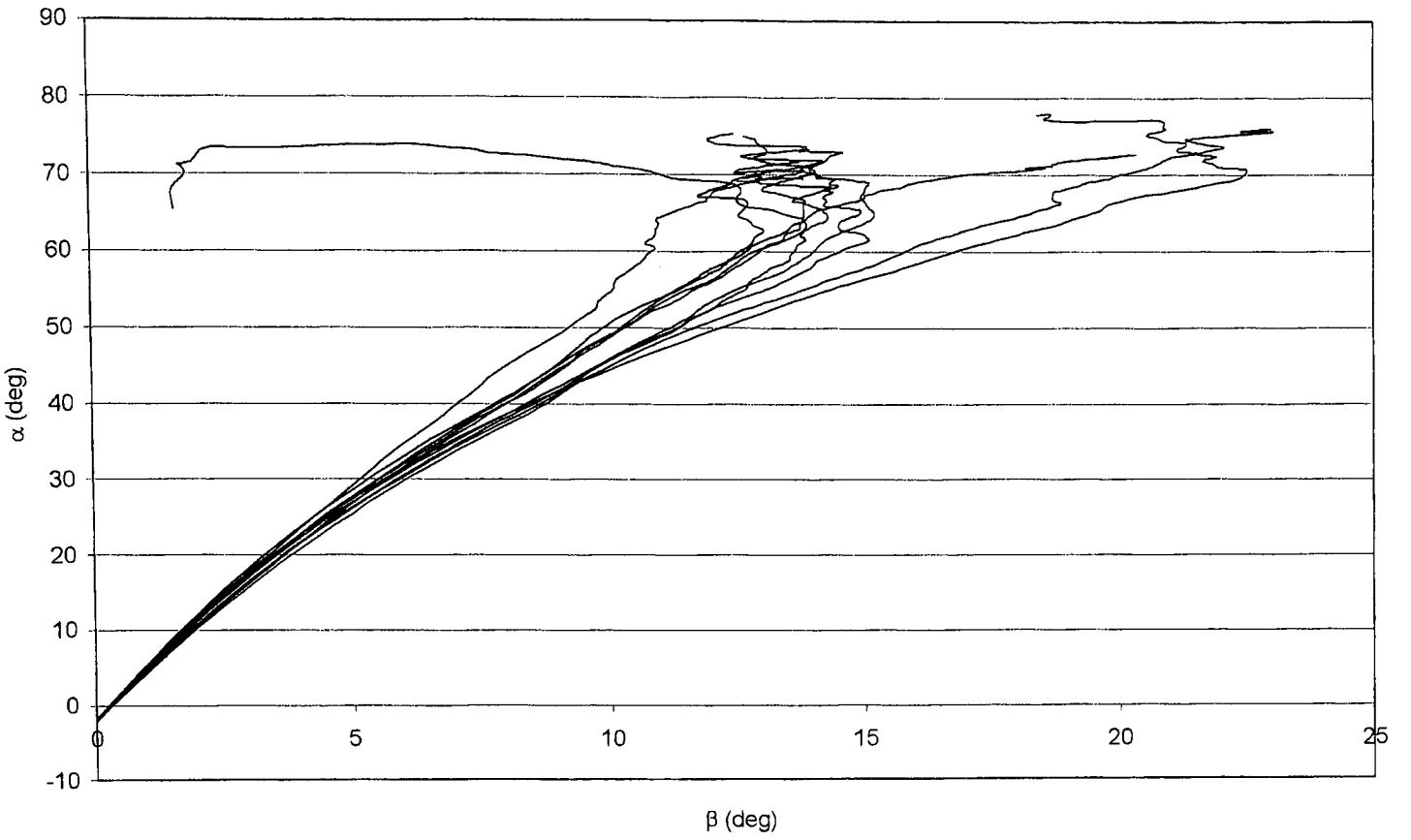


Fig. A4.5. Subject 3 from position 1.

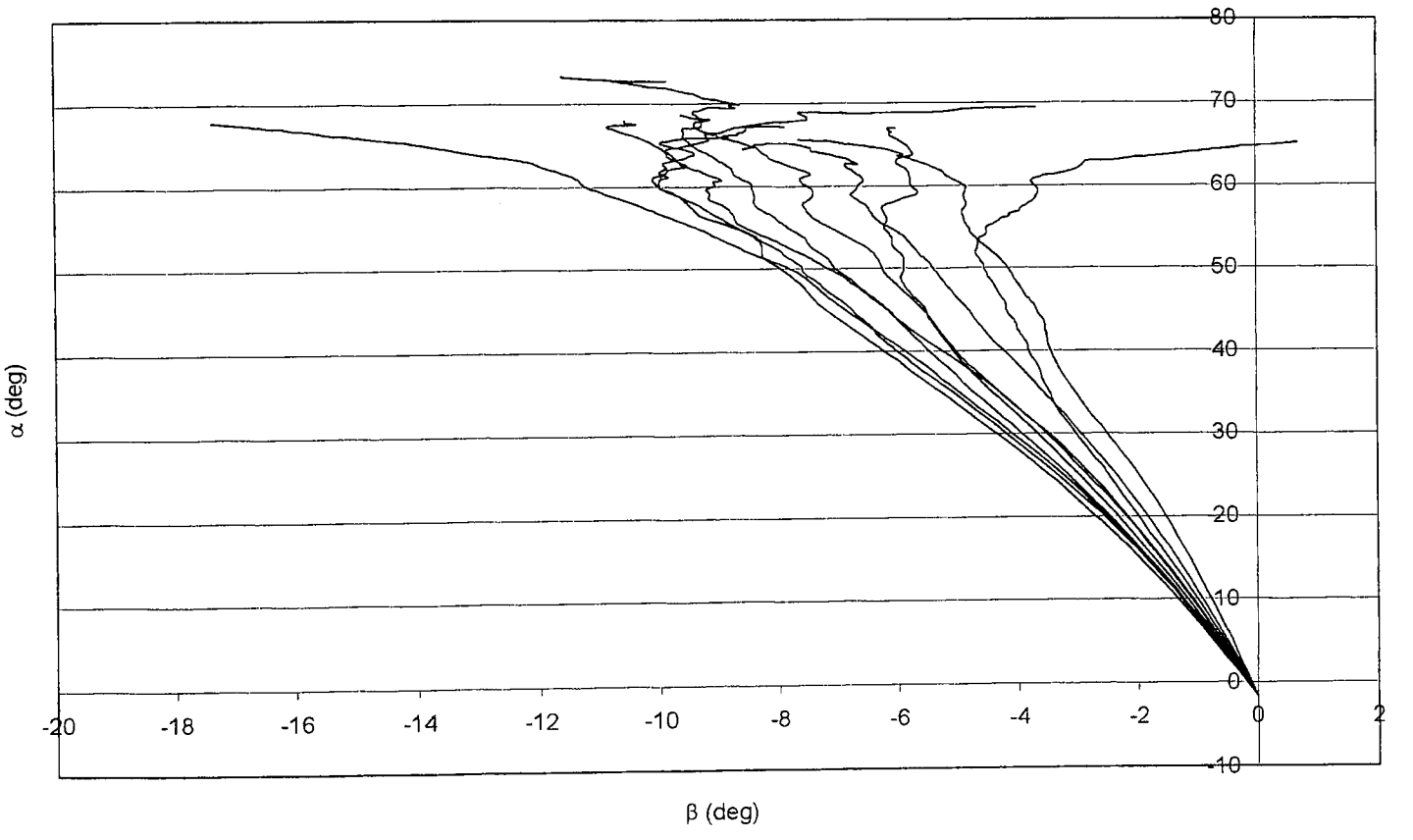


Fig. A4.6. Subject 3 from position 2.

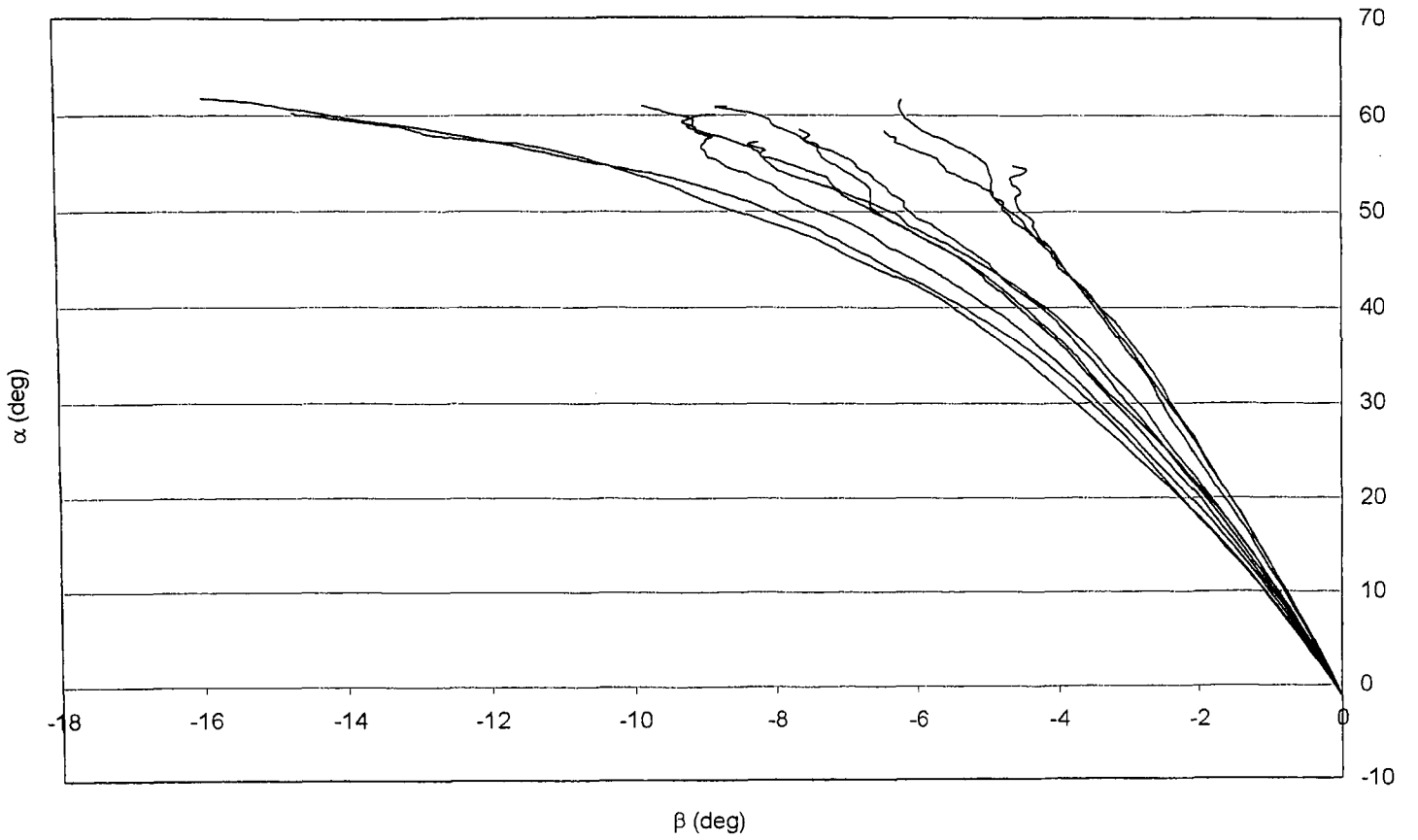


Fig. A4.7. Subject 3 from position 3.

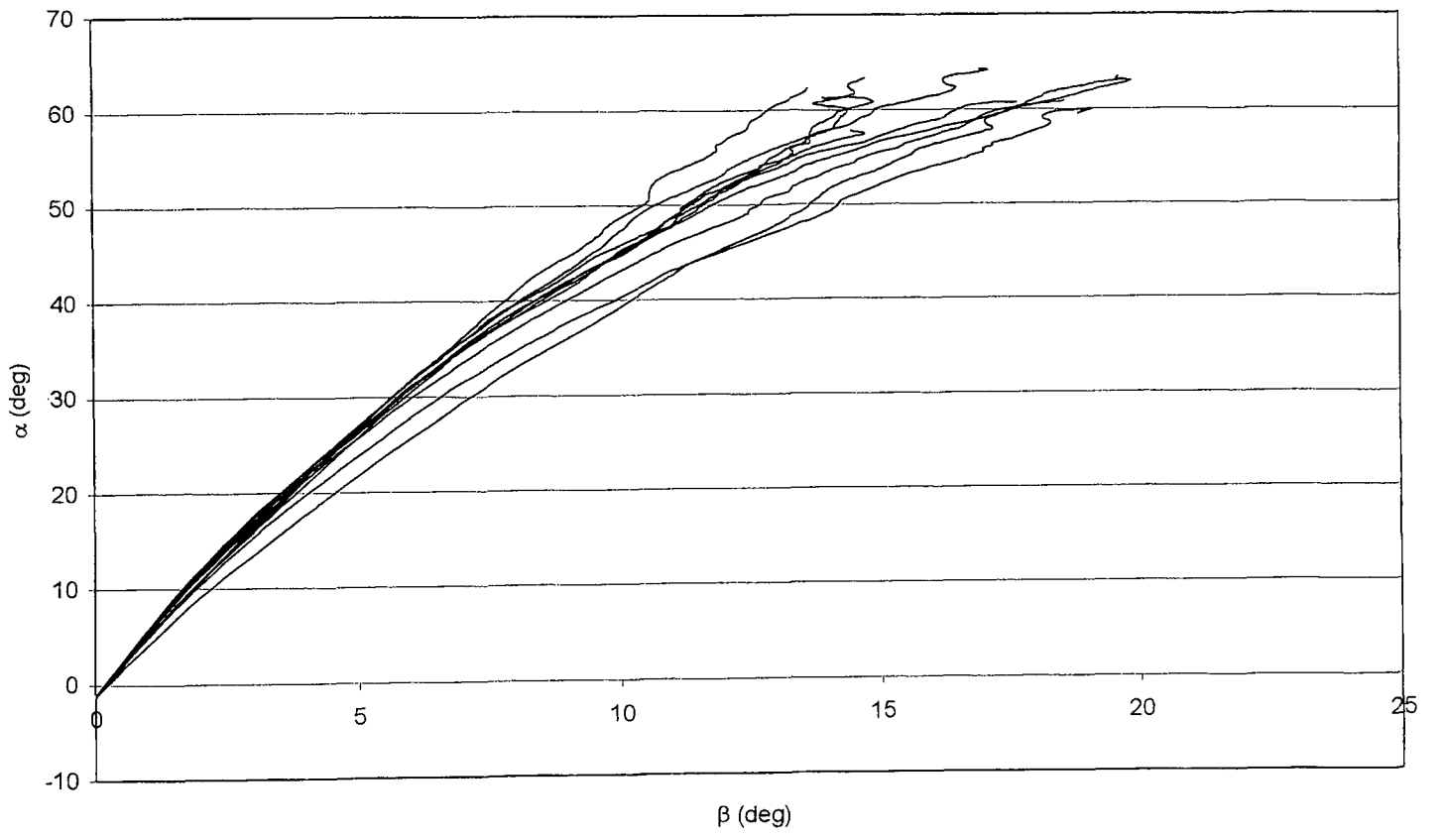


Fig. A4.8. Subject 3 from position 4.

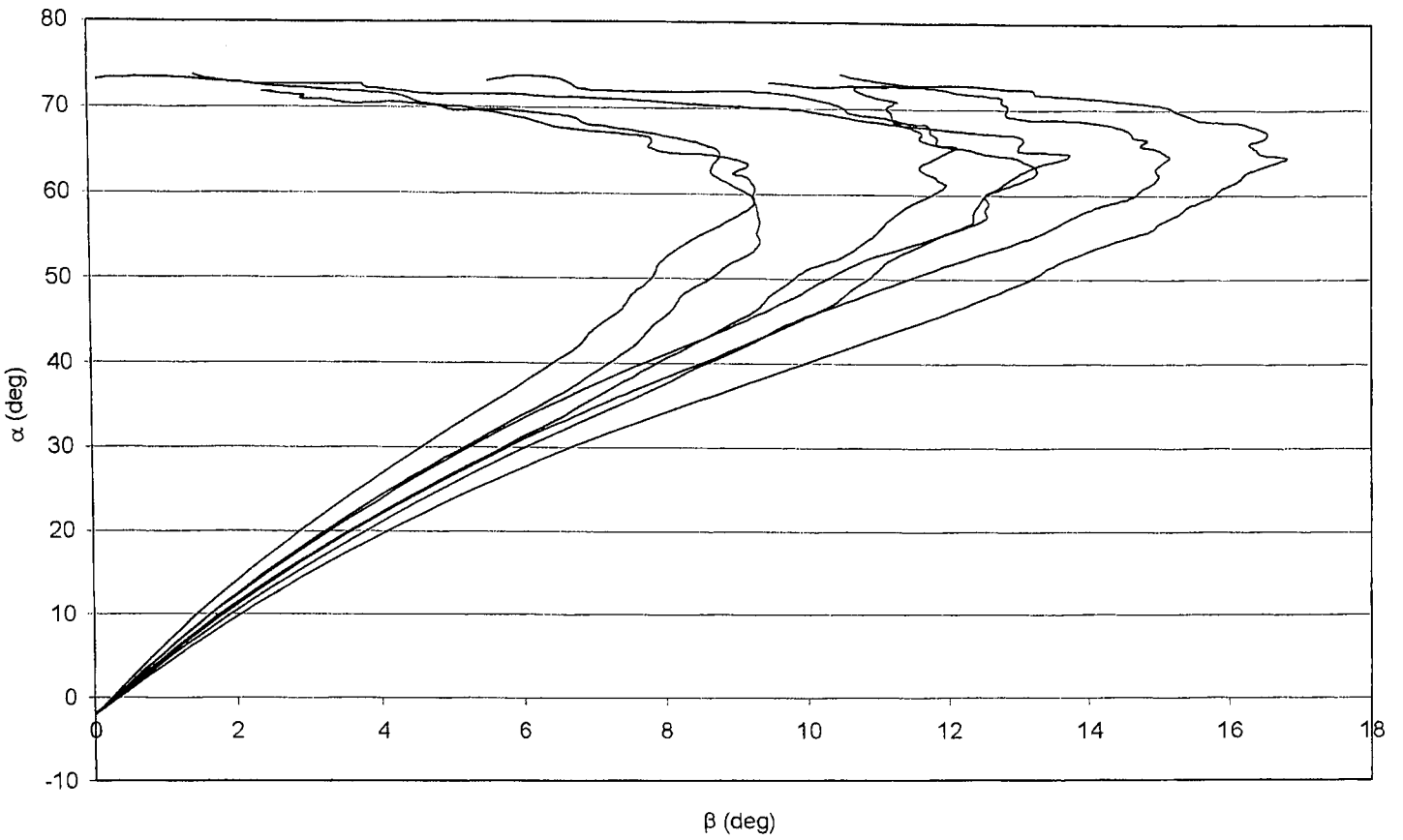


Fig. A4.9. Subject 4 from position 1.

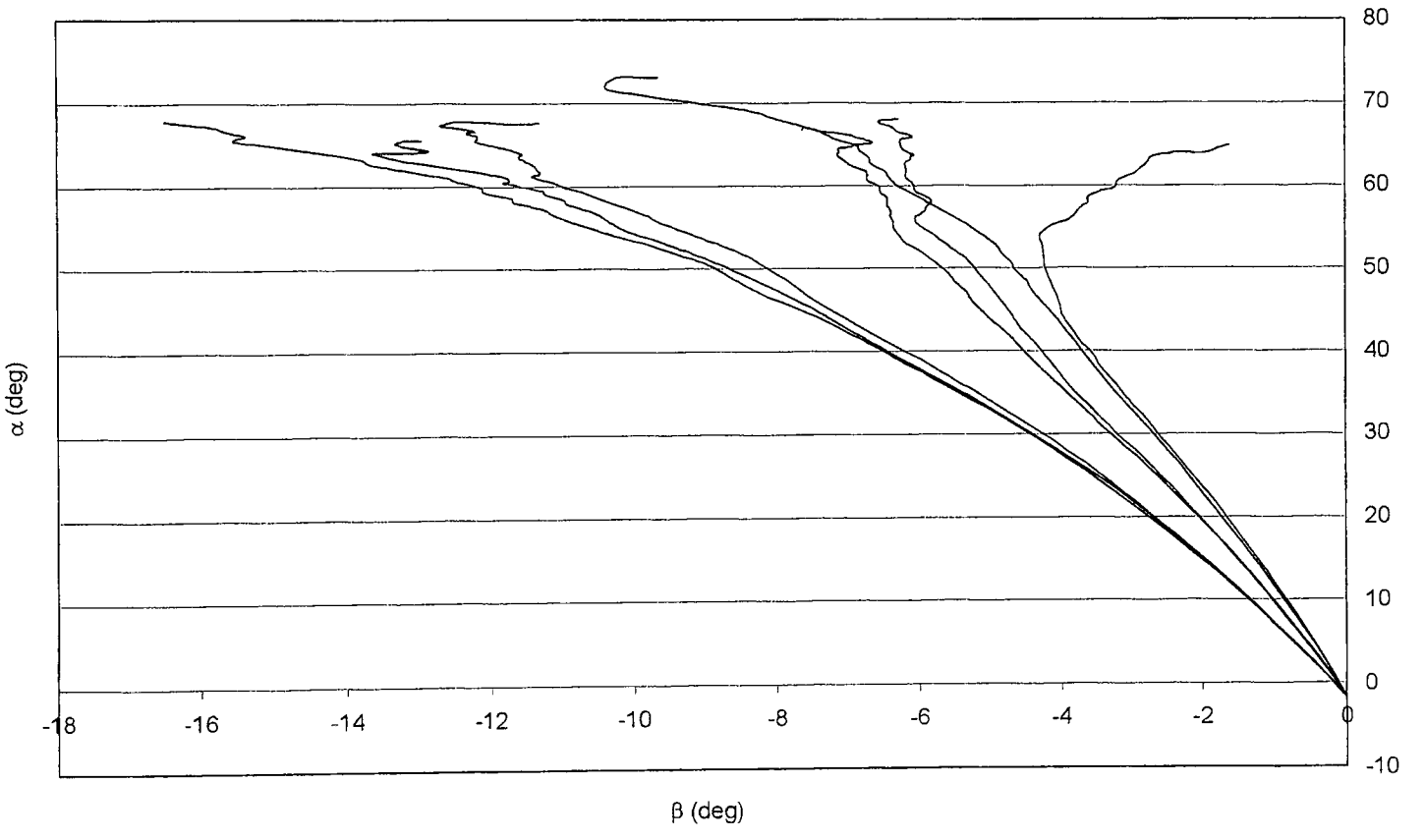


Fig. A4.10. Subject 4 from position 2.

