



Level Up! A Design-based Investigation of a Prototype Digital Game for Children who are Low-attaining in Mathematics.

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Thesis submitted to the University of Oxford for the degree of DPhil Education.

Trinity term, 2013.

ACKNOWLEDGEMENTS

I would like to thank everyone without whose support I would not have been able to complete this research.

Many thanks to all the children and school staff who played the prototype game and told me exactly what they thought about it. Many thanks also to everyone in the University of Oxford's Department of Education, particularly Dr Chris Davies, with whom it has been my privilege to study.

I am especially grateful to Dr Rebecca Eynon, my DPhil Supervisor, for her incisive and always extremely helpful guidance.

Finally, for their patience and encouragement, I would also like to thank my family (especially Tracey, Cate and Oliver) and friends (especially Ann, Ben, Martin and Steve).

This thesis is dedicated to the memory of my friend Dr Jamie Rossiter.

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ABSTRACT

In the UK, as many as 20% of children in primary schools are more than two years behind their peers in mathematics. Research-based intervention for such disadvantaged children has been shown to be effective but not always sufficient, such that alternative approaches might sometimes be necessary. One alternative might involve digital games.

This study used a design-based research approach to investigate a prototype digital game, that implements principles of an effective numeracy intervention and draws on insights from learning theory and the cognitive sciences, designed for children in primary schools who are low-attaining in mathematics. It comprised three cycles of design, intervention, analysis and reflection.

The first research cycle involved the initial design of a prototype digital game, which was researched in one school. The second research cycle involved a second iteration of the game, designed in response to the feedback of teachers and children, which was researched in three schools. The third research cycle involved the design of a final iteration of the game, which to achieve theoretical saturation was researched online with twenty-four schools.

The study has shown that a game that implements principles of an effective numeracy intervention and that draws on insights from learning theory and the cognitive sciences can be designed and can be useful in schools for children who are low attaining in mathematics. However, for it to be taken up by schools, the game has to be perceived by teachers to have achieved a quality threshold. In any case, such a game is of limited use in and of itself. Where the prototype game has been shown to be most useful is when it serves as a fulcrum for social interaction and educationally productive discussion between the children and teaching staff: when it becomes an artefact that both supports individual learning and stimulates, scaffolds and mediates dialogue-based collaborative learning.

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Introduction

In the UK, as many as 20% of children in primary schools are more than two years behind their peers in mathematics (Butterworth *et al.* 2011; National Audit Office 2008; Williams 2008). These children often develop negative attitudes towards mathematics and suffer low levels of self-confidence which impacts severely on their ability to participate fully in the wider school curriculum and can persist into adulthood (Dowker 2005a; Parsons & Bynner 2005; Williams 2008). Children who experience difficulties with mathematics in primary school later on achieve few GCSE examination passes, leave full-time education early, have low life-time earnings, and all too frequently serve time in prison (Gross *et al.* 2009; Foresight Mental Capital and Wellbeing Project 2008; Social Exclusion Unit 2002). Effective intervention for children with mathematics difficulties is therefore important, both for the individual and for society.

Recently developed research-based interventions for children who have mathematical difficulties have been shown to have positive effects (Cohen Kadosh *et al.* 2013; Smith *et al.* 2012; Torgerson *et al.* 2013). However, not every child who is low-attaining in mathematics will benefit fully from any particular intervention. Because of the child's specific experiences or needs, the numeracy intervention on its own can be insufficient and additional or alternative approaches are therefore sometimes necessary (Cohen Kadosh *et al.* 2013; Gersten *et al.* 2009).

One such additional or alternative approach might involve digital games (Dowker 2009; Räsänen *et al.* 2009; Wilson *et al.* 2006b), which are widely acknowledged to be highly motivating (Iacovides *et al.* 2011; Malone 1981; Ryan *et al.* 2006), are frequently claimed to be effective vehicles for learning (de Freitas & Maharg 2011; Gee 2004b;

Prensky 2001a), and have been identified as being especially appropriate for children who have learning difficulties (Sanger *et al.* 1997; Sedighian & Sedighian 1996). However, despite the potential, to date there has been little research into digital games for children low-attaining in mathematics. Furthermore, the research that has been undertaken either uses simple game formats that have little in common with games designed for entertainment (Laurillard & Baajour 2009), thereby missing out on key engagement characteristics, or is grounded in only neuropsychological theory (Räsänen *et al.* 2009; Wilson *et al.* 2006b) rather than in school-based numeracy interventions that have been shown to be effective, thereby missing out on numerous practical and pedagogical insights.