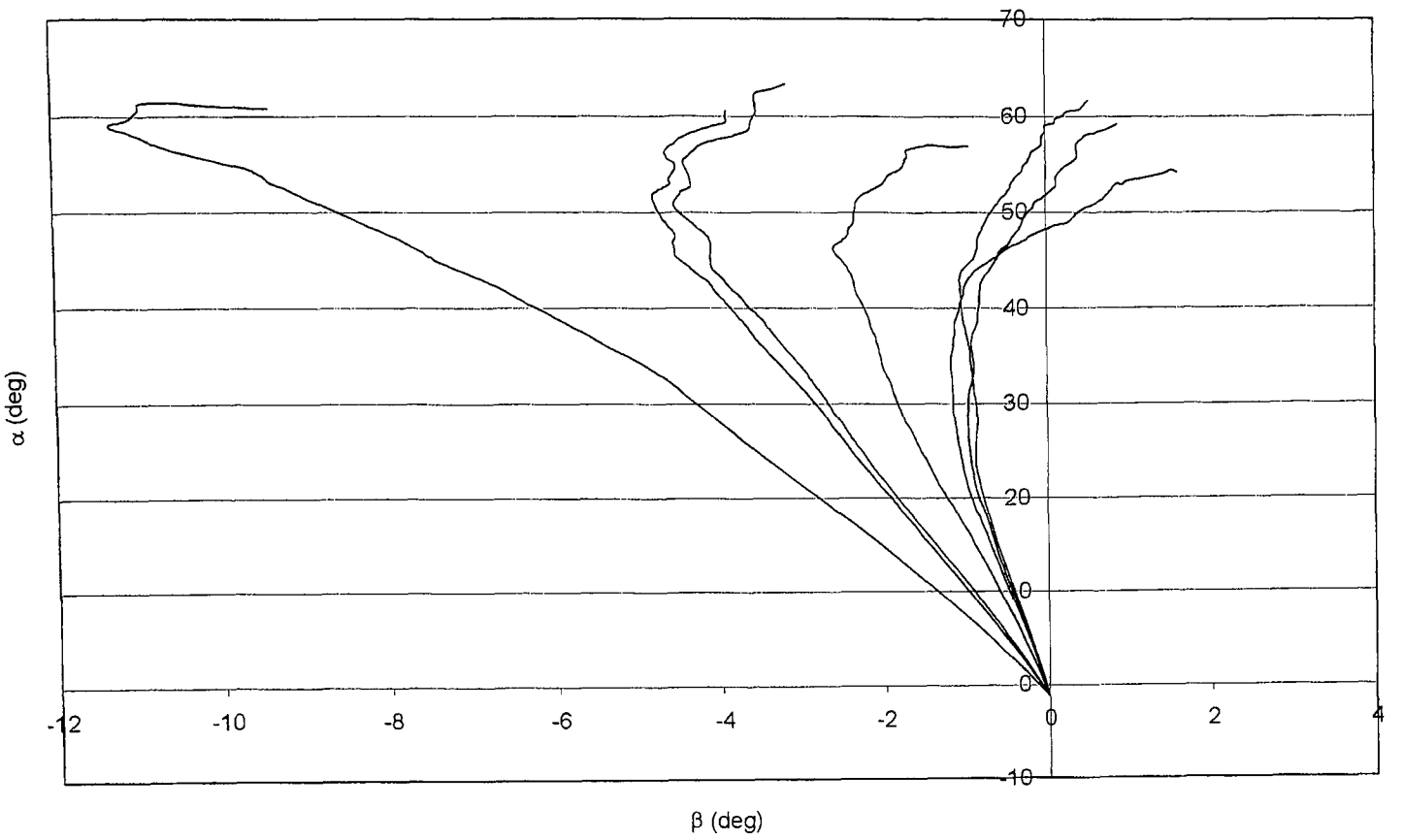


Fig. A4.11. Subject 4 from position 3.

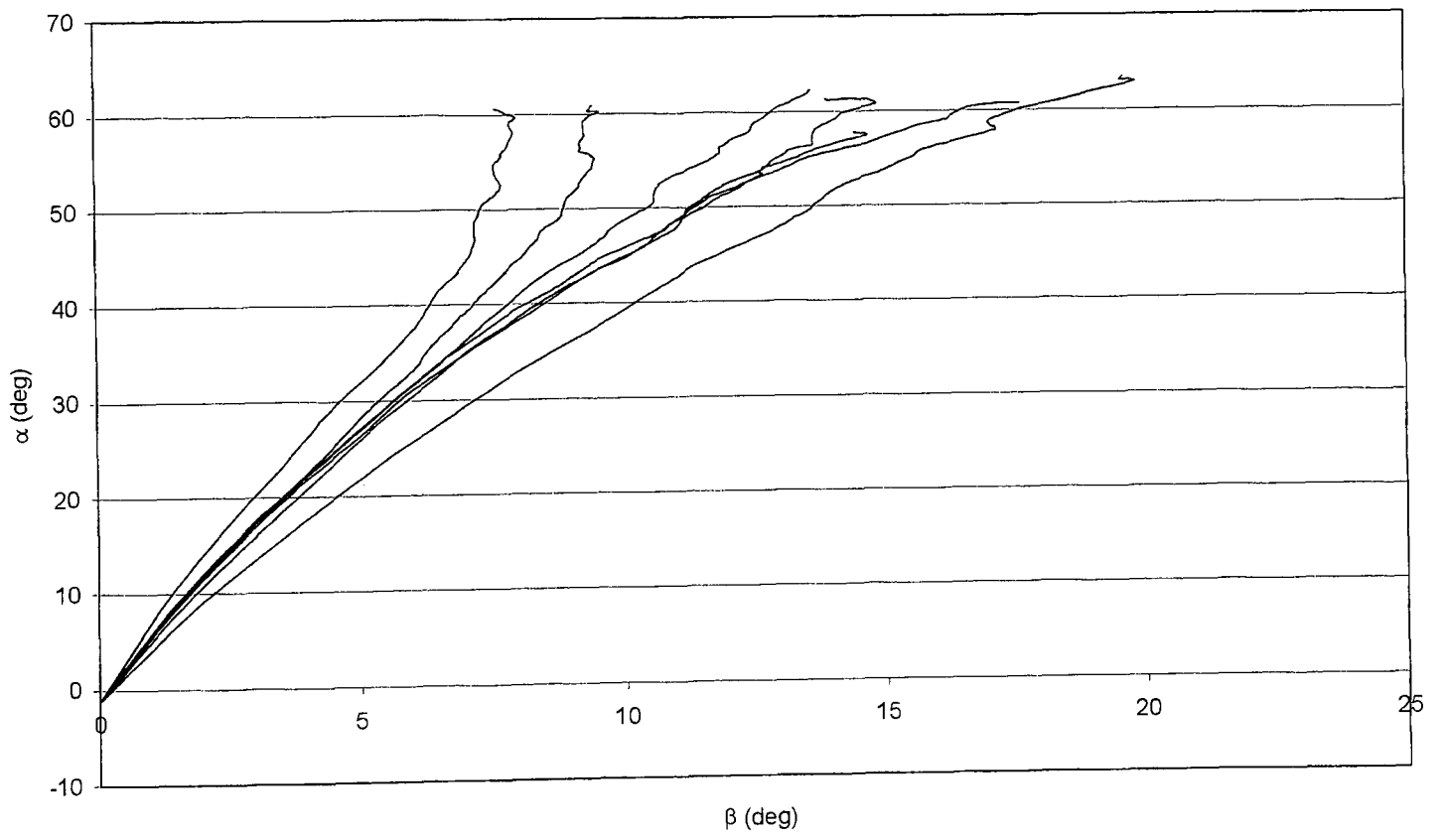


Fig. A4.12. Subject 4 from position 4.

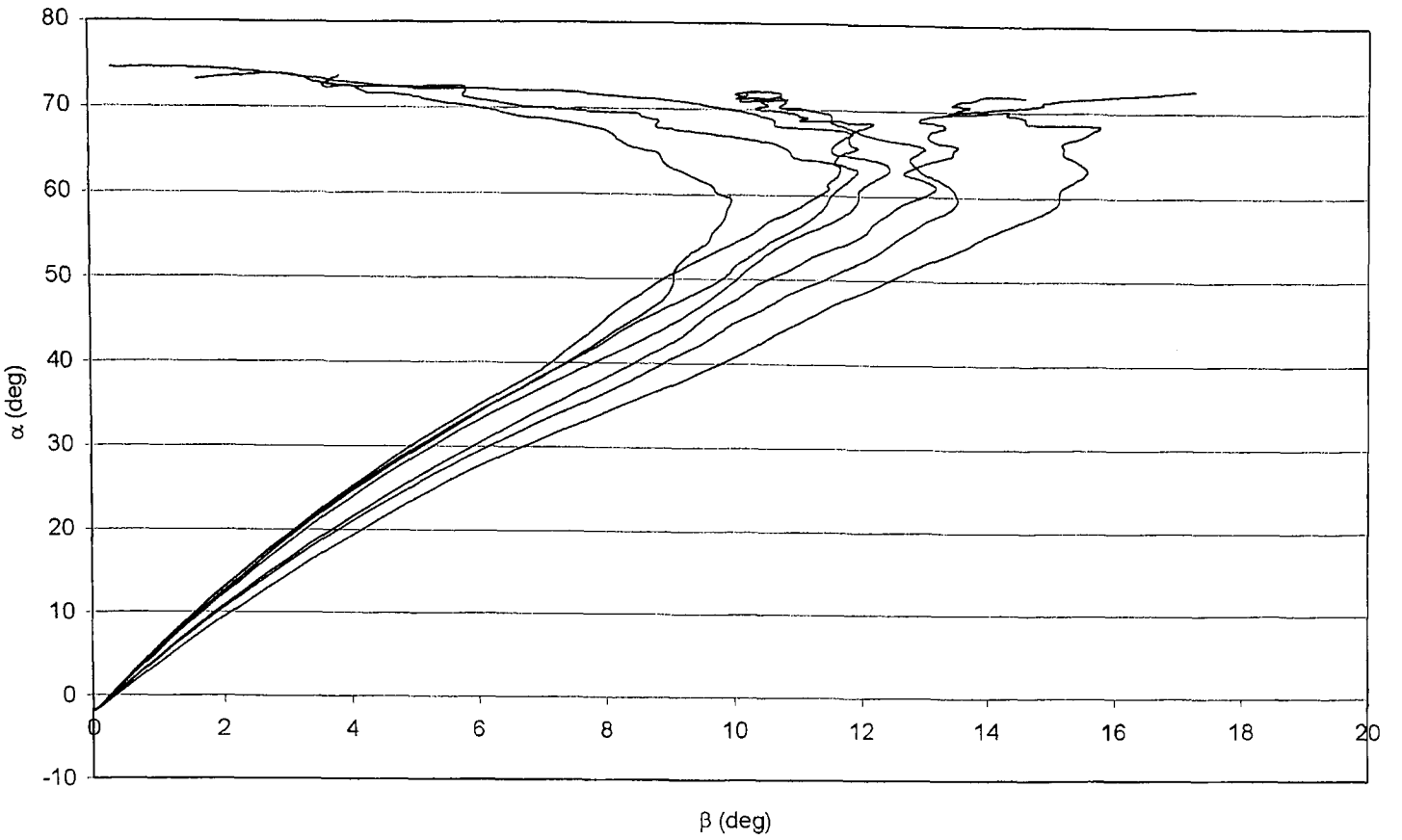


Fig. A4.13. Subject 5 from position 1.

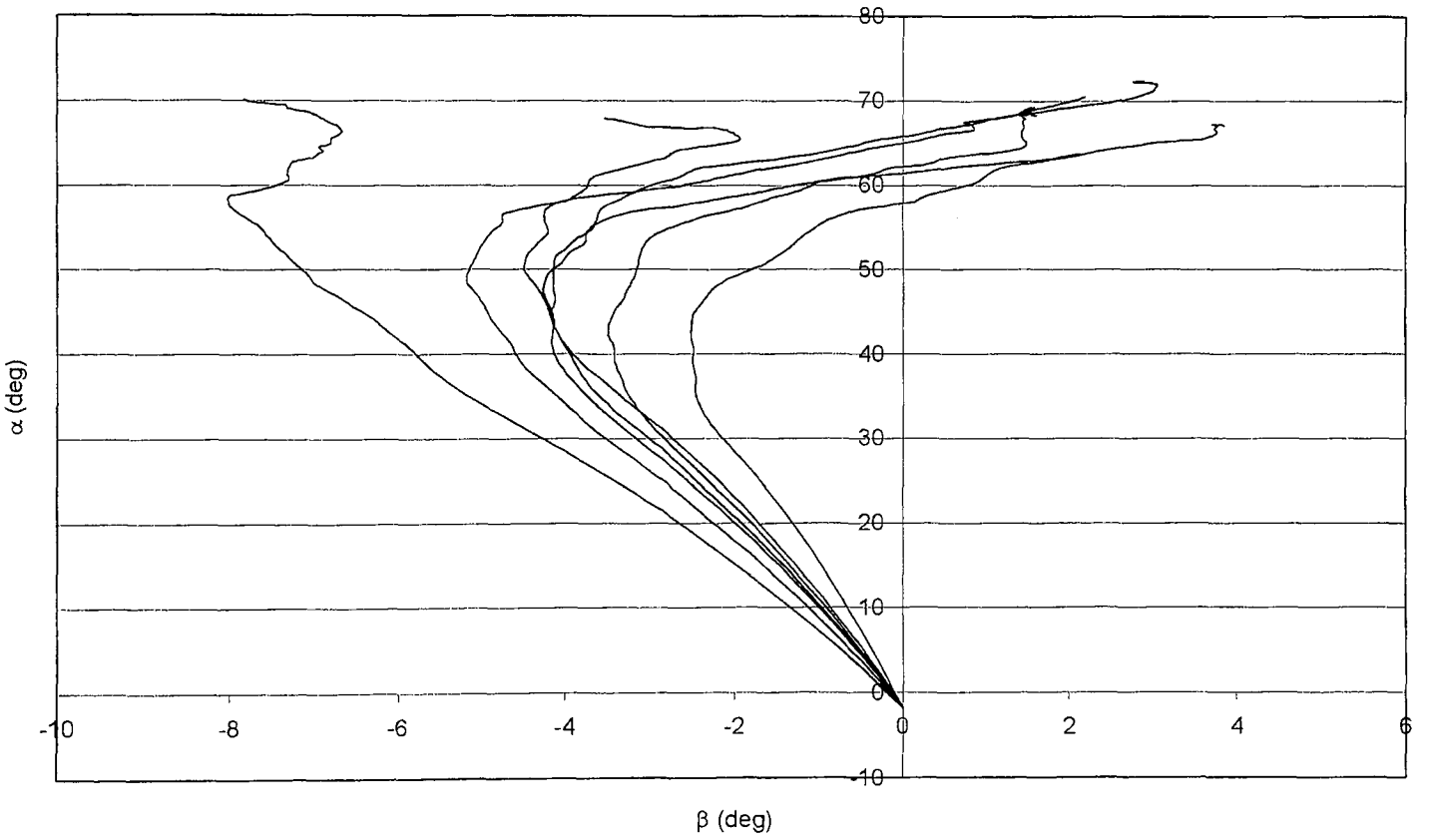


Fig. A4.14. Subject 5 from position 2.

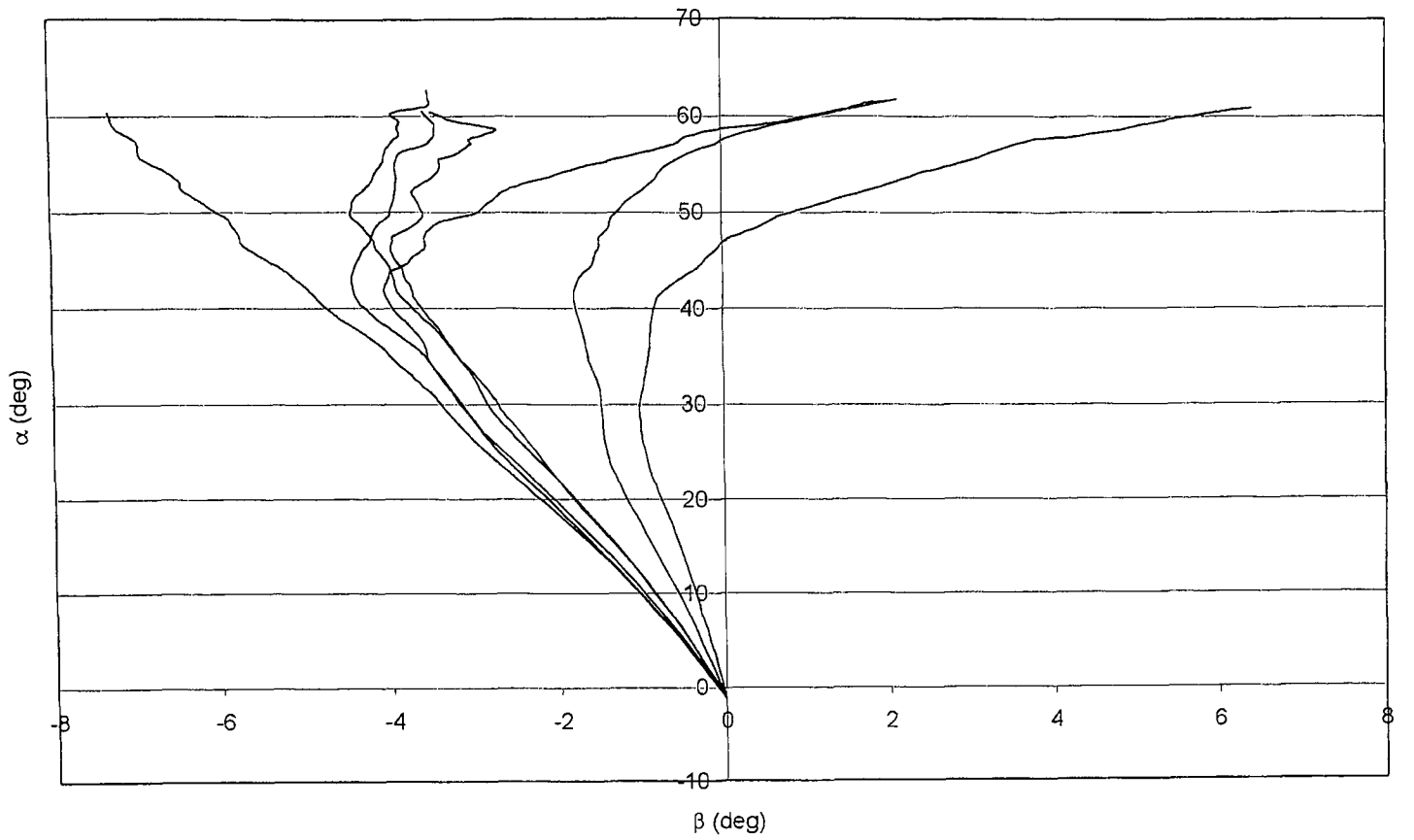


Fig. A4.15. Subject 5 from position 3.