This study sought to address this deficiency and contribute to the research effort, by investigating a digital game for children who are low-attaining in mathematics, designed in the style of an entertainment digital game, that both implements principles of an effective numeracy intervention and draws on insights from learning theory and the cognitive sciences. However, as confirmed by a systematic review of the literature (Chapter 2), no candidate games actually existed. Furthermore, rather than seeking to quantify the effectiveness of a game, which was core to Räsänen and Wilson's research, here the aim was to develop theoretical and practical knowledge about both the process of learning and the medium designed to support that learning (Gravemeijer & Cobb 2006).

Given this context, a design-based research approach was adopted (Design-Based Research Collective 2003), which involved the iterative design and research in schools of a prototype digital game, for children who are low-attaining in mathematics, that built upon an effective numeracy intervention, learning theory and the cognitive sciences (Chapter 3). The study thus set out to address two overarching but deliberately open research questions; open both because of the minimal guidance provided by previous research and to ensure the investigation was free to develop in response to early findings (van den Akker *et al.* 2006b). The first research question was:

How might a prototype digital game be designed to support children who are low-attaining in mathematics?

This involved consideration of the various potential ingredients of a suitable digital game, including games-based learning theory, effective numeracy intervention, learning theory and aspects of the cognitive sciences, and their integration into an appropriate games-based format; the aim being to develop an understanding of a medium designed to support learning.

The second research question was based on the notion that a learning technology's design and the way in which it is used to support learning are co-dependent and thus of equal interest (Birmingham *et al.* 2002; Houssart & Sams 2008; Williamson 2009). This question asked:

What happens when such a game is used in schools?

This research question involved considering the circumstances and consequences of teaching staff using the prototype game to support children in their care who were low-attaining in mathematics; the aim being to develop an understanding of how those children approached the learning of mathematics, in particular their difficulties, how that learning might be supported with an appropriately designed digital game, and how teaching staff chose to use that game.

Drawing on the design-based research approach, the study involved three cycles of design, intervention, analysis and reflection. In each research cycle, the overarching research questions were reconsidered and reformulated to create targeted sub-research questions (discussed in the relevant chapters). Each research cycle effectively functions as a standalone study, albeit with subsequent cycles based on the outcomes of earlier cycles, and thus are presented in this thesis in the style of separate papers (each adopting a three-part structure: design, intervention, analysis and reflection).

The first research cycle (Chapter 4) involved the initial design of a prototype game, grounded in a review of the literature and interviews with experts, which implemented principles of an effective mathematics intervention and drew on research around guided discovery learning, practice and repetition, the spiral curriculum, and modes of representation. This prototype game was then researched in one school, using

participant observation, questionnaires and interviews, in what was in effect an exploratory, low-fidelity laboratory study. The second research cycle (Chapter 5) involved the design of a second iteration of the game based on the outcomes of the previous research cycle, including the input of teaching staff and children. This version of the game was researched in more depth, in three schools, each of which is discussed separately. This cycle involved non-participant observation, questionnaires and interviews. The third research cycle (Chapter 6) involved the design of a third and final iteration of the game based on the outcomes of the second research cycle, which to help achieve theoretical saturation and to situate the research in as authentic a context as possible was researched online with 24 schools. This final cycle involved online questionnaires, interviews, and gameplay data automatically logged by the system.

Together, as discussed in Chapter 7 and concluded in Chapter 8, the three research cycles have shown that a game that implements principles of an effective numeracy intervention and that draws on insights from learning theory and the cognitive sciences (hereinafter summarised as ‘learning theory’) can be designed and can be useful in schools for children who are low attaining in mathematics. However, for it to be taken up by schools, a game designed to support learning has to be perceived by teachers to have achieved a quality threshold. In any case, such a game is of limited use in and of itself. Where the prototype game has been shown to be most useful is when it serves as a fulcrum for social interaction and educationally productive discussion between the children and adults: when it becomes an artefact that both supports individual learning and stimulates, scaffolds and mediates dialogue-based collaborative learning.