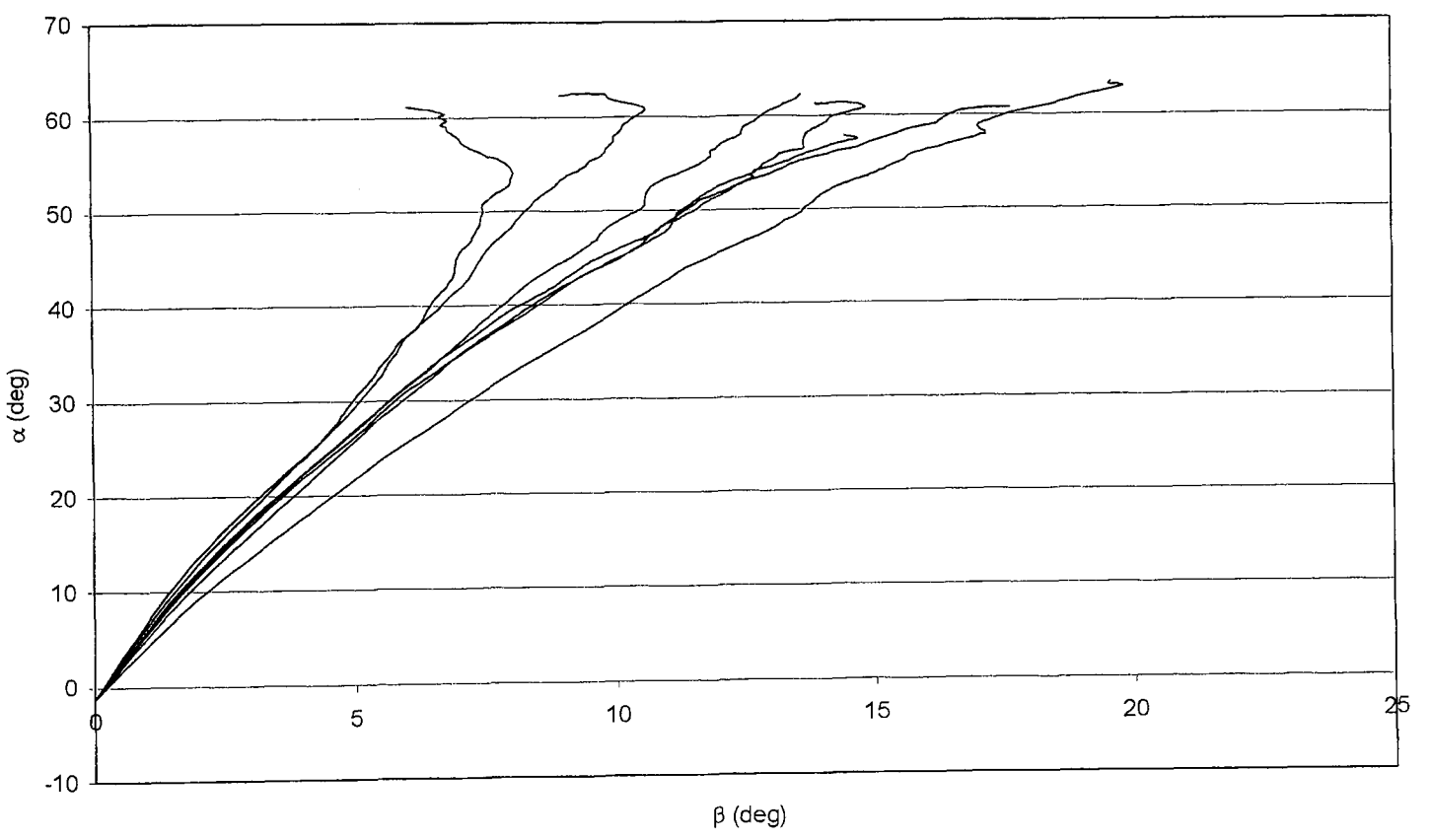


Fig. A4.16. Subject 5 from position 4.

Appendix 6.1. Interception strategies

The programs that implemented the strategies all ran through the same initial steps and terminal steps[1]. The detailed differences are outlined for each strategy. Explanatory remarks within the programs are in *italic* font.

Initial steps:

- Program selects the correct experiment, subject, and trial.
- Defines appropriate constants e.g. Pi, *g*, radians-degrees conversion factor.
- Copies first 10 frames of real fielder's movement across to simulated fielder.
- Captures values used in last copied frame for use in the strategy (positions and visual angle tangents).
- Sets number of frames over which the simulated fielder's position is to be calculated.
- Begins stepwise calculation of simulated fielder's position, frame-by-frame.
- Finds X, Y, and Z co-ordinates of ball in the particular frame in question.
- Height of ball relative to fielder's eye calculated.
- Calculates the value of tan α that gives constant d(tan α)/dt.
- Uses height of ball relative to fielder's eye to find the radius of the circle on which that value of tan α is correct.

Each program then determines where the particular strategy it is designed to model would place the simulated fielder.

Terminal steps:

- Calculates how far the fielder has moved in each axis.
- Values combined to find total movement for that frame.
- Sets maximum running speed and acceleration.
- If necessary, reduces distance travelled in direction of movement to prevent exceeding acceleration or speed limits and re-calculates new fielder position.
- Calculates new visual angle tangents for that simulated fielder's new position
- Moves to next frame.
- Once a trial is complete moves to next trial.
- Once trials are complete moves to next subject.

---

[1] The actual programs used around 180 lines of code. Presented are condensed summaries of the key differences in code.

A6.1.1. Constant δ strategy

```
tand = (xball - xperson) / (yperson - yball)
```

Calculates the value of tan δ that existed in the previous frame.

```
d = Atn(tand)
```

The angle δ itself (in radians)

```
nx = pradius * Sin(d)
ny = pradius * Cos(d)
newxball = Cells(calc + 1, 2)
newyball = Cells(calc + 1, 3)
newxperson = newxball - nx
newyperson = newyball + ny
```

Locates the fielder at a position that gives constant δ.

A6.1.2. Minimum energy strategy

```
For d = beginangle To endangle Step 0.05
nx = pradius * Sin(d)
ny = pradius * Cos(d)
newxball = Cells(calc + 1, 2)
newyball = Cells(calc + 1, 3)
newxperson = newxball + nx
newyperson = newyball + ny
```

Simulated fielder is positioned at 0.05rad intervals around the circle that gives the correct value of tan α.

```
xmove = newxperson - xperson
ymove = newyperson - yperson
dmove = (xmove ^ 2 + ymove ^ 2) ^ 0.5
```

Calculates how far fielder has had to move to get to new position.

```
If dmove < bestdmove Then
    bestdmove = dmove
    bestxperson = newxperson
    bestyperson = newyperson
    bestxmove = xmove
    bestymove = ymove
End If
```

If position is nearer than previous attempt, then position is selected as the best.

A6.1.3. LOT strategy

```
For d = beginangle To endangle Step 0.01
nx = pradius * Sin(d)
ny = pradius * Cos(d)
newxball = Cells(calc + 1, 2)
newyball = Cells(calc + 1, 3)
newxperson = newxball + nx
newyperson = newyball + ny
newtanb2 = ((newxball - newxperson) / (newyperson - newyball)) + (newxperson /
                                                    (newyperson + fixeddist))
```

Simulated fielder is positioned at 0.05rad intervals around the circle that gives the correct value of tan α.

```
bdiff = ((tanb2 - newtanb2) ^ 2) ^ 0.5
xmove = newxperson - xperson
ymove = newyperson - yperson
If bdiff < bestbdiff Then
bestbdiff = bdiff
bestxperson = newxperson
bestyperson = newyperson
bestxmove = xmove
bestymove = ymove
bestdmove = (xmove ^ 2 + ymove ^ 2) ^ 0.5
End If
```

If position is closer to giving constant d(tan β)/dt than previous attempt, then position is selected as the best.

A6.1.4. Conserved alignment strategy

```
For prange = beginrange To endrange
nx = prange * Sin(tan_initalign)
ny = prange * Cos(tan_initalign)
newxball = Cells(calc + 1, 2)
newyball = Cells(calc + 1, 3)
newzball = Cells(calc + 1, 4)
newxperson = newxball + nx
newyperson = newyball + ny
newtana2 = (newzball - 170) / ((newxball - newxperson) ^ 2 + (newyperson -
                                                    newyball) ^ 2) ^ 0.5
```

```
actnewtana2 = tana2 + (tana2 - oldtana2)
        Simulated fielder is positioned at 1cm intervals along the line that brings him into
        alignment with the ball.
adiff = (newtana2 - oldtana2) ^ 2
xmove = newxperson - xperson
ymove = newyperson - yperson
If adiff < bestadiff Then
        bestadiff = adiff
        bestxperson = newxperson
        bestyperson = newyperson
        bestxmove = xmove
        bestymove = ymove
        bestdmove = (xmove ^ 2 + ymove ^ 2) ^ 0.5
 End If
        If position is closer placing the fielder at the correct value of tan α (that which
        gives constant d(tan α)/dt) than previous attempt, then position is selected as the
        best.
```

A6.1.5. Constant γ strategy

```
        Uses iterative process to move the simulated fielder closest to the position that
        gives constant d(tan α)/dt and constant γ.
 For d = beginrange To endrange Step 0.1
 GoSub zangdiff_calc
        Moves simulated fielder around circle that gives correct value of tan α in steps of
        0.1rad to find the position that comes closest to giving constant γ.
 If Zangdiff < bestZangdiff Then
        bestZang = newZang
 End If
        Records best value of γ found thus far.
nextd:
 Next d
 beginrange = bestZang - 0.05
 endrange = bestZang + 0.05
 For d = beginrange To endrange Step 0.005
        Uses smaller steps (0.005rad) to take fielder closer to position on tan α ring that
        gives constant γ.
 GoSub zangdiff_calc
 If Zangdiff < bestZangdiff Then
```

```
  bestxperson = newxperson
  bestyperson = newyperson
  bestd = d
  bestZang = newZang
  End If
nextd2:
  Next d
zangdiff_calc:
        Subroutine that calculates the difference between γt and γt-1.
  nx = pradius * Sin(d)
  ny = pradius * Cos(d)
        The X and Y distances from the ball to where the fielder's predicted position lies
  newxball = Cells(calc + 1, 2)
  newyball = Cells(calc + 1, 3)
  newxperson = newxball + nx
  newyperson = newyball + ny
  newxmove = newxperson - xperson
  newymove = newyperson - yperson
  newZang = Atn(newxmove / newymove)
        Angle of simulated fielder's running.
Zangdiff = Abs(oldZang - newZang)
        Difference between simulated fielder's angle of running in the previous frame and
        angle of running in the current frame.
Return
```

Appendix 6.2. Examples of the performance of the four proposed interception strategies

The figures on the following pages show four examples of the performance of each of the five proposed interception strategies. The figures shown are vertical projections of the movements of the real and simulated fielder as the moved to intercept the ball. The upper two figures ((a) and (b)) on each page show two examples from the experiments from chapter 3 – the 'roof' experiment. Figure (a) is a trial in which the strategy performed well in modelling the interceptive behaviour of the real fielder. Figure (b) is one in which the strategy performed poorly. The lower two figures ((c) and (d)) are from the experiment described in chapter 4 – the 'ground' experiment. Similarly, figure (c) is a trial in which the strategy was relatively successful, whilst figure (d) is one where the strategy was flawed. Filled circles represent the position of the real fielder in each frame of video footage of the trial in question. The axes of each graph define the co-ordinates of the catching area through which the catch took place, giving a plan view of the trial. In each case, the fielder starts in a position on the Y-axis, facing toward the X-axis. The co-ordinates are true positions (they are not Vidi-Clik co-ordinates) and the scale is in centimetres. In the top-right of each graph are the subject number and trial number of the trial represented in that graph, e.g. 3-19 is subject number 3, trial number 19.

A6.2.1. Constant δ strategy- figure A6.1.

Figure (a) shows that the constant δ strategy can produce a very good fit to the human data. The majority of points are virtually coincident and the simulated fielder follows a running path that curves in the same way as that of the real fielder. Figure (b) highlights the sensitivity of the strategy to the previous movement that the real fielder made in the frame before the strategy begins to operate.

Figure (c) is also a good fit to the true data but the running path is not curved. The path followed by the real fielder has a gentle curve whereas the simulated fielder follows a dead straight path. Figure (d) is a poor fit. The human fielder follows a slightly unusual path (it does not curve in the typical manner) but this is not registered on by the constant δ strategy, which sends the simulated fielder on a straight path.

A6.2.2. LOT strategy – figure A6.2.

The LOT strategy performs very well for the trial shown in figure (a); the points are consistently close and the paths curve in a similar fashion. Toward the end of the trial, the real fielder moves slightly further forward in the Y-axis than the simulated fielder. Figure (b) is remarkably similar to figure (b) for the constant δ strategy. Each shows the performance for the respective strategy on the same trial and the similarity in their positioning of the simulated fielder reflects the similarity of the two strategies. Both are send the fielder the wrong way when the strategy begins due to the movement in the previous frame.

Figure (c) is a reasonable fit to the data. The simulated fielder starts to move off in a slightly wrong direction but soon tracks back to the path followed by the real fielder. In figure (d), the path followed by the simulated fielder is a very approximation of the path followed by the real fielder. The real fielder follows an atypically but distinctly curved path. The simulated fielder follows a straight path.

A6.2.3. Minimum energy strategy – figure A6.3.

The strategy performs well in figure (a). Data points and curvature are closely matched. In figure (b), the simulated fielder follows a highly unusual path. This is due to a short spell where the nearest point on the rings of constantly increasing tan α is in a very different direction to that followed by the real fielder. This sends the simulated

fielder off course without violating the rules of the strategy. By the time the simulated fielder begins moving in the correct direction again, it is too late for recovery and the interception point is not reached.

Figure (c) is a reasonable fit to the data. The simulated fielder ends up in a slightly different position to the real fielder but the majority of points are near to the real fielder. In figure (d), again, the minimum energy strategy has produced a highly unusual curving path. The simulated fielder begins moving laterally and follows a path that curves gently, eventually ending up on the same vertical plane as the ball.

A6.2.4. Conserved alignment strategy – figure A6.4.

In figure (a), the simulated fielder follows a path that although is not coincident with the true path, it remains at a close and consistent distance throughout the trial. The rest of the trials shown display a common trait of the conserved alignment strategy. In attempting to restore the original alignment the fielder had with the ball, the strategy sends the simulated fielder moving too quickly in the X-axis. In order to keep tan α increasing at the appropriate rate, the simulated fielder moves further away from the ball in the Y-axis than the real fielder and results in a path with pronounced curvature.

A6.2.5. Constant γ strategy – figure A6.5.

The four strategy examples for the constant γ strategy illustrate how ineffective the strategy was at guiding the simulated fielder to the interception point on a path that corresponded with that of the real fielder. Even the examples demonstrating supposedly good performance of the strategy ((a) and (c)) are far from impressive – the path taken by the simulated fielder does not curve in the manner expected. Figure (b) and figure (d), showing poor performance of the constant γ strategy demonstrate why this strategy is so consistently inefficient. The initial movements of the fielder have a critical effect on the

angle γ, which determines the path the fielder should take. The angle γ can be observed to remain approximately constant in the latter stages of a trial. However, it is likely that this is a result of fielder movements under the guidance of a different strategy. The cue provided by the angle γ cannot be used to guide interceptive behaviour in the early stages of a trial.

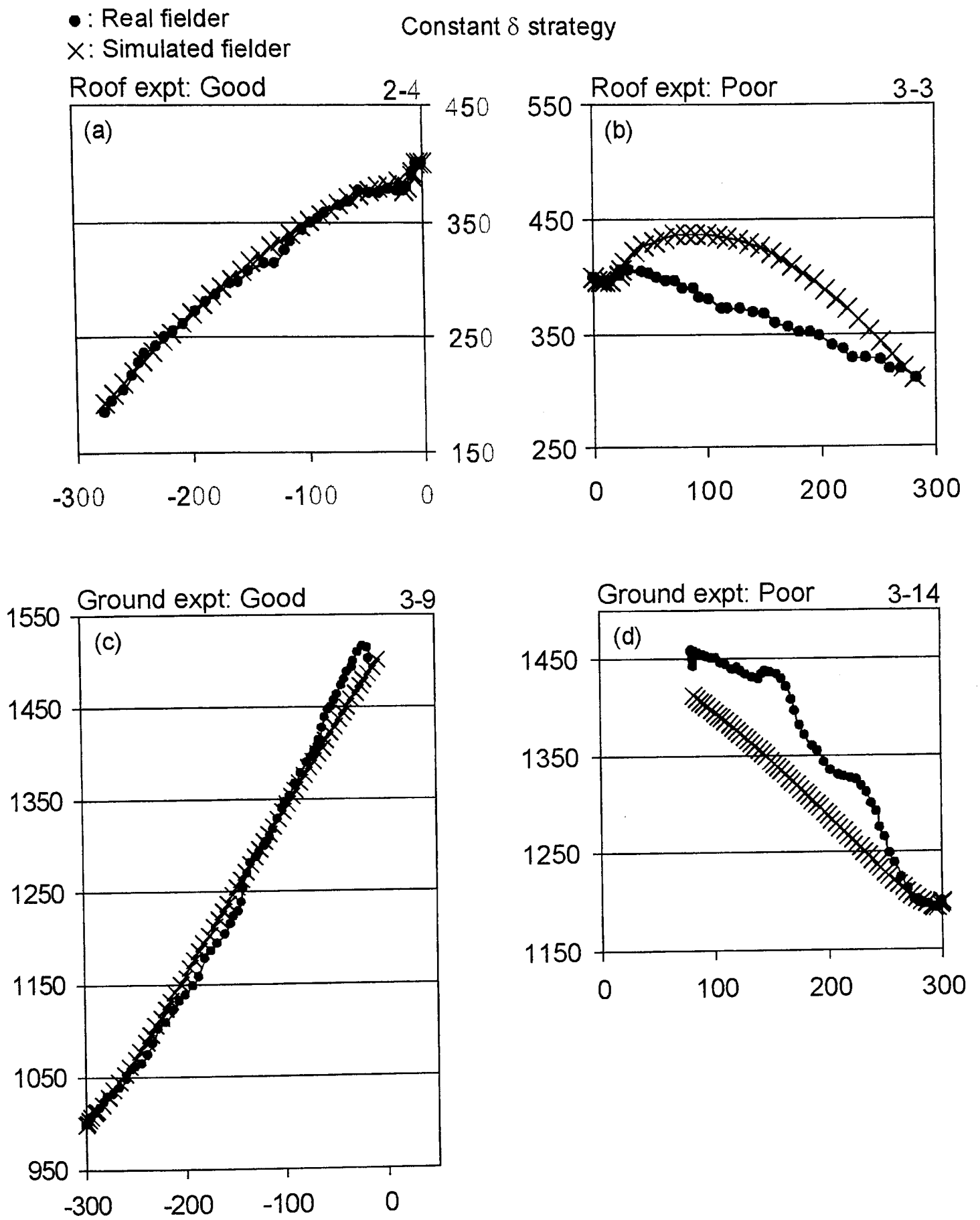

● : Real fielder
×: Simulated fielder
Constant δ strategy
Roof expt: Good
2-4
(a)
450
350
250
150
-300
-200
-100
0
Roof expt: Poor
3-3
(b)
550
450
350
250
0
100
200
300
Ground expt: Good
3-9
(c)
1550
1450
1350
1250
1150
1050
950
-300
-200
-100
0
Ground expt: Poor
3-14
(d)
1450
1350
1250
1150
0
100
200
300

Fig. A6.1.

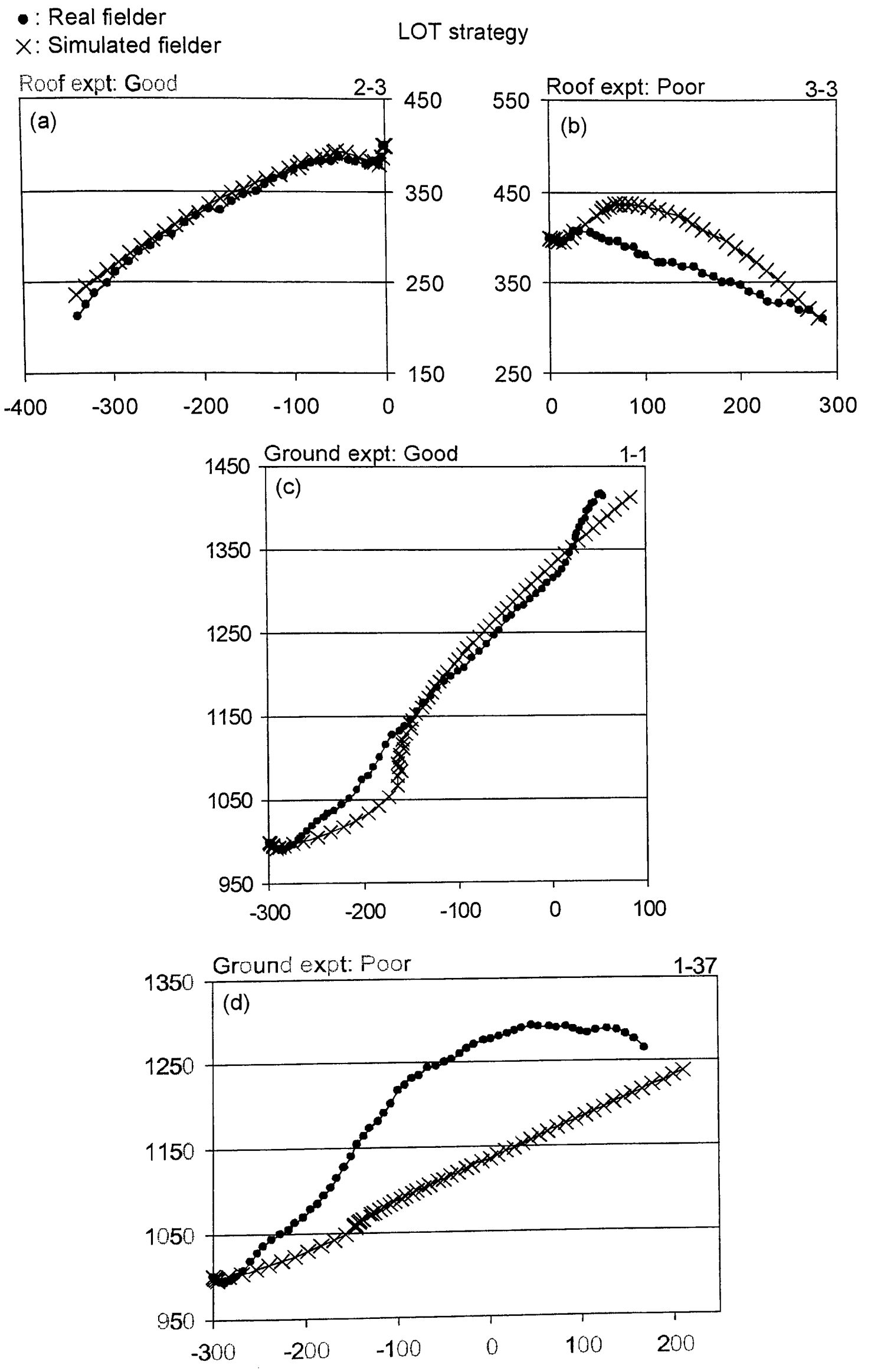

● : Real fielder
×: Simulated fielder
LOT strategy
Roof expt: Good
2-3
(a)
450
350
250
150
-400
-300
-200
-100
0
Roof expt: Poor
3-3
(b)
550
450
350
250
0
100
200
300
Ground expt: Good
1-1
(c)
1450
1350
1250
1150
1050
950
-300
-200
-100
0
100
Ground expt: Poor
1-37
(d)
1350
1250
1150
1050
950
-300
-200
-100
0
100
200

Fig. A6.2.

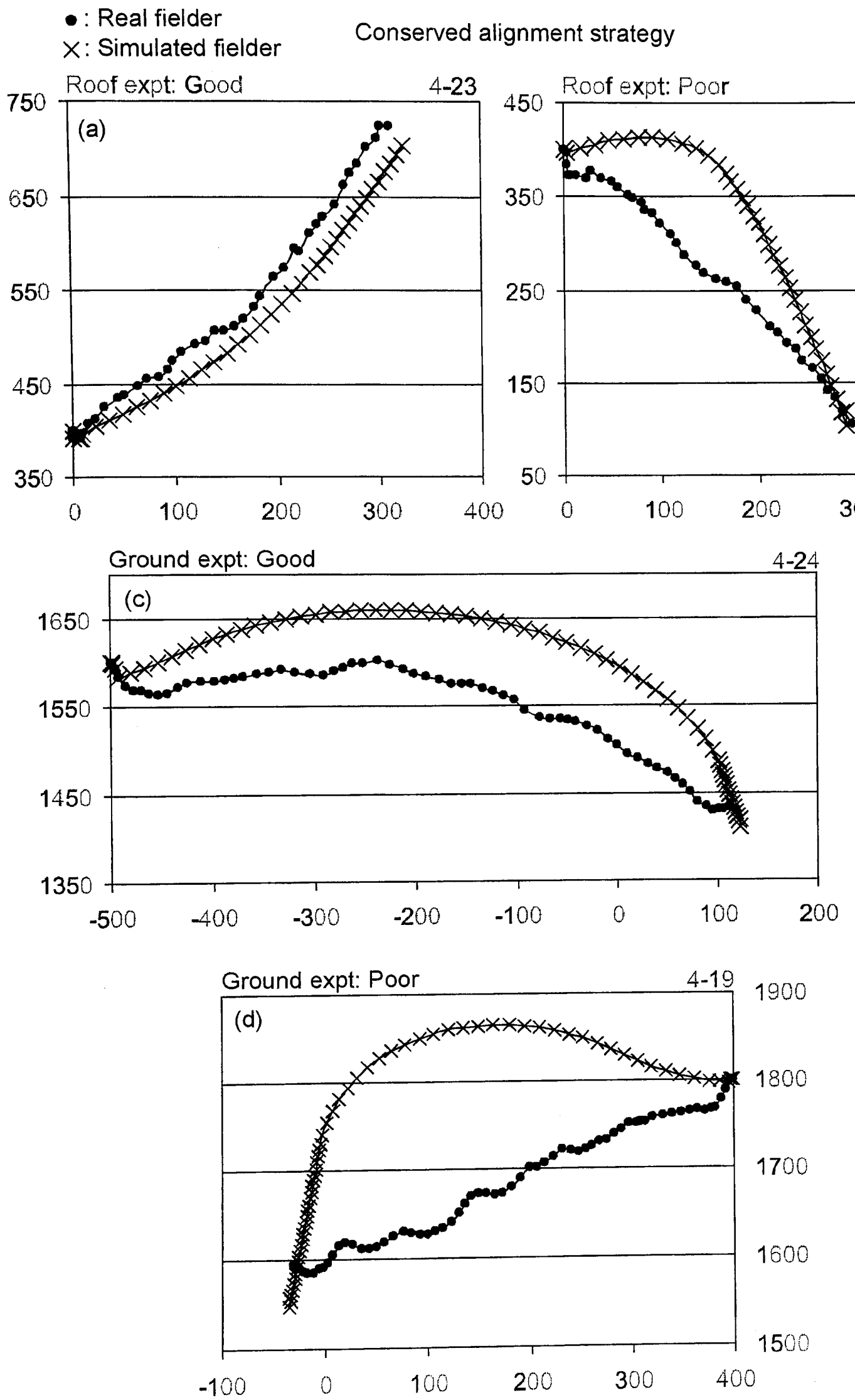

● : Real fielder
× : Simulated fielder
Conserved alignment strategy
Roof expt: Good
4-23
(a)
750
650
550
450
350
0
100
200
300
400
Roof expt: Poor
4-14
(b)
450
350
250
150
50
0
100
200
300
Ground expt: Good
4-24
(c)
1650
1550
1450
1350
-500
-400
-300
-200
-100
0
100
200
Ground expt: Poor
4-19
(d)
1900
1800
1700
1600
1500
-100
0
100
200
300
400

Fig. A6.4.

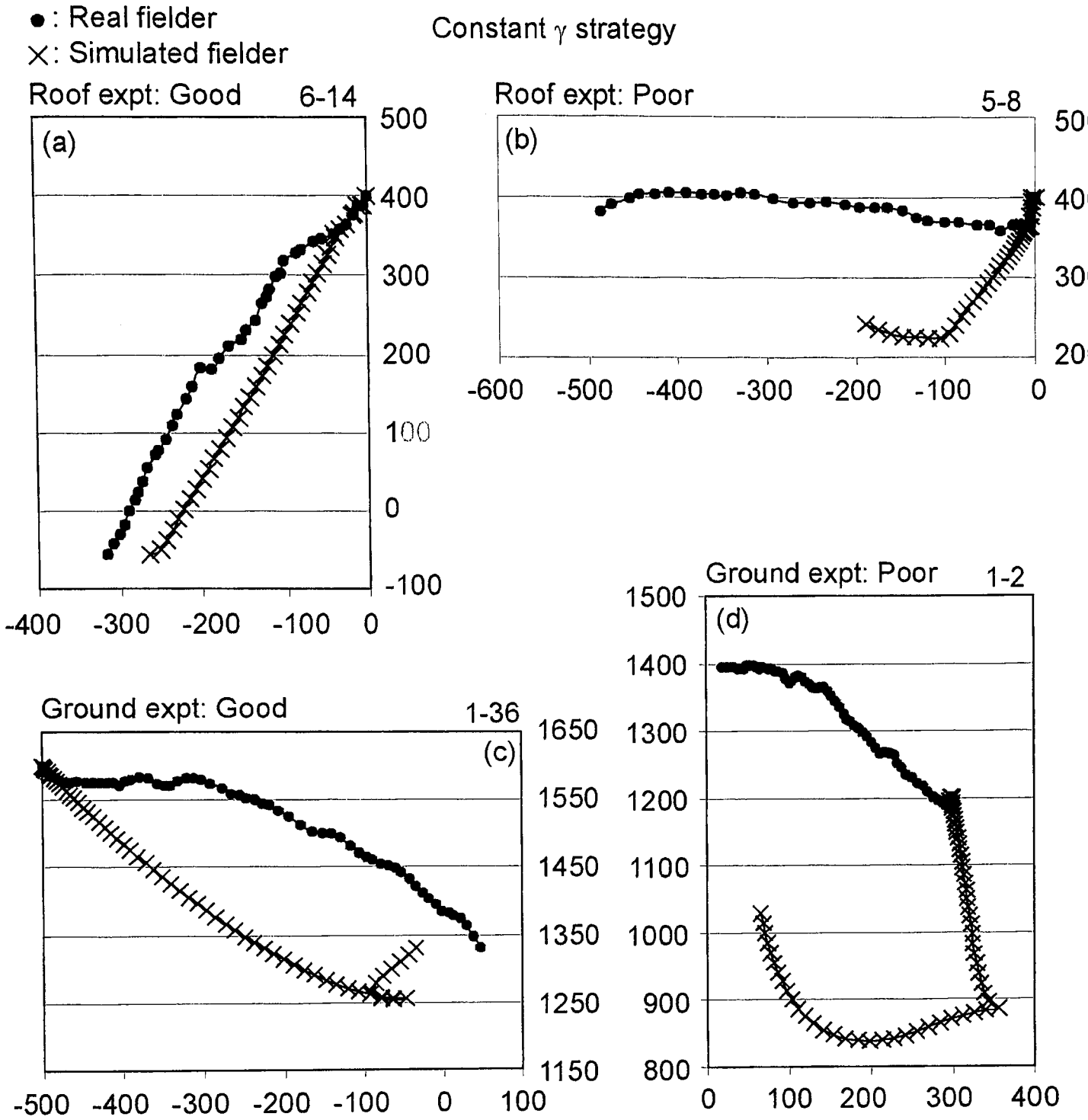

● : Real fielder
×: Simulated fielder
Constant γ strategy
Roof expt: Good 6-14
(a)
500
400
300
200
100
0
-100
-400 -300 -200 -100 0
Roof expt: Poor 5-8
(b)
500
400
300
200
-600 -500 -400 -300 -200 -100 0
Ground expt: Good 1-36
(c)
1650
1550
1450
1350
1250
1150
-500 -400 -300 -200 -100 0 100
Ground expt: Poor 1-2
(d)
1500
1400
1300
1200
1100
1000
900
800
0 100 200 300 400

Fig. A6.5.

Appendix 6.3. Statistics comparing the performance of the five proposed interception strategy models

Unless otherwise stated, 'performance' of a strategy refers to the mean distance that the strategy places the simulated fielder from the real fielder in centimetres.

Case Summaries

Experiment		Constant d	LOT	Min. energy	Align	Constant g
Roof	N	153	153	153	153	153
	Mean	24.9	24.8	34.2	34.2	84.0
	Std. Deviation	11.1	10.8	21.3	12.4	39.8
Ground	N	175	175	175	175	175
	Mean	33.3	50.0	65.2	84.9	226.3
	Std. Deviation	14.5	11.3	22.5	19.2	60.1
Total	N	328	328	328	328	328
	Mean	29.4	38.3	50.7	61.2	159.9
	Std. Deviation	13.6	16.8	26.9	30.2	87.8

Table A6.1. Summary of the performance of the five strategy models.

Ranks

	Experiment	N	Mean Rank	Sum of Ranks
Constant d	Roof	153	133.61	20442.00
	Ground	175	191.51	33514.00
	Total	328		
LOT	Roof	153	85.52	13084.00
	Ground	175	233.55	40872.00
	Total	328		
Min. energy	Roof	153	101.18	15480.00
	Ground	175	219.86	38476.00
	Total	328		
Align	Roof	153	79.41	12149.00
	Ground	175	238.90	41807.00
	Total	328		
Constant g	Roof	153	81.43	12459.00
	Ground	175	237.13	41497.00
	Total	328		

Table A6.2(a). Ranks for Mann-Whitney test comparing performance of each strategy across experiments.

Test Statistics[a]

	Constant d	LOT	Min. energy	Align	Constant g
Mann-Whitney U	8661.000	1303.000	3699.000	368.000	678.000
Wilcoxon W	20442.000	13084.000	15480.000	12149.000	12459.000
Z	-5.517	-14.104	-11.308	-15.196	-14.834
Asymp. Sig. (2-tailed)	.000	.000	.000	.000	.000

a. Grouping Variable: Experiment

Table A6.2(b). Test statistics for the Mann-Whitney test comparing performance of each strategy across experiments.

Ranks

		N	Mean Rank	Sum of Ranks
LOT - Constant d	Negative Ranks	80	97.61	7809.00
	Positive Ranks	248	186.08	46147.00
	Ties	0		
	Total	328		
Min. energy - Constant d	Negative Ranks	47	77.87	3660.00
	Positive Ranks	281	178.99	50296.00
	Ties	0		
	Total	328		
Align - Constant d	Negative Ranks	27	48.96	1322.00
	Positive Ranks	301	174.86	52634.00
	Ties	0		
	Total	328		
Constant g - Constant d	Negative Ranks	6	8.67	52.00
	Positive Ranks	322	167.40	53904.00
	Ties	0		
	Total	328		
Min. energy - LOT	Negative Ranks	101	113.27	11440.00
	Positive Ranks	227	187.30	42516.00
	Ties	0		
	Total	328		
Align - LOT	Negative Ranks	35	57.29	2005.00
	Positive Ranks	293	177.31	51951.00
	Ties	0		
	Total	328		
Constant g - LOT	Negative Ranks	6	11.83	71.00
	Positive Ranks	322	167.34	53885.00
	Ties	0		
	Total	328		
Align - Min. energy	Negative Ranks	66	144.56	9541.00
	Positive Ranks	262	169.52	44415.00
	Ties	0		
	Total	328		
Constant g - Min. energy	Negative Ranks	14	32.86	460.00
	Positive Ranks	314	170.37	53496.00
	Ties	0		
	Total	328		
Constant g - Align	Negative Ranks	15	24.13	362.00
	Positive Ranks	313	171.23	53594.00
	Ties	0		
	Total	328		

Table A6.3(a). Ranks for the Wilcoxon test comparing the performance across strategie in each experiment.

Test Statistics[c]

Experiment		LOT - Constant d	Min. energy - Constant d	Align - Constant d	Min. energy - LOT	Align - LOT	Align - Min. energy
Roof	Z	-.041[a]	-7.298[b]	-8.888[b]	-6.261[b]	-9.108[b]	-3.642[b]
	Asymp. Sig. (2-taile	.967	.000	.000	.000	.000	.000
Ground	Z	-11.376[b]	-11.050[b]	-11.440[b]	-7.432[b]	-11.209[b]	-9.895[b]
	Asymp. Sig. (2-taile	.000	.000	.000	.000	.000	.000

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

Table A6.3(b). Test statistics for the Wilcoxon test comparing performance across strategies in each experiment.

Appendix 6.4. Summary of the parameters used in optimisation of the strategy models

Case Summaries

Experiment	Strategy		Strategy initiation time(sec)	Max. velocity (m/s)	Max. acceleration (m/s/s)
Roof	Constant d	N	20	20	20
		Mean	.38	3.46	3.80
	LOT	N	20	20	20
		Mean	.40	3.49	3.20
	Min. energy	N	20	20	20
		Mean	.14	3.45	4.70
	Alignment	N	20	20	20
		Mean	.40	2.99	1.45
	Total	N	80	80	80
		Mean	.33	3.35	3.29
Ground	Constant d	N	20	20	20
		Mean	.30	2.25	3.80
	LOT	N	20	20	20
		Mean	.39	2.68	2.75
	Min. energy	N	20	20	20
		Mean	.19	2.74	3.15
	Alignment	N	20	20	20
		Mean	.34	2.59	1.00
	Total	N	80	80	80
		Mean	.30	2.56	2.68
Total	Constant d	N	40	40	40
		Mean	.34	2.86	3.80
	LOT	N	40	40	40
		Mean	.39	3.08	2.98
	Min. energy	N	40	40	40
		Mean	.17	3.09	3.93
	Alignment	N	40	40	40
		Mean	.37	2.79	1.23
	Total	N	160	160	160
		Mean	.32	2.95	2.98

Table A6.4.

Appendix 6.5. Statistics assessing the performance of the four optimised interception models

Case Summaries

Mean path diff. (cm)

Experiment	Strategy	N	Mean	Std. Deviation
Roof	Constant d	20	11.0	4.9
	LOT	20	17.9	10.0
	Min. energy	20	19.2	11.2
	Alignment	20	20.7	14.4
	Total	80	17.2	11.1
Ground	Constant d	20	23.5	9.5
	LOT	20	33.7	15.5
	Min. energy	20	35.2	12.9
	Alignment	20	69.3	25.8
	Total	80	40.4	24.1
Total	Constant d	40	17.2	9.8
	LOT	40	25.8	15.2
	Min. energy	40	27.2	14.4
	Alignment	40	45.0	32.1
	Total	160	28.8	22.0

Table A6.5. Mean distance of placement of simulated fielder from real fielder for each frame analysed and for each strategy.

Ranks

Strategy		Experiment	N	Mean Rank	Sum of Ranks
Constant d	Mean path diff. (cm)	Roof	20	13.25	265.00
		Ground	20	27.75	555.00
		Total	40		
LOT	Mean path diff. (cm)	Roof	20	14.45	289.00
		Ground	20	26.55	531.00
		Total	40		
Min. energy	Mean path diff. (cm)	Roof	20	13.65	273.00
		Ground	20	27.35	547.00
		Total	40		
Alignment	Mean path diff. (cm)	Roof	20	11.50	230.00
		Ground	20	29.50	590.00
		Total	40		

Table A6.6(a). Ranks for Mann-Whitney test comparing the performance of each strategy across experiments

Test Statistics [b]

Strategy		Mean path diff. (cm)
Constant d	Mann-Whitney U	55.000
	Wilcoxon W	265.000
	Z	-3.922
	Asymp. Sig. (2-tailed)	.000
	Exact Sig. [2*(1-tailed Sig.)]	.000[a]
LOT	Mann-Whitney U	79.000
	Wilcoxon W	289.000
	Z	-3.273
	Asymp. Sig. (2-tailed)	.001
	Exact Sig. [2*(1-tailed Sig.)]	.001[a]
Min. energy	Mann-Whitney U	63.000
	Wilcoxon W	273.000
	Z	-3.706
	Asymp. Sig. (2-tailed)	.000
	Exact Sig. [2*(1-tailed Sig.)]	.000[a]
Alignment	Mann-Whitney U	20.000
	Wilcoxon W	230.000
	Z	-4.869
	Asymp. Sig. (2-tailed)	.000
	Exact Sig. [2*(1-tailed Sig.)]	.000[a]

a. Not corrected for ties.

b. Grouping Variable: Experiment

Table A6.6(b). Test statistics for Mann-Whitney test comparing performance of each strategy across experiments.

Ranks

Experiment			N	Mean Rank	Sum of Ranks
Roof	Mean path diff. for LOT(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	3	8.33	25.00
		Positive Ranks	17	10.88	185.00
		Ties	0		
		Total	20		
	Mean path diff. for Min. energy(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	4	7.75	31.00
		Positive Ranks	16	11.19	179.00
		Ties	0		
		Total	20		
	Mean path diff. for Alignment(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	7	5.71	40.00
		Positive Ranks	13	13.08	170.00
		Ties	0		
		Total	20		
	Mean path diff. for Min. energy(cm) - Mean path diff. for LOT(cm)	Negative Ranks	9	11.00	99.00
		Positive Ranks	11	10.09	111.00
		Ties	0		
		Total	20		
	Mean path diff. for Alignment(cm) - Mean path diff. for LOT(cm)	Negative Ranks	9	10.33	93.00
		Positive Ranks	11	10.64	117.00
		Ties	0		
		Total	20		
	Mean path diff. for Alignment(cm) - Mean path diff. for Min. energy(cm)	Negative Ranks	10	8.80	88.00
		Positive Ranks	10	12.20	122.00
		Ties	0		
		Total	20		
Ground	Mean path diff. for LOT(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	3	6.33	19.00
		Positive Ranks	17	11.24	191.00
		Ties	0		
		Total	20		
	Mean path diff. for Min. energy(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	4	8.00	32.00
		Positive Ranks	16	11.13	178.00
		Ties	0		
		Total	20		
	Mean path diff. for Alignment(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	0	.00	.00
		Positive Ranks	20	10.50	210.00
		Ties	0		
		Total	20		
	Mean path diff. for Min. energy(cm) - Mean path diff. for LOT(cm)	Negative Ranks	9	10.56	95.00
		Positive Ranks	11	10.45	115.00
		Ties	0		
		Total	20		
	Mean path diff. for Alignment(cm) - Mean path diff. for LOT(cm)	Negative Ranks	3	2.67	8.00
		Positive Ranks	17	11.88	202.00
		Ties	0		
		Total	20		
	Mean path diff. for Alignment(cm) - Mean path diff. for Min. energy(cm)	Negative Ranks	1	2.00	2.00
		Positive Ranks	19	10.95	208.00
		Ties	0		
		Total	20		

Table A6.7(a). Ranks for Wilcoxon test comparing performance across strategies in each experiment.