Research premises

A review of the key academic literature (teaching and learning, mathematical difficulties, games-based learning) and interviews with ten experts in fields relevant to the study (Appendix A), identified a sequence of research premises. These premises both provided a rationale and suggested the novel approach for the study. They can be summarised as follows.

(1) Many children who would not be identified as having special education needs, as many as 20% of a typical primary school classroom, are low-attaining in mathematics (Butterworth *et al.* 2011; National Audit Office 2008; Williams 2008). The various difficulties experienced by these children often impact severely on their educational prospects (Gross 2007) and can persist into adulthood (Parsons & Bynner 2005), which suggests that effective early intervention is important. (2) Research-based interventions for such children, for example Mathematics Recovery (Wright *et al.* 2006), Numbers Count (Dunn *et al.* 2010) and Catch Up Numeracy (Cohen Kadosh *et al.* 2013), have been shown to be effective, but not always sufficient. Therefore, additional approaches, possibly involving games, might sometimes be necessary (Dowker 2009). (3) Computer games are very popular and can be highly engaging and motivating (ESA 2013; Parliamentary Office of Science and Technology 2012; Wouters *et al.* 2013). (4) Computer games, because they respond to the skills and input of the player, give instant feedback, and allow players to take control and affect outcomes, also have potential for learning (Gee 2004b; Malone 1980; Prensky 2001a). (5) Whereas games-based learning has most often been researched with mainstream learners, for whom traditional teaching is already usually adequate, it might be especially suitable for

children who are low-attaining, helping them to re-engage with or access the learning (Sanger *et al.* 1997; Sedighian & Sedighian 1996). (6) Few examples of games-based learning are grounded in learning theory. Each of these premises are explored in detail below.

Literature searches were conducted in the databases Search Oxford Libraries Online (SOLO), The British Education Index, Educational Resources Information Center (ERIC), SCOPUS, and Google Scholar. This was supplemented by cascade searches derived from the literature identified in the databases.

2.1 CHILDREN LOW-ATTAINING IN MATHEMATICS

Research premise 1: *Many children who would not be identified as having special education needs are low-attaining in mathematics.*

In the UK and elsewhere, many children who would not otherwise be identified as having special needs are low-attaining in mathematics, the precise number depending on how 'low-attaining' is understood and the social and cultural context (Gross 2007; National Mathematics Advisory Panel 2008). For example, studies from several countries suggest that about 6% of children have severe difficulties with arithmetic (Butterworth 2005; Butterworth & Yeo 2004; Bzufka *et al.* 2000), while other studies suggest that around 20% of children have difficulties that are less severe but which still cause significant educational and functional difficulties: these children are more likely to leave school without qualifications and they are less able to perform everyday tasks such as extracting information from graphs or timetables (Bynner & Parsons 1997a; Parsons & Bynner 2005). In the UK, concerns have been raised about children's achievements in mathematics at all educational stages (Paterson *et al.* 2010). For example, Gross (2007) noted that in the 2005 Key Stage 2 SATS, 5.9% of Year 6 pupils achieved below Level 3 in mathematics, while the Department of Children, Schools and Families concluded that almost a quarter of primary school children did not achieve the expected standard in mathematics (National Audit Office 2008).

Research has also shown that children who are low-attaining in mathematics repeatedly experience failure throughout their school career, failure to make progress or to keep up with their peers. This is highly correlated with low levels of self-confidence, negative attitudes towards mathematics, and disengagement from learning (Dowker 2005b). Mathematical difficulties can impact severely on children's ability to participate fully in the wider school curriculum (Gross *et al.* 2009), all too frequently contributes to disruptive behaviour in the classroom which can lead to truancy or exclusion (Gross & McChrystal 2001), and inevitably contributes to the child's negative spiral of cumulative disadvantage which can have consequences far beyond the classroom (Stanovich 2000). More than other children, those who have difficulties with mathematics often need additional support to address their anxieties and low self-efficacy (Dweck 1975), in order to motivate them to re-engage with learning in mathematics (Reusser 2000).