Test Statistics[b]

Experiment		Mean path diff. for LOT(cm) - Mean path diff. for Constant d(cm)	Mean path diff. for Min. energy(cm) - Mean path diff. for Constant d(cm)	Mean path diff. for Alignment (cm) - Mean path diff. for Constant d(cm)	Mean path diff. for Min. energy(cm) - Mean path diff. for LOT(cm)	Mean path diff. for Alignment (cm) - Mean path diff. for LOT(cm)	Mean path diff. for Alignment (cm) - Mean path diff. for Min. energy(cm)
Roof	Z	-2.987[a]	-2.763[a]	-2.427[a]	-.224[a]	-.448[a]	-.635[a]
	Asymp. Sig. (2-tailed	.003	.006	.015	.823	.654	.526
Ground	Z	-3.211[a]	-2.725[a]	-3.920[a]	-.373[a]	-3.621[a]	-3.845[a]
	Asymp. Sig. (2-tailed	.001	.006	.000	.709	.000	.000

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table A6.7(b). Test statistics for Wilcoxon test comparing across strategies in each experiment.

Ranks

		N	Mean Rank	Sum of Ranks
Mean path diff. for LOT(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	6	14.00	84.00
	Positive Ranks	34	21.65	736.00
	Ties	0		
	Total	40		
Mean path diff. for Min. energy(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	8	15.63	125.00
	Positive Ranks	32	21.72	695.00
	Ties	0		
	Total	40		
Mean path diff. for Alignment(cm) - Mean path diff. for Constant d(cm)	Negative Ranks	7	6.57	46.00
	Positive Ranks	33	23.45	774.00
	Ties	0		
	Total	40		
Mean path diff. for Min. energy(cm) - Mean path diff. for LOT(cm)	Negative Ranks	18	20.78	374.00
	Positive Ranks	22	20.27	446.00
	Ties	0		
	Total	40		
Mean path diff. for Alignment(cm) - Mean path diff. for LOT(cm)	Negative Ranks	12	12.50	150.00
	Positive Ranks	28	23.93	670.00
	Ties	0		
	Total	40		
Mean path diff. for Alignment(cm) - Mean path diff. for Min. energy(cm)	Negative Ranks	11	11.09	122.00
	Positive Ranks	29	24.07	698.00
	Ties	0		
	Total	40		

Table A6.8(a). Ranks for the Wilcoxon test comparing performance of across strategies in all trials.

Test Statistics[b]

	Mean path diff. for LOT(cm) - Mean path diff. for Constant d(cm)	Mean path diff. for Min. energy(cm) - Mean path diff. for Constant d(cm)	Mean path diff. for Alignment (cm) - Mean path diff. for Constant d(cm)	Mean path diff. for Min. energy(cm) - Mean path diff. for LOT(cm)	Mean path diff. for Alignment (cm) - Mean path diff. for LOT(cm)	Mean path diff. for Alignment (cm) - Mean path diff. for Min. energy(cm)
Z	-4.382[a]	-3.831[a]	-4.893[a]	-.484[a]	-3.495[a]	-3.871[a]
Asymp. Sig. (2-tailed	.000	.000	.000	.628	.000	.000

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table A6.8(b) Test statistics for the Wilcoxon test comparing performance of across strategies in all trials.

Ranks

		N	Mean Rank	Sum of Ranks
Error in estimate of fielder position - Mean path diff. for Constant d(cm)	Negative Ranks	18	24.56	442.00
	Positive Ranks	22	17.18	378.00
	Ties	0		
	Total	40		
Error in estimate of fielder position - Mean path diff. for LOT(cm)	Negative Ranks	26	25.23	656.00
	Positive Ranks	14	11.71	164.00
	Ties	0		
	Total	40		
Error in estimate of fielder position - Mean path diff. for Min. energy(cm)	Negative Ranks	29	24.41	708.00
	Positive Ranks	11	10.18	112.00
	Ties	0		
	Total	40		
Error in estimate of fielder position - Mean path diff. for Alignment(cm)	Negative Ranks	29	24.93	723.00
	Positive Ranks	11	8.82	97.00
	Ties	0		
	Total	40		

Table A6.9(a) Ranks for the Wilcoxon test comparing the performance of each strategy with the inherent error in estimating the real fielder's position.

Test Statistics[b]

	Error in estimate of fielder position - Mean path diff. for Constant d(cm)	Error in estimate of fielder position - Mean path diff. for LOT(cm)	Error in estimate of fielder position - Mean path diff. for Min. energy(cm)	Error in estimate of fielder position - Mean path diff. for Alignment(cm)
Z	-.430[a]	-3.307[a]	-4.006[a]	-4.207[a]
Asymp. Sig. (2-tailed)	.667	.001	.000	.000

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Table A6.9(b) Test statistics for the Wilcoxon test comparing the performance of each strategy with the inherent error in estimating the real fielder's position.

Appendix 6.6. Statistics used in further analysis of optimised strategies

Case Summaries

Strategy	Experiment		Mean tan a diff.	Mean tan b diff.	Mean tan d diff.	Average velocity of fielder (cm/s)
Constant d	Roof	N	20	20	20	20
		Mean	.05	.01	.02	254.23
		Std. Deviation	.04	.01	.01	35.53
	Ground	N	20	20	20	20
		Mean	.07	.03	.04	168.45
		Std. Deviation	.07	.02	.03	30.79
	Total	N	40	40	40	40
		Mean	.06	.02	.03	211.34
		Std. Deviation	.06	.02	.02	54.44
LOT	Roof	N	20	20	20	20
		Mean	.05	.05	.06	254.23
		Std. Deviation	.03	.06	.07	35.53
	Ground	N	20	20	20	20
		Mean	.07	.06	.08	168.45
		Std. Deviation	.09	.05	.06	30.79
	Total	N	40	40	40	40
		Mean	.06	.05	.07	211.34
		Std. Deviation	.06	.06	.06	54.44
Min. energy	Roof	N	20	20	20	20
		Mean	.05	.02	.03	254.23
		Std. Deviation	.04	.02	.02	35.53
	Ground	N	20	20	20	20
		Mean	.10	.03	.04	168.45
		Std. Deviation	.08	.02	.02	30.79
	Total	N	40	40	40	40
		Mean	.08	.02	.03	211.34
		Std. Deviation	.06	.02	.02	54.44
Alignment	Roof	N	20	20	20	20
		Mean	.05	.03	.04	254.23
		Std. Deviation	.03	.04	.05	35.53
	Ground	N	20	20	20	20
		Mean	.23	.08	.11	168.45
		Std. Deviation	.30	.08	.10	30.79
	Total	N	40	40	40	40
		Mean	.14	.05	.07	211.34
		Std. Deviation	.23	.07	.09	54.44
Total	Roof	N	80	80	80	80
		Mean	.05	.03	.03	254.23
		Std. Deviation	.03	.04	.04	34.85
	Ground	N	80	80	80	80
		Mean	.12	.05	.07	168.45
		Std. Deviation	.18	.05	.07	30.20
	Total	N	160	160	160	160
		Mean	.08	.04	.05	211.34
		Std. Deviation	.13	.05	.06	53.92

Table A6.10. Summary of mean differences of visual angle tangents experienced by the simulated vs. the real fielder. Also shown is the average velocity required to reach the interception point for the real fielder.

Ranks

		N	Mean Rank	Sum of Ranks
Mean tan a diff. (LOT) - Mean tan a diff. (Constant d)	Negative Ranks	20	18.40	368.00
	Positive Ranks	20	22.60	452.00
	Ties	0		
	Total	40		
Mean tan a diff. (Min. energy) - Mean tan a diff. (Constant d)	Negative Ranks	9	20.00	180.00
	Positive Ranks	31	20.65	640.00
	Ties	0		
	Total	40		
Mean tan a diff. (Alignment) - Mean tan a diff. (Constant d)	Negative Ranks	11	14.82	163.00
	Positive Ranks	29	22.66	657.00
	Ties	0		
	Total	40		
Mean tan a diff. (Min. energy) - Mean tan a diff. (LOT)	Negative Ranks	10	21.60	216.00
	Positive Ranks	30	20.13	604.00
	Ties	0		
	Total	40		
Mean tan a diff. (Alignment) - Mean tan a diff. (LOT)	Negative Ranks	13	14.85	193.00
	Positive Ranks	27	23.22	627.00
	Ties	0		
	Total	40		
Mean tan a diff. (Alignment) - Mean tan a diff. (Min. energy)	Negative Ranks	10	21.20	212.00
	Positive Ranks	30	20.27	608.00
	Ties	0		
	Total	40		

Table A6.11(a). Ranks for the Wilcoxon test comparing the error in tan α experienced by the simulated fielder across strategies.

Test Statistics[b]

	Mean tan a diff. (LOT) - Mean tan a diff. (Constant d)	Mean tan a diff. (Min. energy) - Mean tan a diff. (Constant d)	Mean tan a diff. (Alignment) - Mean tan a diff. (Constant d)	Mean tan a diff. (Min. energy) - Mean tan a diff. (LOT)	Mean tan a diff. (Alignment) - Mean tan a diff. (LOT)	Mean tan a diff. (Alignment) - Mean tan a diff. (Min. energy)
Z	-.565[a]	-3.091[a]	-3.320[a]	-2.608[a]	-2.917[a]	-2.661[a]
Asymp. Sig. (2-tailed)	.572	.002	.001	.009	.004	.008

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table A6.11(b). Test statistics for the Wilcoxon test comparing the error in tan α experienced by the simulated fielder across strategies.

Ranks

		N	Mean Rank	Sum of Ranks
Mean tan b diff. (LOT) - Mean tan b diff. (Constant d)	Negative Ranks	8	10.38	83.00
	Positive Ranks	32	23.03	737.00
	Ties	0		
	Total	40		
Mean tan b diff. (Min. energy) - Mean tan b diff. (Constant d)	Negative Ranks	16	21.25	340.00
	Positive Ranks	24	20.00	480.00
	Ties	0		
	Total	40		
Mean tan b diff. (Alignment) - Mean tan b diff. (Constant d)	Negative Ranks	7	16.71	117.00
	Positive Ranks	33	21.30	703.00
	Ties	0		
	Total	40		
Mean tan b diff. (Min. energy) - Mean tan b diff. (LOT)	Negative Ranks	25	24.68	617.00
	Positive Ranks	15	13.53	203.00
	Ties	0		
	Total	40		
Mean tan b diff. (Alignment) - Mean tan b diff. (LOT)	Negative Ranks	18	21.17	381.00
	Positive Ranks	22	19.95	439.00
	Ties	0		
	Total	40		
Mean tan b diff. (Alignment) - Mean tan b diff. (Min. energy)	Negative Ranks	13	12.31	160.00
	Positive Ranks	27	24.44	660.00
	Ties	0		
	Total	40		

Table A6.12(a). Ranks for the Wilcoxon test comparing the error in tan β experienced by the simulated fielder across strategies.

Test Statistics[c]

	Mean tan b diff. (LOT) - Mean tan b diff. (Constant d)	Mean tan b diff. (Min. energy) - Mean tan b diff. (Constant d)	Mean tan b diff. (Alignment) - Mean tan b diff. (Constant d)	Mean tan b diff. (Min. energy) - Mean tan b diff. (LOT)	Mean tan b diff. (Alignment) - Mean tan b diff. (LOT)	Mean tan b diff. (Alignment) - Mean tan b diff. (Min. energy)
Z	-4.395[a]	-.941[a]	-3.938[a]	-2.782[b]	-.390[a]	-3.360[a]
Asymp. Sig. (2-tailed)	.000	.347	.000	.005	.697	.001

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test

Table A6.12(b). Test statistics for the Wilcoxon test comparing the error in tan β experienced by the simulated fielder across strategies.

Ranks

		N	Mean Rank	Sum of Ranks
Mean tan d diff. (LOT) - Mean tan d diff. (Constant d)	Negative Ranks	7	9.43	66.00
	Positive Ranks	33	22.85	754.00
	Ties	0		
	Total	40		
Mean tan d diff. (Min. energy) - Mean tan d diff. (Constant d)	Negative Ranks	15	20.73	311.00
	Positive Ranks	25	20.36	509.00
	Ties	0		
	Total	40		
Mean tan d diff. (Alignment) - Mean tan d diff. (Constant d)	Negative Ranks	7	15.29	107.00
	Positive Ranks	33	21.61	713.00
	Ties	0		
	Total	40		
Mean tan d diff. (Min. energy) - Mean tan d diff. (LOT)	Negative Ranks	25	24.76	619.00
	Positive Ranks	15	13.40	201.00
	Ties	0		
	Total	40		
Mean tan d diff. (Alignment) - Mean tan d diff. (LOT)	Negative Ranks	18	19.44	350.00
	Positive Ranks	22	21.36	470.00
	Ties	0		
	Total	40		
Mean tan d diff. (Alignment) - Mean tan d diff. (Min. energy)	Negative Ranks	10	15.30	153.00
	Positive Ranks	30	22.23	667.00
	Ties	0		
	Total	40		

Table A6.13(a). Ranks for the Wilcoxon test comparing the error in tan δ experienced by the simulated fielder across strategies.

Test Statistics[c]

	Mean tan d diff. (LOT) - Mean tan d diff. (Constant d)	Mean tan d diff. (Min. energy) - Mean tan d diff. (Constant d)	Mean tan d diff. (Alignment) - Mean tan d diff. (Constant d)	Mean tan d diff. (Min. energy) - Mean tan d diff. (LOT)	Mean tan d diff. (Alignment) - Mean tan d diff. (LOT)	Mean tan d diff. (Alignment) - Mean tan d diff. (Min. energy)
Z	-4.624[a]	-1.331[a]	-4.073[a]	-2.809[b]	-.806[a]	-3.454[a]
Asymp. Sig. (2-tailed)	.000	.183	.000	.005	.420	.001

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test

Table A6.13(b). Test statistics for the Wilcoxon test comparing the error in tan δ experienced by the simulated fielder across strategies.

Correlations

Strategy				Average velocity of fielder (cm/s)
Constant d	Kendall's tau_b	Average velocity of fielder (cm/s)	Correlation Coefficient	1.000
			Sig. (2-tailed)	.
		Mean path diff. (cm)	Correlation Coefficient	-.333**
			Sig. (2-tailed)	.002
		Mean tan a diff.	Correlation Coefficient	.018
			Sig. (2-tailed)	.870
		Mean tan b diff.	Correlation Coefficient	-.238*
			Sig. (2-tailed)	.030
		Mean tan d diff.	Correlation Coefficient	-.259*
			Sig. (2-tailed)	.019
LOT	Kendall's tau_b	Average velocity of fielder (cm/s)	Correlation Coefficient	1.000
			Sig. (2-tailed)	.
		Mean path diff. (cm)	Correlation Coefficient	-.197
			Sig. (2-tailed)	.073
		Mean tan a diff.	Correlation Coefficient	.041
			Sig. (2-tailed)	.709
		Mean tan b diff.	Correlation Coefficient	-.064
			Sig. (2-tailed)	.560
		Mean tan d diff.	Correlation Coefficient	-.092
			Sig. (2-tailed)	.402
Min. energy	Kendall's tau_b	Average velocity of fielder (cm/s)	Correlation Coefficient	1.000
			Sig. (2-tailed)	.
		Mean path diff. (cm)	Correlation Coefficient	-.259*
			Sig. (2-tailed)	.019
		Mean tan a diff.	Correlation Coefficient	-.110
			Sig. (2-tailed)	.316
		Mean tan b diff.	Correlation Coefficient	-.092
			Sig. (2-tailed)	.402
		Mean tan d diff.	Correlation Coefficient	-.151
			Sig. (2-tailed)	.169
Alignment	Kendall's tau_b	Average velocity of fielder (cm/s)	Correlation Coefficient	1.000
			Sig. (2-tailed)	.
		Mean path diff. (cm)	Correlation Coefficient	-.367**
			Sig. (2-tailed)	.001
		Mean tan a diff.	Correlation Coefficient	-.303**
			Sig. (2-tailed)	.006
		Mean tan b diff.	Correlation Coefficient	-.100
			Sig. (2-tailed)	.363
		Mean tan d diff.	Correlation Coefficient	-.169
			Sig. (2-tailed)	.124

**. Correlation is significant at the .01 level (2-tailed).

*. Correlation is significant at the .05 level (2-tailed).

Table A6.14. Correlations between average velocity required to reach the interception point and the mean errors in position, tan α, tan β, and tan δ for each strategy (N = 40 for each test)

Appendix 6.7. Statistics for the comparison of good vs. bad trials for the constant δ strategy

Group		Mean path diff(cm)	Mean tan a diff	Mean tan b diff	Mean tan d diff	Average velocity of fielder (cm/s)
Poor	N	8	8	8	8	8
	Mean	32.67	.08	.05	.06	172.46
Good	N	32	32	32	32	32
	Mean	13.38	.05	.01	.02	221.06
Total	N	40	40	40	40	40
	Mean	17.24	.06	.02	.03	211.34

(a)

Group		Strategy initiation time(s)	Max. velocity (m/s)	Max accel. (m/s/s)	Depth movement
Poor	N	8	8	8	8
	Mean	.28	2.38	3.63	3.00
Good	N	32	32	32	32
	Mean	.36	2.98	3.84	3.00
Total	N	40	40	40	40
	Mean	.34	2.86	3.80	3.00

(b)

Group		r^2(lin) for tan b vs. time	Sign of squared parameter for fit to tan b	r^2(lin) for tan d vs. time	Sign of squared parameter for fit to tan d
Poor	N	8	8	8	8
	Mean	.60	-1.00	.88	-1.00
Good	N	32	32	32	32
	Mean	.86	.13	.69	.062
Total	N	40	40	40	40
	Mean	.80	-.1	.73	-.15

(c)

Tables A6.15(a)-(c). Summary of data compared across good and poor trial groups for the performance of the constant δ strategy.

Ranks

	Effectivity	N	Mean Rank	Sum of Ranks
Mean path diff. (cm)	Poor	8	36.50	292.00
	Good	32	16.50	528.00
	Total	40		
Mean tan a diff.	Poor	8	24.88	199.00
	Good	32	19.41	621.00
	Total	40		
Mean tan b diff.	Poor	8	33.75	270.00
	Good	32	17.19	550.00
	Total	40		
Mean tan d diff.	Poor	8	34.50	276.00
	Good	32	17.00	544.00
	Total	40		
Average velocity of fielder (cm/s)	Poor	8	12.38	99.00
	Good	32	22.53	721.00
	Total	40		
Strategy initiation time(sec)	Poor	8	16.81	134.50
	Good	32	21.42	685.50
	Total	40		
Max. velocity(m/s)	Poor	8	13.38	107.00
	Good	32	22.28	713.00
	Total	40		
Max. acceleration (m/s/s)	Poor	8	20.88	167.00
	Good	32	20.41	653.00
	Total	40		
Depth movement	Poor	8	20.50	164.00
	Good	32	20.50	656.00
	Total	40		
Rsq(lin) for (tan b) vs time	Poor	8	9.38	75.00
	Good	32	23.28	745.00
	Total	40		
Sign of squared parameter for fit to tan b	Poor	8	11.50	92.00
	Good	32	22.75	728.00
	Total	40		
Rsq(lin) for (tan d) vs time	Poor	8	24.88	199.00
	Good	32	19.41	621.00
	Total	40		
Sign of linear gradient for fit to tan d	Poor	8	12.00	96.00
	Good	32	22.63	724.00
	Total	40		

Table A6.16(a). Ranks for the Mann-Whitney test comparing the mean performance of the constant δ strategy across good vs. poor trial groups.

	Mean path diff(cm)	Mean tan a diff	Mean tan b diff	Mean tan d diff	Average velocity of fielder (cm/s)
Mann-Whitney U	.000	93	22	16	63
Wilcoxon W	528	621	550	544	99
Z	-4.328	-1.183	-3.584	-3.787	-2.198
Asymp sig.(2-tailed)	.000	.237	.000	.000	.028
Exact sig. [2 * (1-tailed)]	.000	.249	.000	.000	.027

(b)(i)

	Strategy initiation time(s)	Max. velocity (m/s)	Max accel. (m/s/s)	Depth movement
Mann-Whitney U	98.5	71	125	128
Wilcoxon W	134.5	107	653	656
Z	-1.003	-1.963	-.108	.000
Asymp sig.(2-tailed)	.316	.050	.914	1.000
Exact sig. [2 * (1-tailed)]	.325	.055	.934	1.000

(b)(ii)

	r^2(lin) for tan b vs. time	Sign of squared parameter for fit to tan b	r^2(lin) for tan d vs. time	Sign of squared parameter for fit to tan d
Mann-Whitney U	39	56	93	60
Wilcoxon W	75	92	621	96
Z	-3.009	-2.824	-1.183	-2.684
Asymp sig.(2-tailed)	.003	.005	.237	.007
Exact sig. [2 * (1-tailed)]	.002	.013	.249	.020

(b)(iii)

Tables A6.16(b)(i-iii). Test statistics for the Mann-Whitney test comparing the mean performance of the constant δ strategy across good vs. poor trial groups.

	Effectivity	
	Poor	Good
	Sign of linear gradient for fit to tan d	Sign of linear gradient for fit to tan d
	Count	Count
-1.00	8	15
1.00		17

Table A6.17 Frequency with which tan δ increased or decreased across the groups.

Appendix 7.1. Questionnaire for experiment 1

Name:

Age:

Ball games skill (above average/average/below average):

You are required to answer some questions about how you catch balls. Imagine a ball launched upwards at an angle of about 45 degrees from level ground on a calm day. If you watch the ball, you know whether you are standing in the right place to catch it or whether you need to move. We are trying to find out what you can describe about how you know this.

1. Imagine a ball thrown to you from 20m away that you can catch comfortably without moving. Can you describe how you would know as you watched the ball that you did not have to move to catch it?

2. Another ball is thrown to you from 20m away. This time you know that it is going to land in front of where you are standing and in order to catch it you will have to run forwards. Can you describe how you would know, from looking at the ball in your initial position, that you had to run forwards to catch it?

3. Again, a ball is thrown to you from 20m away. This time you know that the ball will land behind you and in order to catch it you will have to run backwards. Can you describe how you would know that you had to run backwards to catch it?

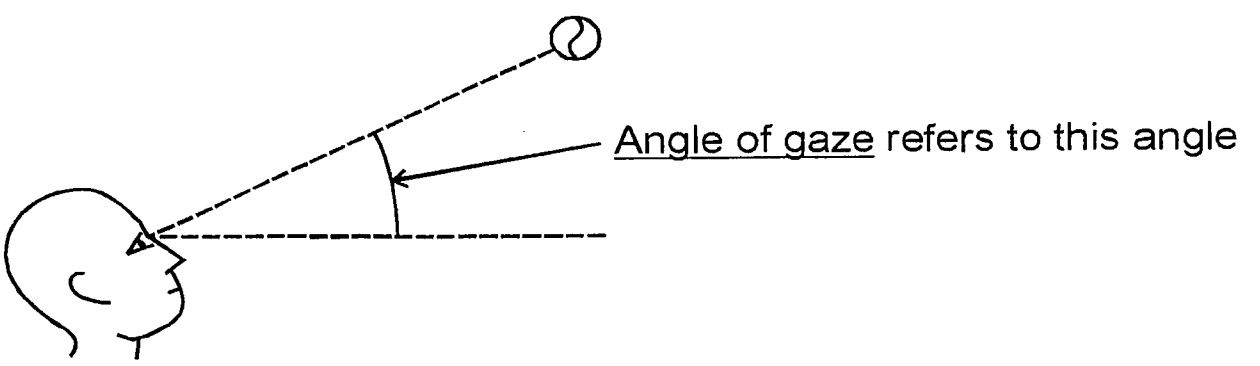
4. In questions 2 and 3, you imagined having to move to catch the ball. Can you describe how you would know as you moved that you were moving at an appropriate speed to catch the ball, or, what would tell you that you needed to move faster or slower?

Thankyou for your help in this study.

Appendix 7.2. Questionnaire for experiment 2

Catching experiment

Thankyou for your help in this study. If you have *any* questions at *any* stage please ask. It is important that you understand what you are doing and what it is you are being asked. This experiment is examining how your ***angle of gaze*** changes as you watch a ball that is thrown towards you. Angle of gaze refers to the angle through which your line of sight is raised above horizontal in order to fixate the ball.



If you were to look at something at eye level, directly in front of you, your angle of gaze would be 0°. If you were stood on the ground and watched a rocket take off in front of you, your angle of gaze would increase. As you watch a parachutist fall to Earth, your angle of gaze decreases.

Imagine the situation where a friend is going to throw balls gently towards you from a distance of about 8 metres. You are going to watch the balls from a *stationary* position as they fly through the air. On the next page, there are descriptions of five different trajectories that the ball could follow. You are asked to describe how you believe your ***angle of gaze changes during the flight of these imaginary balls***. Visualise their trajectory and if it helps, act out how you think your angle of gaze changes as the balls approach you.

You are also asked to indicate your ***confidence*** in the accuracy of your judgement. You may feel certain that your response is a perfect description of what would happen in the given situation. Alternatively, you may feel that your response was a complete guess. Next to each question, there is a space for you to indicate your confidence in each judgement. Your rating can range from 0-10. A rating of 10 indicates that you are *absolutely certain* that your response is the correct description of how you believe your angle of gaze would change. Putting 0 indicates that you feel your response was a *complete guess*.

Confidence rating:

0 1 2 3 4 5 6 7 8 9 10

Complete guess.....Fairly sure.....Absolutely certain

Remember you are to describe how your angle of gaze changes from the moment the ball leaves the hand of the thrower until the end of its flight, whether that is when it lands, when you catch it, or once it has gone over your head. Try and make your descriptions as complete as possible and consider your confidence in the accuracy of each description.

Throw descriptions	What happened to your angle of gaze?	Confidence (0-10)
1. The ball is thrown so that it lands a couple of metres short of your position.		
2. The ball is thrown so that you catch it low at around knee level.		
3. The ball is thrown so that catch it at eye level just in front of your face (it would hit you in the face if you missed it).		
4. The ball is thrown so that you have to reach high above your head to catch it.		
5. The ball is thrown with such force that it flies over your head.		

Appendix 7.3. Statistics for experiment 2

Since 'eye-level' trials were critical, it is scores for 'eye-level' trials that were compared.

Descriptive Statistics

	N	Mean	Std. Deviation
NR	24	.31	.44
PM	24	.29	.39
ZD	24	.13	.27
Valid N (listwise)	24		

Table A7.1. Mean scores given to trials by three different raters

Ranks

	Mean Rank
NR	2.17
PM	2.15
ZD	1.69

Table A7.2. Ranks for Kendall's W test of concordance for the comparison of the scores given by the three raters.

Test Statistics

N	24
Kendall's W [a]	.207
Chi-Square	9.941
df	2
Asymp. Sig.	.007

a. Kendall's Coefficient of Concordance

Table A7.3. Test statistics for Kendall's W test of concordance for the comparison of the scores given by the three raters.

Case Summaries

Pre-trial accuracy

Trajectory type	N	Mean	Std. Deviation
Ball fell short	24	1.000	.000
Ball caught low	24	.979	.102
Ball caught at eye level	24	.313	.438
Ball caught high	24	.812	.385
Ball went overhead	24	1.000	.000
Total	120	.821	.371

Table A7.4. Mean accuracy scores for the responses of subjects to each of the five different trajectory types.

Ranks

		N	Mean Rank	Sum of Ranks
Pre-trial accuracy, type 3 trial - Pre-trial accuracy, type 1 trial	Negative Ranks	33	17.82	588.00
	Positive Ranks	1	7.00	7.00
	Ties	14		
	Total	48		
Pre-trial accuracy, type 3 trial - Pre-trial accuracy, type 2 trial	Negative Ranks	34	19.43	660.50
	Positive Ranks	3	14.17	42.50
	Ties	11		
	Total	48		
Pre-trial accuracy, type 4 trial - Pre-trial accuracy, type 3 trial	Negative Ranks	4	15.38	61.50
	Positive Ranks	25	14.94	373.50
	Ties	19		
	Total	48		
Pre-trial accuracy, type 5 trial - Pre-trial accuracy, type 3 trial	Negative Ranks	2	14.75	29.50
	Positive Ranks	33	18.20	600.50
	Ties	13		
	Total	48		

Table A7.5(a). Ranks for Wilcoxon tests comparing mean scores for 'Ball caught at eye level' trajectory responses with those for each other trajectory type.

Test Statistics[c]

	Pre-trial accuracy, type 3 trial - Pre-trial accuracy, type 1 trial	Pre-trial accuracy, type 3 trial - Pre-trial accuracy, type 2 trial	Pre-trial accuracy, type 4 trial - Pre-trial accuracy, type 3 trial	Pre-trial accuracy, type 5 trial - Pre-trial accuracy, type 3 trial
Z	-5.149[a]	-4.824[a]	-3.546[b]	-4.887[b]
Asymp. Sig. (2-tailed)	.000	.000	.000	.000

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

Table A7.5(b). Test statistics for Wilcoxon tests comparing mean scores for 'Ball caught at eye level' trajectory responses with those for each other trajectory type.

Case Summaries

Pre-trial confidence

Trajectory type	N	Mean	Std. Deviation
Ball fell short	24	7.54	2.04
Ball caught low	24	7.13	2.13
Ball caught at eye level	24	7.08	1.72
Ball caught high	24	7.17	1.63
Ball went overhead	24	7.29	1.83
Total	120	7.24	1.86

Table A7.6. Mean confidence scores applied by subjects to their responses to each trajectory type.

Ranks

	Mean Rank
Pre-trial confidence, type 1 trial	3.43
Pre-trial confidence, type 2 trial	2.96
Pre-trial confidence, type 3 trial	2.89
Pre-trial confidence, type 4 trial	2.70
Pre-trial confidence, type 5 trial	3.03

Test Statistics[a]

N	48
Chi-Square	8.351
df	4
Asymp. Sig.	.080

a. Friedman Test

Tables A7.7(a) & (b). Ranks and test statistics for the Friedman test of confidence ratings across trajectory types.

Correlations

			Skill level
Kendall's tau_b	Pre-trial accuracy	Correlation Coefficient	-.134
		Sig. (2-tailed)	.488
		N	24

Table A7.8. Correlation between subjects' skill rating and their score for eye-level trials.

Appendix 7.4. Statistics for experiment 2a

Case Summaries

Question		Accuracy	Confidence
Short	N	11	11
	Mean	1.00	7.00
	Std. Deviation	.00	1.73
Low	N	11	11
	Mean	1.00	6.45
	Std. Deviation	.00	1.13
At eye	N	11	11
	Mean	4.55E-02	7.18
	Std. Deviation	.15	.75
High	N	11	11
	Mean	.64	6.82
	Std. Deviation	.50	1.83
Overhead	N	11	11
	Mean	1.00	7.00
	Std. Deviation	.00	1.48
Total	N	55	55
	Mean	.74	6.89
	Std. Deviation	.44	1.41

Table A7.9. Summary of mean accuracy and confidence scores for subjects in experiment 2a.

Ranks

		N	Mean Rank	Sum of Ranks
'At eye' - accuracy - 'Short' - accuracy	Negative Ranks	11	6.00	66.00
	Positive Ranks	0	.00	.00
	Ties	0		
	Total	11		
'At eye' - accuracy - 'Low' - accuracy	Negative Ranks	11	6.00	66.00
	Positive Ranks	0	.00	.00
	Ties	0		
	Total	11		
'High' - accuracy - 'At eye' - accuracy	Negative Ranks	0	.00	.00
	Positive Ranks	7	4.00	28.00
	Ties	4		
	Total	11		
'Overhead' - accuracy - 'At eye' - accuracy	Negative Ranks	0	.00	.00
	Positive Ranks	11	6.00	66.00
	Ties	0		
	Total	11		

Test Statistics[c]

	'At eye' - accuracy - 'Short' - accuracy	'At eye' - accuracy - 'Low' - accuracy	'High' - accuracy - 'At eye' - accuracy	'Overhead' - accuracy - 'At eye' - accuracy
Z	-3.207[a]	-3.207[a]	-2.530[b]	-3.207[b]
Asymp. Sig. (2-tailed)	.001	.001	.011	.001

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

Tables A7.10(a) & (b). Ranks and test statistics for the Wilcoxon tests comparing subjects' accuracy for the 'At eye' trajectory with that for each of the other trajectory types.

Ranks

	Mean Rank
'Short' - confidence	3.36
'Low' - confidence	2.23
'At eye' - confidence	3.27
'High' - confidence	3.09
'Overhead' confidence	3.05

Test Statistics[a]

N	11
Chi-Square	5.434
df	4
Asymp. Sig.	.246

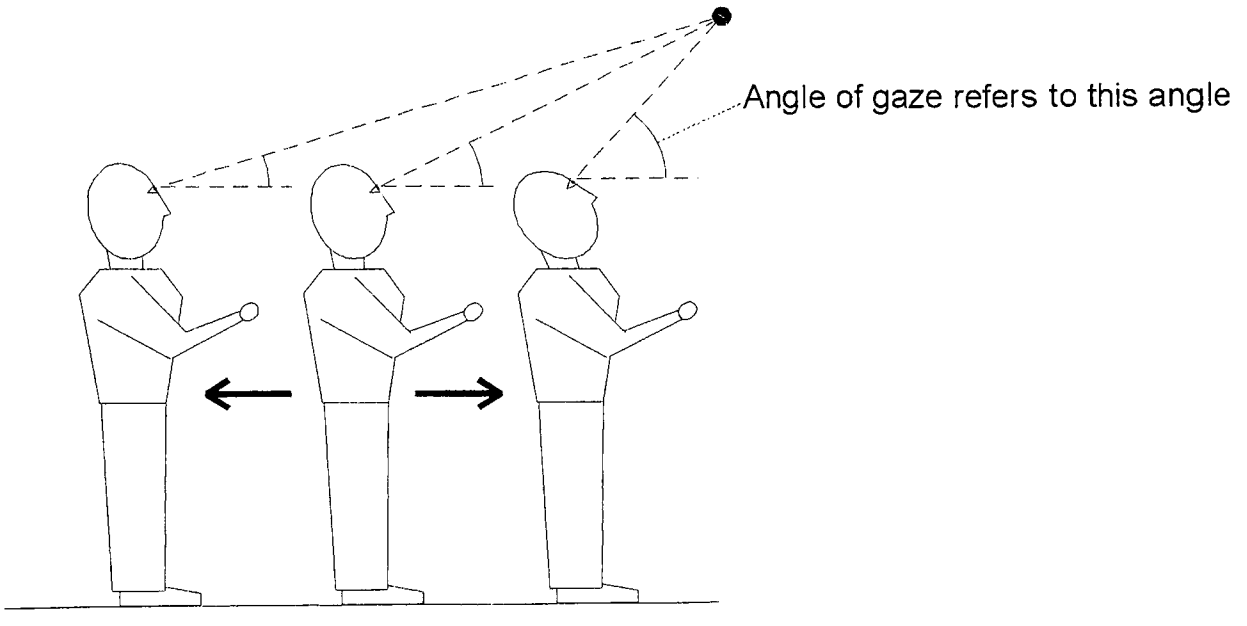
a. Friedman Test

Tables A7.11(a) & (b). Ranks and test statistics for the Friedman test comparing subjects' confidence the accuracy of their responses for each of the five trajectory types.

Appendix 7.5. Questionnaire for experiment 3

Catching experiment

Thankyou for your help in this study. If you have *any* questions at *any* stage please ask. It is important that you understand what you are doing and what it is you are being asked. This experiment is examining how your ***angle of gaze*** changes as you move to catch a ball that is thrown towards you. Angle of gaze refers to the angle through which your line of sight is raised above horizontal in order to fixate the ball.



If you were to look at something at eye level, directly in front of you, your angle of gaze would be 0°. If you were stood on the ground and watched a rocket take off in front of you, your angle of gaze would increase. As you watch a parachutist fall to Earth, your angle of gaze decreases. If you ran towards or away from something which was stationary in the air your angle of gaze would change (See above diagram).

Imagine the situation where a friend is going to throw balls gently towards you from a distance of about 12 metres, using an underarm action. You are going to move forwards or backwards (although <u>not</u> sideways) to try to catch the balls. On the next page, there are descriptions of different trajectories that the ball could follow and how you might move to catch it.

You are asked to describe how you believe your ***angle of gaze changes as you run to try to catch these imaginary balls***. Visualise their trajectory and if it helps, act out how you think your angle of gaze changes as the balls approach you.

You are also asked to indicate your ***confidence*** in the accuracy of your judgement. You may feel certain that your response is a perfect description of what would happen in the given situation. Alternatively, you may feel that your response was a complete guess. Next to each question, there is a space for you to indicate your confidence in each judgement. Your rating can range from 0-10. A rating of 10 indicates that you are *absolutely certain* that your response is the correct description of how you believe your angle of gaze would change. Putting 0 indicates that you feel your response was a *complete guess*.

Confidence rating:

0 1 2 3 4 5 6 7 8 9 10

Complete guess.....Fairly sure.....Absolutely certain

Remember you are to describe how your angle of gaze changes from the moment the ball leaves the hand of the thrower until the end of its flight, whether that is when it lands, when you catch it, or once it has gone over your head. Try to make your descriptions as complete as possible and consider your confidence in the accuracy of each description.

Throw descriptions	**What happened to your angle of gaze?**	**Confidence (0-10)**
1. The ball thrown softly. You run 4m forward but don't reach it in time and the ball hits the ground.		
2. The ball is thrown slightly further. You run forwards 4m and just catch it at knee level.		
3. The ball is thrown further again. You run forwards 4m and catch it comfortably (if you didn't make the catch, it would hit you in the eye).		
4. The ball is thrown further so that you have to move backwards. You run back 4m and catch it comfortably (if you didn't make the catch, it would hit you in the eye).		
5. The ball is thrown even further. You run backward 4m and just manage to catch it arms stretched above your head.		
6. The ball is thrown with such force that, despite you running back 4m, it still flies over your head.		

Appendix 7.6. Statistics for experiment 3

Case Summaries

Type		Accuracy	Confidence
Short (run forward)	N	19	19
	Mean	1.000	7.53
	Std. Deviation	.000	2.44
Low (run forward)	N	19	19
	Mean	1.000	7.00
	Std. Deviation	.000	2.65
At eye (run forward)	N	19	19
	Mean	.158	6.53
	Std. Deviation	.336	2.37
At eye (run backward)	N	19	19
	Mean	.158	6.16
	Std. Deviation	.291	2.43
High (run backward)	N	19	19
	Mean	.842	7.05
	Std. Deviation	.291	2.22
Overhead (run backward)	N	19	19
	Mean	.947	6.68
	Std. Deviation	.158	2.58
Total	N	114	114
	Mean	.684	6.82
	Std. Deviation	.438	2.44

Table A7.12. Summary of mean accuracy and confidence scores for subjects in experiment 3.

Ranks

		N	Mean Rank	Sum of Ranks
Acc.(runs forward - caught at eye) - Acc.(runs forward - ball lands short)	Negative Ranks	28	14.50	406.00
	Positive Ranks	0	.00	.00
	Ties	2		
	Total	30		
Acc.(runs forward - caught at eye) - Acc.(runs forward - caught low)	Negative Ranks	28	14.50	406.00
	Positive Ranks	0	.00	.00
	Ties	2		
	Total	30		
Acc.(runs backward - caught high) - Acc.(runs backward - caught at eye)	Negative Ranks	0	.00	.00
	Positive Ranks	19	10.00	190.00
	Ties	11		
	Total	30		
Acc.(runs backward - goes overhead) - Acc.(runs backward - caught at eye)	Negative Ranks	0	.00	.00
	Positive Ranks	16	8.50	136.00
	Ties	3		
	Total	19		

Test Statistics[c]

	Acc.(runs forward - caught at eye) - Acc.(runs forward - ball lands short)	Acc.(runs forward - caught at eye) - Acc.(runs forward - caught low)	Acc.(runs backward - caught high) - Acc.(runs backward - caught at eye)	Acc.(runs backward - goes overhead) - Acc.(runs backward - caught at eye)
Z	-5.070[a]	-5.070[a]	-4.065[b]	-3.819[b]
Asymp. Sig. (2-tailed)	.000	.000	.000	.000

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

Tables A7.13(a) & (b). Ranks and test statistics for the Wilcoxon tests comparing mean scores the two types of 'At eye' trajectories with all other trajectory types.

Ranks

	Mean Rank
Conf.(runs forward - lands short)	4.18
Conf.(runs forward - caught low)	3.92
Conf.(runs forward - caught at eye)	3.08
Conf.(runs backward - caught at eye)	2.76
Conf.(runs backward - caught high)	3.42
Conf.(runs backward - goes overhead)	3.63

Test Statistics[a]

N	19
Chi-Square	11.321
df	5
Asymp. Sig.	.045

a. Friedman Test

Tables A7.14(a) & (b). Ranks and test statistics for the Friedman test of confidence ratings across trajectory types for experiment 3.

Appendix 7.7. Scoring legends for the assessing the accuracy of responses of subjects in the Recognition condition in experiment 4.

Response	Trajectory type				
	Short	Low	At eye	High	Overhead
(a)	*0.5*	*0.5*	*0*	*0*	*0*
(b)	*1*	*1*	*0*	*0*	*0*
(c)	*0.5*	*0.5*	*0*	*0*	*0*
(d)	*0*	*0*	*0.5*	*0*	*0*
(e)	*0*	*0*	*1*	*0*	*0*
(f)	*0*	*0*	*0.5*	*0.5*	*0.5*
(g)	*0*	*0*	*0*	*1*	*1*

Table A7.15. Scoring legend for cued responses in the Pre-catch phase.

Response	Trajectory type				
	Short	Low	At eye	High	Overhead
(a)	*0.5*	*0.5*	*0*	*0*	*0*
(b)	*1*	*1*	*0*	*0*	*0*
(c)	*0.5*	*0.5*	*1**	*0*	*0*
(d)	*0*	*0*	*1**	*0*	*0*
(e)	*0*	*0*	*1**	*0.5**	*0*
(f)	*0*	*0*	*1**	*0.5*	*0.5*
(g)	*0*	*0*	*0*	*1*	*1*

Table A7.16. Scoring legend for cued responses in the Post-catch (* : Scores with a star indicate this is the maximum score possible for this response to this type of trial, dependent on the actual α variation observed).