In addition, studies have shown that there are about four times as many adults who have very low numeracy skills as there are adults who have very low literacy skills (Bynner & Parsons 1997b); while other research estimates that the failure to address mathematical difficulties costs individuals as much as £114,000 in lifetime earnings (Foresight Mental Capital and Wellbeing Project 2008), and costs the UK as much as £2.4 billion annually (Gross *et al.* 2009). This might be because people with poor numeracy skills tend to leave full-time education at the earliest opportunity and usually without qualifications (Bynner & Parsons 1997a), or because they are more likely to be unemployed, more likely to be depressed, more likely to be ill and more likely to be in prison (Butterworth & Yeo 2004; Carpentier *et al.* 2010). Two thirds of young prisoners, for example, have numeracy skills at or below the level of an 11-year-old child (Social Exclusion Unit 2002).

While needs are specific to each individual, children who are low-attaining in mathematics often experience difficulties with fundamental procedures such as counting, addition, and estimation, or with the language and vocabulary of mathematics. Others over-rely on counting because they lack more appropriate strategies, or they use one mathematical operation where another would be more

appropriate, or they misapply rules that they have been taught because they do not understand the concept behind the rule (Dowker 2004). Some children low-attaining in mathematics also have problems with their working memory, they have difficulty in planning and keeping track of the steps needed to solve a problem or they consistently use the same incorrect strategy for similar problems (Passolunghi 2006). Meanwhile, mathematical difficulties and mathematical anxieties often go hand in hand, although there is little research to suggest which comes first, whether mathematical anxiety causes mathematical difficulties or vice versa (Krinzinger *et al.* 2009; Rubinsten & Tannock 2010). However, various possible causes of mathematical anxiety have been identified: for example, helplessness and stress, leading to high levels of cortisone in the brain and thus inhibiting thinking and memory, and loss of self-perceived social-esteem, as children become aware of the differences between their mathematical achievements and those of others in their class (Dickerson & Kemeny 2004).

While the causes of mathematical difficulties have attracted considerable attention over recent years (*cf.* Butterworth 2009; Dehaene 2000; Geary 2011), much of the emphasis has been on the condition known as dyscalculia, parallel to dyslexia in reading, which is attributed to the individual's learner's neurocognitive dysfunction (Butterworth 2005). However, dyscalculia is still conceptually fuzzy (Desoete *et al.* 2004; Gifford 2006; Mazzocco & Myers 2003) and less attention has been given to other factors which might be equally as important. These other factors might include absenteeism, perhaps caused by challenging home circumstances, the incremental way in which mathematics is often taught, perhaps missing earlier lessons means that you have little chance understanding what's being taught in subsequent lessons, the different rates at which individual children develop cognitively, perhaps for some children topics are introduced 'too' early, and possibly poor teaching: 'mathematical learning difficulties, even if proven to have a genetic or hereditary component, do not appear "out of the blue"¹ but manifests itself,

¹ All emphases within quotations (shown by double quotation marks or italics) are in the original.

as combinations of environmental and neurodevelopmental problems, in instructional and sociological contexts' (Reusser 2000, p.2).

All of these factors require further research, but the fact that so many children low-attaining in mathematics given appropriate support make rapid and substantial progress suggests that mathematical difficulties are amenable to intervention (Dunn *et al.* 2010; Holmes & Dowker, in press; Wright *et al.* 2006). Meanwhile, the strong association between early and later mathematical difficulties (Bynner & Parsons 1997a; Fennema 1989) suggest that early intervention for children low-attaining in mathematics is likely to be important.

In summary, there are many children who are low-attaining in mathematics at school, only a relatively small proportion of whom might be said to have special education needs. Nevertheless, these difficulties cause the individual children and society at large many problems – psychological, sociological and economic – and thus deserve our attention.

2.2 INTERVENTION IS EFFECTIVE BUT NOT ALWAYS SUFFICIENT.

Research premise 2: *Intervention for children low-attaining in mathematics has been shown to be effective but not always sufficient, such that additional approaches might sometimes be necessary.*

Whereas there are a multitude of interventions for children who have difficulties learning to read (Brooks 2007), there are far fewer interventions for children who have difficulties with mathematics (Dowker 2009). Notable examples of interventions for children low-attaining in mathematics are Mathematics Recovery (Wright *et al.* 2006), Numeracy Recovery (Dowker 2001), Numbers Count (Dunn *et al.* 2010) and Catch Up Numeracy (Holmes & Dowker, in press). Two of these interventions, Mathematics Recovery and Numbers Count, were designed for the lowest achieving children, approximately 5% of any class, and involve approximately half an hour of individual intervention per day delivered by highly-trained teachers. Both have been shown to

have some positive effect (Smith *et al.* 2012; Torgerson *et al.* 2011). The other two interventions, Numeracy Recovery and Catch Up Numeracy, were designed for the larger group of children whose problems are less severe and for whom intensive intervention may not be economic or practical. Because they are lighter touch and do not require the involvement of specialist teachers, these latter interventions are more suitable for a games-based interpretation and so will be considered in more detail.