Appendix 7.8. Statistics for the Pre-catch phase of experiment 4

Ranks

		N	Mean Rank	Sum of Ranks
Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball falling short	Negative Ranks	7	4.00	28.00
	Positive Ranks	0	.00	.00
	Ties	1		
	Total	8		
Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball caught low	Negative Ranks	7	4.00	28.00
	Positive Ranks	0	.00	.00
	Ties	1		
	Total	8		
Pre-trial accuracy: Ball caught high - Pre-trial accuracy: Ball caught at eye level	Negative Ranks	0	.00	.00
	Positive Ranks	5	3.00	15.00
	Ties	3		
	Total	8		
Pre-trial accuracy: Ball going overhead - Pre-trial accuracy: Ball caught at eye level	Negative Ranks	0	.00	.00
	Positive Ranks	6	3.50	21.00
	Ties	2		
	Total	8		

Test Statistics[c]

	Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball falling short	Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball caught low	Pre-trial accuracy: Ball caught high - Pre-trial accuracy: Ball caught at eye level	Pre-trial accuracy: Ball going overhead - Pre-trial accuracy: Ball caught at eye level
Z	-2.530[a]	-2.428[a]	-2.121[b]	-2.333[b]
Asymp. Sig. (2-tailed)	.011	.015	.034	.020

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

Tables A7.17(a) & (b). Ranks and test statistics for the Wilcoxon tests comparing mean scores for 'At eye' trajectories with each of the other trajectories for Free Recall subjects in the pre-catch phase of experiment 4.

Ranks

	Mean Rank
Pre-trial confidence: Ball falling short	3.31
Pre-trial confidence: Ball caught low	3.06
Pre-trial confidence: Ball caught at eye level	3.31
Pre-trial confidence: Ball caught high	2.56
Pre-trial confidence: Ball going overhead	2.75

Test Statistics[a]

N	8
Chi-Square	2.090
df	4
Asymp. Sig.	.719

a. Friedman Test

Tables A7.18(a) & (b). Ranks and test statistics for the Friedman test of pre-catch confidence ratings for Free Recall subjects across trajectory types for experiment 4.

Ranks

		N	Mean Rank	Sum of Ranks
Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball falling short	Negative Ranks	8	5.06	40.50
	Positive Ranks	1	4.50	4.50
	Ties	7		
	Total	16		
Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball caught low	Negative Ranks	9	5.72	51.50
	Positive Ranks	2	7.25	14.50
	Ties	5		
	Total	16		
Pre-trial accuracy: Ball caught high - Pre-trial accuracy: Ball caught at eye level	Negative Ranks	3	4.67	14.00
	Positive Ranks	5	4.40	22.00
	Ties	8		
	Total	16		
Pre-trial accuracy: Ball going overhead - Pre-trial accuracy: Ball caught at eye level	Negative Ranks	2	6.75	13.50
	Positive Ranks	9	5.83	52.50
	Ties	5		
	Total	16		

Test Statistics[c]

	Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball falling short	Pre-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball caught low	Pre-trial accuracy: Ball caught high - Pre-trial accuracy: Ball caught at eye level	Pre-trial accuracy: Ball going overhead - Pre-trial accuracy: Ball caught at eye level
Z	-2.309[a]	-2.121[a]	-.577[b]	-2.093[b]
Asymp. Sig. (2-tailed)	.021	.035	.564	.043

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

Tables A7.19(a) & (b). Ranks and test statistics for the Wilcoxon tests comparing mean scores for 'At eye' trajectories with each of the other trajectory types for Recognition subjects in the pre-catch phase of experiment 4.

Ranks

	Mean Rank
Pre-trial confidence: Ball falling short	3.34
Pre-trial confidence: Ball caught low	2.91
Pre-trial confidence: Ball caught at eye level	2.81
Pre-trial confidence: Ball caught high	2.69
Pre-trial confidence: Ball going overhead	3.25

Test Statistics[a]

N	16
Chi-Square	2.895
df	4
Asymp. Sig.	.576

a. Friedman Test

Tables A7.20(a) & (b). Test statistics for the Friedman test of pre-catch confidence ratings for Recognition subjects across trajectory types for experiment 4.

Ranks

	Condition	N	Mean Rank	Sum of Ranks
Pre-trial accuracy	Free Recall condition	40	62.16	2486.50
	Recognition condition	80	59.67	4773.50
	Total	120		

Test Statistics[a]

	Pre-trial accuracy
Mann-Whitney U	1533.500
Wilcoxon W	4773.500
Z	-.435
Asymp. Sig. (2-tailed)	.664

a. Grouping Variable: Condition

Tables A7.21(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing the mean accuracy of all responses given in the Free Recall condition with those given in the Recognition condition.

Ranks

	Condition	N	Mean Rank	Sum of Ranks
Pre-trial accuracy	Free Recall condition	8	8.50	68.00
	Recognition condition	16	14.50	232.00
	Total	24		

Test Statistics[b]

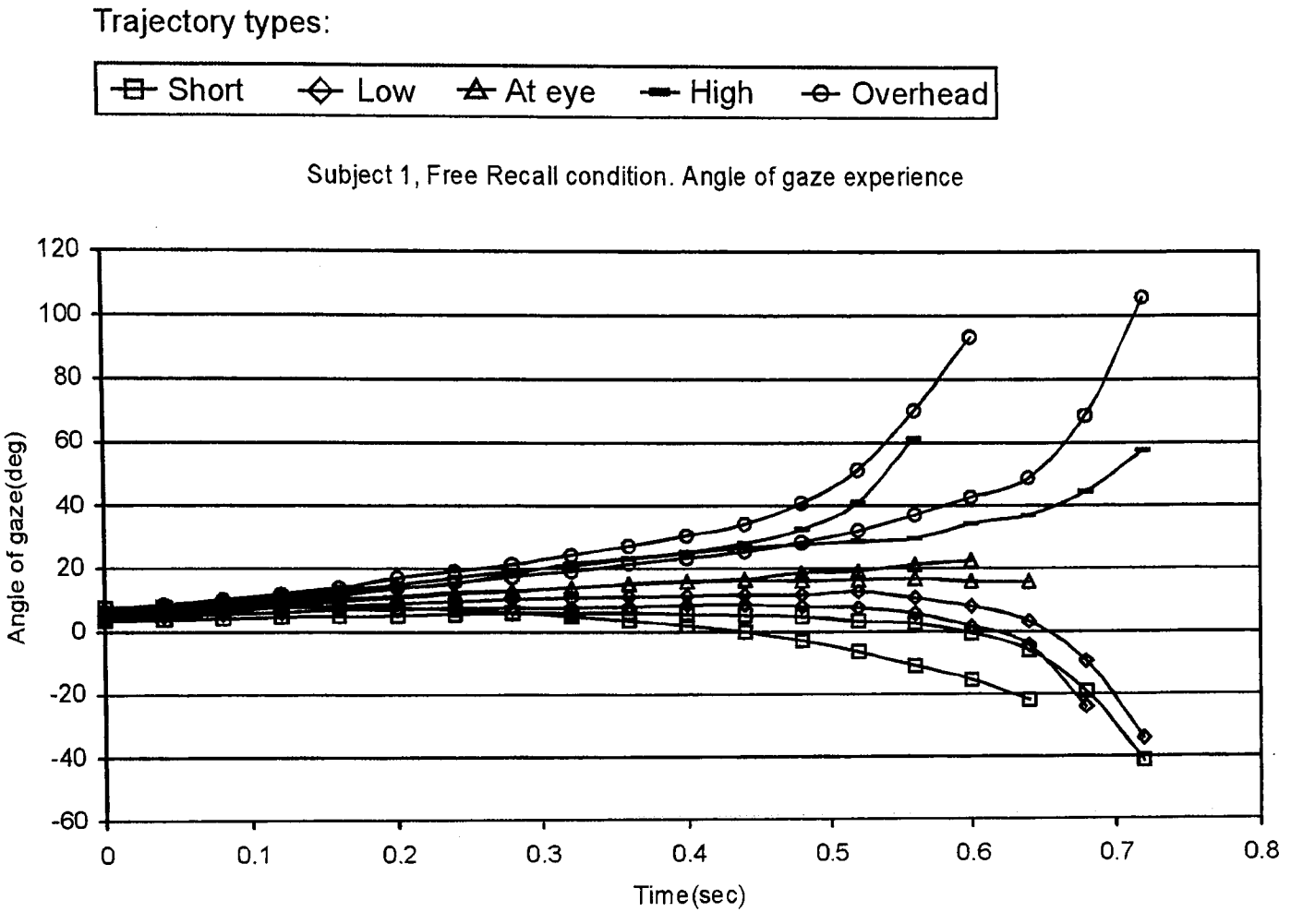
	Pre-trial accuracy
Mann-Whitney U	32.000
Wilcoxon W	68.000
Z	-2.089
Asymp. Sig. (2-tailed)	.037
Exact Sig. [2*(1-tailed Sig.)]	.052[a]

a. Not corrected for ties.

b. Grouping Variable: Condition

Tables A7.22(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing the mean accuracy of 'At eye' trajectory responses given in the Free Recall condition with those given in the Recognition condition.

Appendix 7.9. Examples of angle of gaze experience



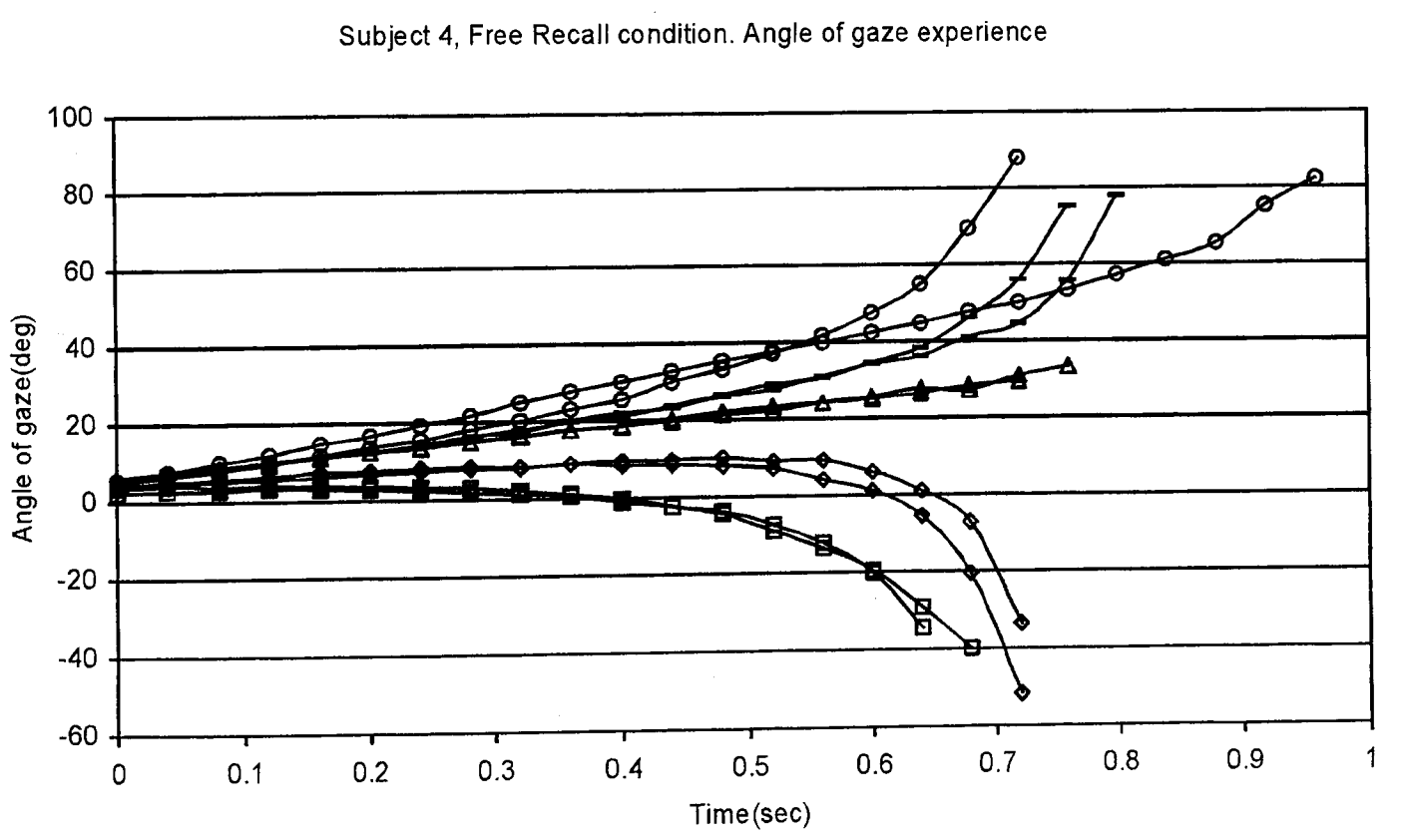


Fig. A7.1 Examples of the angle of gaze variation experienced by two subjects in the Free Recall condition.

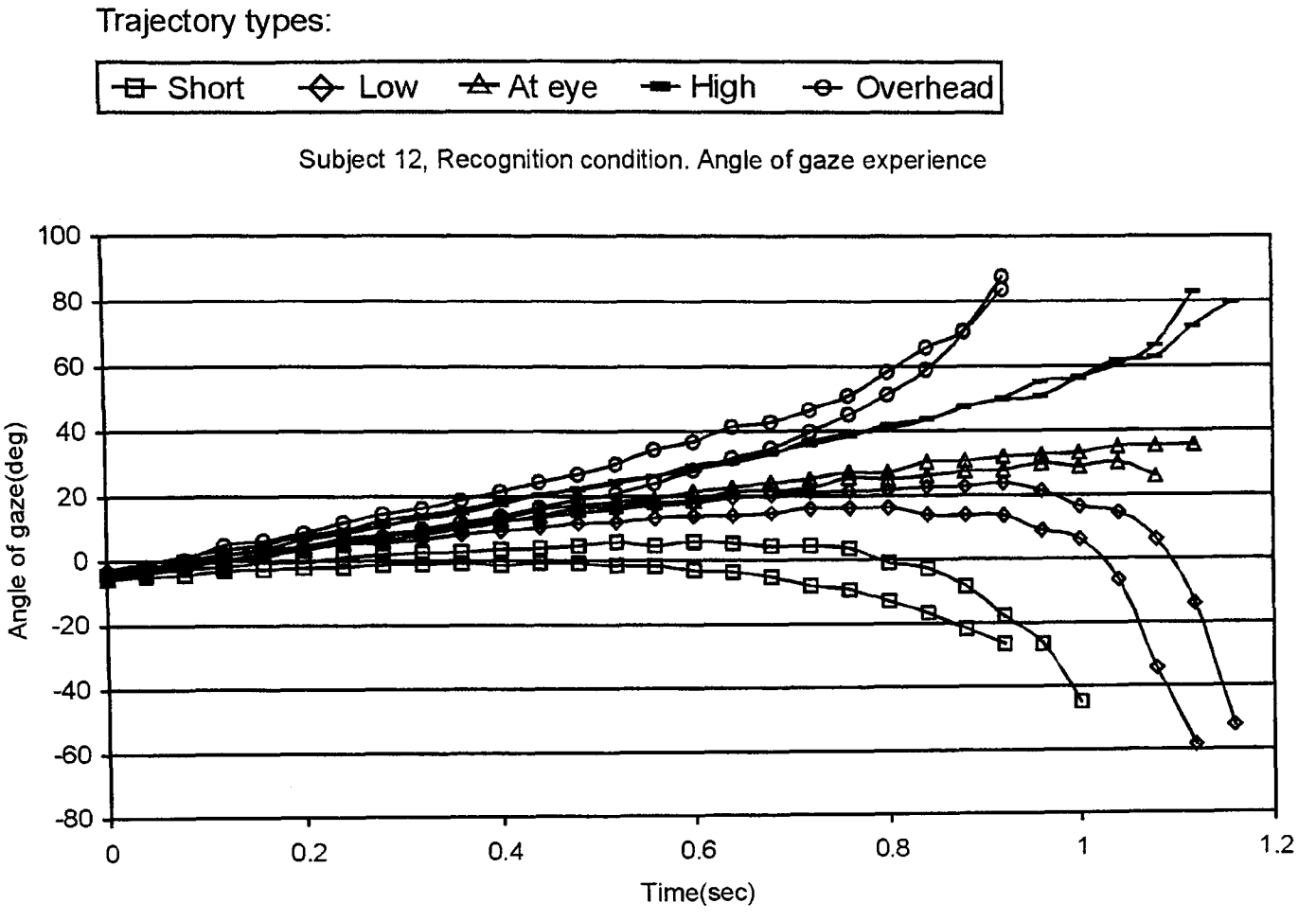


Fig. A7.2 Examples of the angle of gaze variation experienced by two subjects in the Recognition condition.

Appendix 7.10. Statistics for the Post-catch phase of experiment 4

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum
Scores of NR	30	.7583	.3742	.00	1.00
Rater 1	30	.6083	.4030	.00	1.00
Rater 2	30	.7667	.3768	.00	1.00

Table A7.23 Mean scores given to a random selection of 30 trials by three different raters.

Ranks

	Mean Rank
Scores of NR	2.17
Rater 1	1.63
Rater 2	2.20

Test Statistics

N	30
Kendall's W[a]	.328
Chi-Square	19.676
df	2
Asymp. Sig.	.000

a. Kendall's Coefficient of Concordance

Tables A7.24(a) & (b). Ranks and test statistics for the Kendall's W test of concordance for the comparison of scores given by the three raters.

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum
Pre-trial accuracy	8	.19	.37	0	1
Mean post-trial accuracy	8	.50	.35	.00	1.00

Table A7.25 Summary of the accuracy of responses given by Free Recall subjects, pre- and post-trial.

Ranks

		N	Mean Rank	Sum of Ranks
Mean post-trial accuracy - Pre-trial accuracy	Negative Ranks	1[a]	3.00	3.00
	Positive Ranks	5[b]	3.60	18.00
	Ties	2[c]		
	Total	8		

a. Mean post-trial accuracy < Pre-trial accuracy

b. Mean post-trial accuracy > Pre-trial accuracy

c. Pre-trial accuracy = Mean post-trial accuracy

Test Statistics[b]

	Mean post-trial accuracy - Pre-trial accuracy
Z	-1.590[a]
Asymp. Sig. (2-tailed)	.112

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Tables A7.26(a) & (b). Ranks and test statistics for the Wilcoxon test comparing the accuracy of responses given by subjects in the Free Recall group for the critical 'At eye' trajectory, pre- and post-trial.

Ranks

		N	Mean Rank	Sum of Ranks
Mean post-trial accuracy: Ball caught at eye level - Mean post-trial accuracy: Ball falling short	Negative Ranks	7	4.57	32.00
	Positive Ranks	1	4.00	4.00
	Ties	0		
	Total	8		
Mean post-trial accuracy: Ball caught at eye level - Mean post-trial accuracy: Ball caught low	Negative Ranks	6	3.50	21.00
	Positive Ranks	0	.00	.00
	Ties	2		
	Total	8		
Mean post-trial accuracy: Ball caught high - Mean post-trial accuracy: Ball caught at eye level	Negative Ranks	3	3.33	10.00
	Positive Ranks	3	3.67	11.00
	Ties	2		
	Total	8		
Mean post-trial accuracy: Ball going overhead - Mean post-trial accuracy: Ball caught at eye level	Negative Ranks	1	2.50	2.50
	Positive Ranks	5	3.70	18.50
	Ties	2		
	Total	8		

Test Statistics[c]

	Mean post-trial accuracy: Ball caught at eye level - Mean post-trial accuracy: Ball falling short	Mean post-trial accuracy: Ball caught at eye level - Mean post-trial accuracy: Ball caught low	Mean post-trial accuracy: Ball caught high - Mean post-trial accuracy: Ball caught at eye level	Mean post-trial accuracy: Ball going overhead - Mean post-trial accuracy: Ball caught at eye level
Z	-1.975[a]	-2.232[a]	-.108[b]	-1.725[b]
Asymp. Sig. (2-tailed)	.048	.026	.914	.084

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

Tables A7.27(a) & (b). Ranks and test statistics for the Wilcoxon tests comparing the Free Recall subjects' mean Post-trial scores for 'At eye' trajectories with scores for each of the other trajectory types.

Ranks

	Mean Rank
Mean post-trial confidence: Ball falling short	2.25
Mean post-trial confidence: Ball caught low	3.19
Mean post-trial confidence: Ball caught at eye level	3.94
Mean post-trial confidence: Ball caught high	2.94
Mean post-trial confidence: Ball going overhead	2.69

Test Statistics[a]

N	8
Chi-Square	6.264
df	4
Asymp. Sig.	.180

a. Friedman Test

Tables A7.28(a) & (b). Ranks and test statistics for the Friedman test examining confidence in responses given Post-trial by subjects in the Free Recall condition across trajectory types.