Numeracy Recovery, which was researched in depth but not widely implemented, was developed for the lowest achieving 20% of children. It adopted a componential approach to numeracy (Dowker 2001), which is the view that numeracy is made up of multiple abilities and that it comprises many content areas and many cognitive processes and forms of understanding. At a first level, numeracy knowledge may be divided into three broad categories: factual knowledge, procedural knowledge and conceptual knowledge (Delazer 2003), with all of which children who are low-attaining in mathematics often have considerable difficulty (Woodward 2006). Factual knowledge includes facts about addition and multiplication, and names given to numbers and operations; procedural knowledge guides written, oral and concrete mathematical procedures and algorithms; and conceptual knowledge involves the understanding of mathematical operations and principles, such as that of commutativity, that allows one to make inferences or to relate the different aspects of numeracy knowledge.

In turn, these three broad categories may be subdivided into a multitude of numeracy components which although inter-related are independently developing. Weakness in any one component can impact on performance in other components, partly because difficulty with one component may prevent the child perceiving and using relationships between them (Dowker 2005b). Numeracy Recovery focused on nine components of numeracy that earlier research had shown to be important to early mathematical development (Denvir & Brown 1986; Geary & Hoard 2005; Ginsburg 1977). These were: (i) counting; (ii) counting-related principles, such as order irrelevance and repeated addition and subtraction; (iii) reading and writing numbers; (iv) understanding place value; (v) word problem solving; (vi) translation between numeracy problems in

different formats, for example from word problems to objects such as counters; (vii) derived fact strategies, calculating new facts on the basis of known facts, in addition and subtraction; (viii) estimation, including evaluating the reasonableness of an estimation; and (ix) number fact retrieval, such as common number bonds.

Numeracy Recovery was researched with 168 children (Dowker 2001). The participants were first assessed on the components of numeracy, to profile their abilities across the components. Subsequently, over 30 weeks, they were given 30 minutes a week of individual remedial intervention by the classroom teacher in the specific components with which they had been found to have difficulties. The results both reinforced the componential view of numeracy and showed that children's numeracy difficulties could be addressed by intervention which is based on the componential view and which takes account of the specific strengths and weakness of the individual child. Analysis also showed that many of the participating children were better with some components than with others, so that it is misleading to label individuals as globally good or bad at mathematics, and that the components were not hierarchical: a child might perform well at what might seem to be a rather more difficult task, such as solving word problems, while performing poorly at what might seem to be an easier component, such as counting verbally (Dowker 2005a).

The numeracy intervention

The final intervention noted above, Catch Up Numeracy (hereinafter, the numeracy intervention), will be discussed in some detail: its principles were implemented in the prototype digital game designed for this research². Research has shown that the numeracy intervention

can lead to very marked improvements in arithmetic for children who are low-attaining in mathematics. Children who received this targeted non-intensive component-based intervention made two and a half times as

² While these principles might typically be reviewed in the methodology section of a thesis, the design-based nature of this study make it more appropriate to discuss them here.

much gain over time as would be expected on the basis of the passage of time alone. (Holmes & Dowker, in press)

Given that these children often start more than two years behind their peers, this achievement is especially notable.

The numeracy intervention was developed in response to frequent requests from schools for a numeracy intervention as effective and practical as the Catch Up Literacy intervention, which over the previous decade had been implemented successfully in clusters of schools by more than 80 local authorities across the UK (Holmes *et al.* 2012). It synthesised the pragmatic framework of Catch Up Literacy and the conceptual framework of Numeracy Recovery (Dowker 2005a), and was developed iteratively (as a design-based research process, Brown 1992, an approach discussed in Chapter 3), drawing on the experiences of school staff and children involved in pilot studies (Holmes & Dowker, in press).