Ranks

		N	Mean Rank	Sum of Ranks
Mean post-trial accuracy: Ball falling short - Pre-trial accuracy: Ball falling short	Negative Ranks	4	3.25	13.00
	Positive Ranks	3	5.00	15.00
	Ties	9		
	Total	16		
Mean post-trial accuracy: Ball caught low - Pre-trial accuracy: Ball caught low	Negative Ranks	5	5.10	25.50
	Positive Ranks	4	4.88	19.50
	Ties	7		
	Total	16		
Mean post-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball caught at eye level	Negative Ranks	5	8.40	42.00
	Positive Ranks	7	5.14	36.00
	Ties	4		
	Total	16		
Mean post-trial accuracy: Ball caught high - Pre-trial accuracy: Ball caught high	Negative Ranks	6	3.83	23.00
	Positive Ranks	2	6.50	13.00
	Ties	8		
	Total	16		
Mean post-trial accuracy: Ball going overhead - Pre-trial accuracy: Ball going overhead	Negative Ranks	6	3.75	22.50
	Positive Ranks	2	6.75	13.50
	Ties	8		
	Total	16		

Test Statistics[c]

	Mean post-trial accuracy: Ball falling short - Pre-trial accuracy: Ball falling short	Mean post-trial accuracy: Ball caught low - Pre-trial accuracy: Ball caught low	Mean post-trial accuracy: Ball caught at eye level - Pre-trial accuracy: Ball caught at eye level	Mean post-trial accuracy: Ball caught high - Pre-trial accuracy: Ball caught high	Mean post-trial accuracy: Ball going overhead - Pre-trial accuracy: Ball going overhead
Z	-.172[a]	-.375[b]	-.239[b]	-.711[b]	-.639[b]
Asymp. Sig. (2-tailed)	.863	.708	.811	.477	.523

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test

Tables A7.29(a) & (b). Ranks and test statistics for the Wilcoxon test comparing the accuracy of Pre- and Post trial responses made by subjects in the Recognition group for each trajectory.

Ranks

	Mean Rank
Mean post-trial confidence: Ball falling short	2.78
Mean post-trial confidence: Ball caught low	2.81
Mean post-trial confidence: Ball caught at eye level	3.41
Mean post-trial confidence: Ball caught high	2.72
Mean post-trial confidence: Ball going overhead	3.28

Test Statistics[a]

N	16
Chi-Square	2.950
df	4
Asymp. Sig.	.566

a. Friedman Test

Tables A7.30(a) & (b). Ranks and test statistics for the Friedman test examining confidence in responses given Post-trial by subjects in the Recognition condition across trajectory types.

Appendix 8.1. Example of running patterns for the experiment in chapter 8

Figure A8.1 shows three typical running patterns from the catching experiment in chapter 8

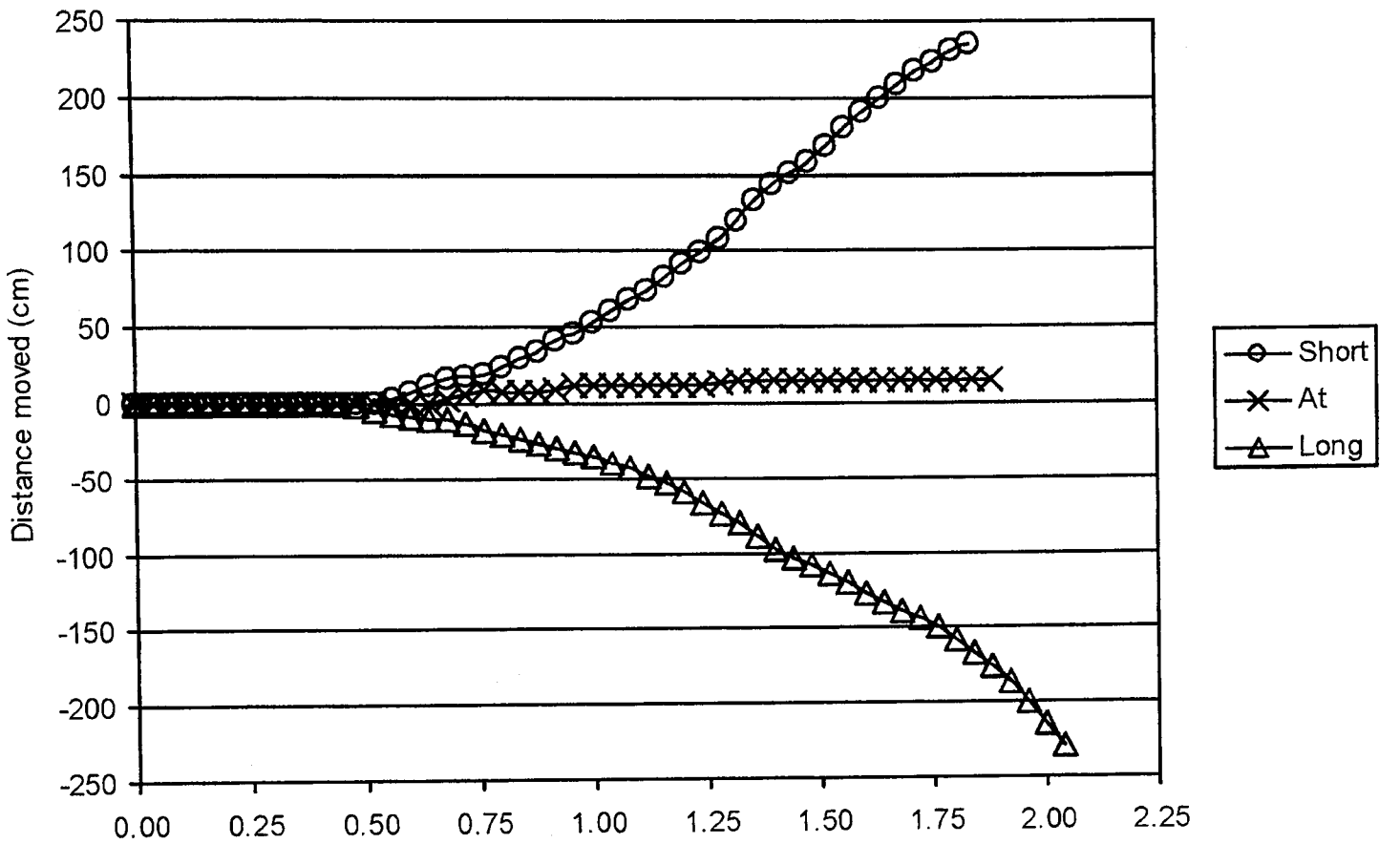


Fig. A8.1 Typical fielder movements moving to catch the three different types of trajectory (for clarity, the graph shows the data for every 0.12seconds although the fielder's position was actually sampled very 0.04seconds).

The time at which the fielder moved was taken as the first frame in which the fielder moved in the correct direction toward the interception point. For the two trials in which the fielder had to move shown in figure A8.1, this would be around 0.5seconds (examining individual graphs closely allowed more accurate appraisal). The video footage was then edited so that the fielders saw the trajectory of the ball in all frames up to the frame before they began to move.

For trials in which the fielder did not have to move, there is no clear marker of when they 'know' that they did not have to move to catch the ball. Fielders were

therefore shown the average duration of footage that it took them to decide whether to move forwards or backwards. This was based on the assumption that if they had to move forward or backward, then they would probably have begun to do so by that point.

Appendix 8.2. Statistics for experiment 1

Ranks

	Trial type	N	Mean Rank	Sum of Ranks
RT(sec)	Short	60	43.38	2603.00
	Long	60	77.62	4657.00
	Total	120		

Test Statistics[a]

	RT(sec)
Mann-Whitney U	773.000
Wilcoxon W	2603.000
Z	-5.428
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Trial type

Tables A8.1(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing subjects' reaction time to 'Short' and 'Long' trajectories.

Ranks

	Skill	N	Mean Rank	Sum of Ranks
RT(sec)	Novice	40	59.29	2371.50
	Expert	80	61.11	4888.50
	Total	120		

Test Statistics[a]

	RT(sec)
Mann-Whitney U	1551.500
Wilcoxon W	2371.500
Z	-.272
Asymp. Sig. (2-tailed)	.786

a. Grouping Variable: Skill

Tables A8.2(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing the reaction time of Novice and Expert fielders.

Ranks

	Skill	N	Mean Rank	Sum of Ranks
Accuracy	Novice	60	95.50	5730.00
	Expert	120	88.00	10560.00
	Total	180		

Test Statistics[a]

	Accuracy
Mann-Whitney U	3300.000
Wilcoxon W	10560.000
Z	-1.301
Asymp. Sig. (2-tailed)	.193

a. Grouping Variable: Skill

Tables A8.3(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing the accuracy of responses of Novice and Expert fielders to all video clips.

Ranks

Trial type		Skill	N	Mean Rank	Sum of Ranks
Short	Accuracy	Novice	20	35.00	700.00
		Expert	40	28.25	1130.00
		Total	60		
At	Accuracy	Novice	20	31.00	620.00
		Expert	40	30.25	1210.00
		Total	60		
Long	Accuracy	Novice	20	30.50	610.00
		Expert	40	30.50	1220.00
		Total	60		

Table A8.4(a). Ranks for the Mann-Whitney test comparing the accuracy of responses of Novice and Expert fielders to video clips, separated by trajectory type.

Test Statistics[a]

Trial type		Accuracy
Short	Mann-Whitney U	310.000
	Wilcoxon W	1130.000
	Z	-2.282
	Asymp. Sig. (2-tailed)	.023
At	Mann-Whitney U	390.000
	Wilcoxon W	1210.000
	Z	-.184
	Asymp. Sig. (2-tailed)	.854
Long	Mann-Whitney U	400.000
	Wilcoxon W	1220.000
	Z	.000
	Asymp. Sig. (2-tailed)	1.000

a. Grouping Variable: Skill

Table A8.4(b). Test statistics for the Mann-Whitney test comparing the accuracy of responses of Novice and Expert fielders to video clips, separated by trajectory type.

Ranks

Trial type		Vision	N	Mean Rank	Sum of Ranks
Short	Accuracy	Monocular	15	27.00	405.00
		Binocular	45	31.67	1425.00
		Total	60		
	Confidence	Monocular	15	33.53	503.00
		Binocular	45	29.49	1327.00
		Total	60		
At	Accuracy	Monocular	15	33.00	495.00
		Binocular	45	29.67	1335.00
		Total	60		
	Confidence	Monocular	15	33.73	506.00
		Binocular	45	29.42	1324.00
		Total	60		
Long	Accuracy	Monocular	15	30.00	450.00
		Binocular	45	30.67	1380.00
		Total	60		
	Confidence	Monocular	15	30.77	461.50
		Binocular	45	30.41	1368.50
		Total	60		

Table A8.5(a). Ranks for Mann-Whitney tests comparing accuracy of and confidence in responses given under monocular or binocular conditions.

Test Statistics[a]

Trial type		Accuracy	Confidence
Short	Mann-Whitney U	285.000	292.000
	Wilcoxon W	405.000	1327.000
	Z	-1.449	-.793
	Asymp. Sig. (2-tailed)	.147	.428
At	Mann-Whitney U	300.000	289.000
	Wilcoxon W	1335.000	1324.000
	Z	-.750	-.840
	Asymp. Sig. (2-tailed)	.453	.401
Long	Mann-Whitney U	330.000	333.500
	Wilcoxon W	450.000	1368.500
	Z	-.339	-.070
	Asymp. Sig. (2-tailed)	.735	.945

a. Grouping Variable: Vision

Table A8.5(b). Test statistics for Mann-Whitney tests comparing accuracy of and confidence in responses given under monocular or binocular conditions.

Ranks

	Trial type	N	Mean Rank	Sum of Ranks
Accuracy	Short	60	68.50	4110.00
	At	60	52.50	3150.00
	Total	120		

Test Statistics[a]

	Accuracy
Mann-Whitney U	1320.000
Wilcoxon W	3150.000
Z	-3.228
Asymp. Sig. (2-tailed)	.001

a. Grouping Variable: Trial type

Tables A8.6(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing the accuracy of responses to 'Short' vs. 'At' video clips.

Ranks

	Trial type	N	Mean Rank	Sum of Ranks
Accuracy	At	60	49.50	2970.00
	Long	60	71.50	4290.00
	Total	120		

Test Statistics[a]

	Accuracy
Mann-Whitney U	1140.000
Wilcoxon W	2970.000
Z	-4.728
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Trial type

Tables A8.7(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing the accuracy of responses to 'Long' vs. 'At' video clips.

Ranks

	Trial type	N	Mean Rank	Sum of Ranks
Accuracy	Short	60	57.50	3450.00
	Long	60	63.50	3810.00
	Total	120		

Test Statistics[a]

	Accuracy
Mann-Whitney U	1620.000
Wilcoxon W	3450.000
Z	-1.818
Asymp. Sig. (2-tailed)	.069

a. Grouping Variable: Trial type

Tables A8.8(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing the accuracy of responses to 'Short' vs. 'Long' video clips.

Ranks

	Skill	N	Mean Rank	Sum of Ranks
Confidence	Novice	60	91.44	5486.50
	Expert	120	90.03	10803.50
	Total	180		

Test Statistics[a]

	Confidence
Mann-Whitney U	3543.500
Wilcoxon W	10803.500
Z	-.173
Asymp. Sig. (2-tailed)	.862

a. Grouping Variable: Skill

Tables A8.9(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing Novice and Expert subjects' confidence in the accuracy of their responses.

Ranks

	Trial type	N	Mean Rank	Sum of Ranks
Confidence	Short	60	70.13	4208.00
	At	60	50.87	3052.00
	Total	120		

Test Statistics[a]

	Confidence
Mann-Whitney U	1222.000
Wilcoxon W	3052.000
Z	-3.066
Asymp. Sig. (2-tailed)	.002

a. Grouping Variable: Trial type

Tables A8.10(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing subjects' confidence in the accuracy of their responses to 'Short' vs. 'At' video clips.

Ranks

	Trial type	N	Mean Rank	Sum of Ranks
Confidence	At	60	50.05	3003.00
	Long	60	70.95	4257.00
	Total	120		

Test Statistics[a]

	Confidence
Mann-Whitney U	1173.000
Wilcoxon W	3003.000
Z	-3.335
Asymp. Sig. (2-tailed)	.001

a. Grouping Variable: Trial type

Tables A8.11(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing subjects' confidence in the accuracy of their responses to 'Long' vs. 'At' video clips.

Ranks

	Trial type	N	Mean Rank	Sum of Ranks
Confidence	Short	60	60.60	3636.00
	Long	60	60.40	3624.00
	Total	120		

Test Statistics[a]

	Confidence
Mann-Whitney U	1794.000
Wilcoxon W	3624.000
Z	-.032
Asymp. Sig. (2-tailed)	.974

a. Grouping Variable: Trial type

Tables A8.12(a) & (b). Ranks and test statistics for the Mann-Whitney test comparing subjects' confidence in the accuracy of their responses to 'Short' vs. 'Long' video clips.

Ranks

Trial type		Vision	N	Mean Rank	Sum of Ranks
Short	Confidence	Monocular	15	33.53	503.00
		Binocular	45	29.49	1327.00
		Total	60		
At	Confidence	Monocular	15	33.73	506.00
		Binocular	45	29.42	1324.00
		Total	60		
Long	Confidence	Monocular	15	30.77	461.50
		Binocular	45	30.41	1368.50
		Total	60		

Test Statistics[a]

Trial type		Confidence
Short	Mann-Whitney U	292.000
	Wilcoxon W	1327.000
	Z	-.793
	Asymp. Sig. (2-tailed)	.428
At	Mann-Whitney U	289.000
	Wilcoxon W	1324.000
	Z	-.840
	Asymp. Sig. (2-tailed)	.401
Long	Mann-Whitney U	333.500
	Wilcoxon W	1368.500
	Z	-.070
	Asymp. Sig. (2-tailed)	.945

a. Grouping Variable: Vision

Tables A8.13(a) & (b). Ranks and test statistics for the Mann-Whitney test of subjects' confidence in response accuracy across viewing conditions and trajectory type.

Correlations

			Accuracy
Kendall's tau_b	Confidence	Correlation Coefficient	.177**
		Sig. (2-tailed)	.007
		N	180

**. Correlation is significant at the .01 level (2-tailed).

Table A8.14. Kendall's τ correlation between subjects' accuracy and their confidence in accuracy of their responses.

Appendix 8.3. Statistics for experiment 2

Ranks

Trial type		Skill level	N	Mean Rank	Sum of Ranks
Short	Score	Novice	72	94.75	6822.00
		Expert	108	87.67	9468.00
		Total	180		
	Confidence	Novice	72	90.42	6510.00
		Expert	108	90.56	9780.00
		Total	180		
At	Score	Novice	72	91.50	6588.00
		Expert	108	89.83	9702.00
		Total	180		
	Confidence	Novice	72	88.39	6364.00
		Expert	108	91.91	9926.00
		Total	180		
Long	Score	Novice	72	90.75	6534.00
		Expert	108	90.33	9756.00
		Total	180		
	Confidence	Novice	72	95.82	6899.00
		Expert	108	86.95	9391.00
		Total	180		

Test Statistics[a]

Trial type		Score	Confidence
Short	Mann-Whitney U	3582.000	3882.000
	Wilcoxon W	9468.000	6510.000
	Z	-1.366	-.018
	Asymp. Sig. (2-tailed)	.172	.986
At	Mann-Whitney U	3816.000	3736.000
	Wilcoxon W	9702.000	6364.000
	Z	-.243	-.451
	Asymp. Sig. (2-tailed)	.808	.652
Long	Mann-Whitney U	3870.000	3505.000
	Wilcoxon W	9756.000	9391.000
	Z	-.071	-1.131
	Asymp. Sig. (2-tailed)	.943	.258

a. Grouping Variable: Skill level

Tables A8.15(a) & (b). Ranks and test statistics for the Mann-Whitney tests comparing Novice vs. Expert subjects in the accuracy of their responses and their confidence in the accuracy of those responses.

Binomial Test

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Score	Group 1	1	78	.577778	.33	.000[a]
	Group 2	0	57	.42		
	Total		135	1.00		

a. Based on Z Approximation.

Table A8.16. Statistics for binomial test examining whether performance was still better than chance for video clips viewed with 8 frames removed.

Correlations

			Reduction (frames)
Kendall's tau_b	Score	Correlation Coefficient	.213**
		Sig. (2-tailed)	.000
		N	540
	Confidence	Correlation Coefficient	.250**
		Sig. (2-tailed)	.000
		N	540

**. Correlation is significant at the .01 level (2-tailed).

Table A8.17. Kendall's τ correlation for the relationship between the reduction in video clip duration and both accuracy and confidence in responses.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.234[a]	.055	.053	.45

a. Predictors: (Constant), Reduction (frames)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	6.163	1	6.163	31.037	.000[a]
	Residual	106.835	538	.199		
	Total	112.998	539			

a. Predictors: (Constant), Reduction (frames)

b. Dependent Variable: Score

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.941	.047		20.027	.000
	Reduction (frames)	4.778E-02	.009	.234	5.571	.000

a. Dependent Variable: Score

Tables A8.18(a), (b), & (c). Statistics for the linear regression model of accuracy on reduction in frames.

Correlations

			Score
Kendall's tau_b	Confidence	Correlation Coefficient	.258**
		Sig. (2-tailed)	.000
		N	540

**. Correlation is significant at the .01 level (2-tailed).

Table A8.19. Correlation between subjects' accuracy of responses and their associated confidence in the accuracy of that response.

Correlations

Trial type				Score
Short	Kendall's tau_b	Reduction (frames)	Correlation Coefficient	.210**
			Sig. (2-tailed)	.002
			N	180
At	Kendall's tau_b	Reduction (frames)	Correlation Coefficient	.113
			Sig. (2-tailed)	.096
			N	180
Long	Kendall's tau_b	Reduction (frames)	Correlation Coefficient	.367**
			Sig. (2-tailed)	.000
			N	180

**. Correlation is significant at the .01 level (2-tailed).

Table A8.20. Kendall's τ correlation between subjects' accuracy of response and the reduction in frames viewed, separated by trajectory type.

Appendix 9.1. Statistics for chapter 9

Correlations

			Peak value of tan a (deg)	Difference in X position at peak(cm)	r2 for linear fit to tan a vs. time	Required average speed (cm/s)
Kendall's tau_b	Peak value of tan a (deg)	Correlation Coefficient	1.000	-.422**	-.545**	-.085
		Sig. (2-tailed)	.	.000	.000	.432
		N	41	41	41	41
	Difference in X position at peak(cm)	Correlation Coefficient	-.422**	1.000	.365**	-.078
		Sig. (2-tailed)	.000	.	.001	.472
		N	41	41	41	41
	r2 for linear fit to tan a vs. time	Correlation Coefficient	-.545**	.365**	1.000	.177
		Sig. (2-tailed)	.000	.001	.	.103
		N	41	41	41	41
	Required average speed(cm/s)	Correlation Coefficient	-.085	-.078	.177	1.000
		Sig. (2-tailed)	.432	.472	.103	.
		N	41	41	41	41

**. Correlation is significant at the .01 level (2-tailed).

Table A9.1. Kendall's τ correlations between various properties of trials.

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