From Numeracy Recovery, the numeracy intervention adopted the componential view of numeracy and the nine components. The development began with identifying, codifying and simplifying key elements of the earlier intervention, so that they might easily be accessed and used effectively by teachers and classroom assistants. From Catch Up Literacy, the numeracy intervention adopted features such as its four stage structure, the levels of achievement, and the importance of effective management. Each of these features was evaluated from the perspective of a prospective numeracy intervention based on the component model of numeracy, and then adapted as appropriate so that it was straightforward to deliver by classroom assistants. Ensuring that the numeracy intervention was both practical and sustainable was seen as being critical to its success, on the premise that if it is not sustainable, no matter how good it is, few will benefit.

The numeracy intervention scaffolds the child's progress in terms of two dimensions: the components of numeracy noted earlier and levels of achievement. Each component is divided into twelve levels which together provide a proxy indicator of progress, by using number ranges to represent gradually increasing levels of difficulty. For example, Level 1 covers numbers up to five, Level 6 covers numbers up to twenty,

and Level 12 covers numbers up to one thousand. It is these two dimensions which made the numeracy intervention particularly interesting from the perspective of a prototype digital game: the componential approach to numeracy and the levels of achievement resonate with focused activities and progress levels often found in entertainment games (Adams & Rollings 2006; Salen & Zimmerman 2003; Schell 2008). The authors of the numeracy intervention recommend that it is delivered in two 15 minute individual sessions a week, with each session involving only one numeracy component and one number range. This aims to minimise cognitive overload for learners who are low-attaining in mathematics (Kirschner *et al.* 2009; Moreno 2004; Sweller 1994) and distinguishes this intervention from most mainstream mathematics teaching.

Three example components of numeracy will be discussed, one from each of the three categories of arithmetical knowledge. Each of these components has been highlighted by previous research (Canobi *et al.* 1998; Shiffrin & Schneider 1977; Siegler & Booth 2004) and identified by teaching staff as presenting particular difficulties in the classroom (Evans 2008). For the same reasons, each of these components was implemented in the prototype digital game designed for the present study, which is why they are considered here in some detail. The three components are: remembered facts, which is an example of factual knowledge; estimation, an example of procedural knowledge; and derived facts, which involves both conceptual and procedural knowledge.

Remembered facts knowledge, the automatic recall of arithmetical facts, has been identified as a prerequisite for the efficient and effective use of working memory in arithmetical computation (National Mathematics Advisory Panel 2008; Shiffrin & Schneider 1977). If children are able to remember, for example, the sum of two numbers, rather than having to compute that sum each time it is encountered, working memory is available for higher order or more complex mathematical thinking. In many classrooms it is thus common for children to be encouraged to work on their 'number bonds', to learn for automatic recall all the pairs of numbers that when added together make another number (for example, the number bonds for 10 include 2 and 8, 3 and 7, and 4 and 6). Research suggests that many of those children who are low-attaining in mathematics remember few or insufficient of these arithmetical facts, such

that they all too frequently have to rely upon and thus it might be said 'squander' their sometimes limited working memory (Dowker 2005b; Passolunghi 2006).

Estimation knowledge, based on subitisation, has been identified as an important precursor to number skill acquisition and mathematical competence (Butterworth & Laurillard 2010; Dehaene 2000). For example, a deficit in a child's subitisation capacity, operationalised as their ability to estimate the number of dots on a screen, is used by one leading researcher as a marker for dyscalculia (Butterworth 2003). Estimation is also an important specific skill, both in everyday life (for example, estimating the cost of shopping in a basket) and in higher-order mathematics, where estimating before computing an answer to a mathematical problem allows the reasonableness of the computed answer to be assessed. Research suggests that many of those children who are low-attaining in mathematics have difficulty both estimating the answer to and identifying 'good' estimates for arithmetical computations, which can also impact on their abilities in the other components of numeracy (Siegler & Booth 2004).

The *derived facts* component involves the ability to derive new arithmetical facts based on given arithmetical facts, which has been shown to be important in the development and acquisition of arithmetical computation skills (Canobi *et al.* 1998; Dowker 2005b). Being competent in *derived facts* means knowing and being able to apply a number of conceptual principles. The numeracy intervention focuses on four of these. The identity principle is the most basic. If an arithmetical operation produces a given result, the repetition of the same arithmetical operation will produce the same result. This allows the child to derive the answer to an incomplete number sentence, the unknown fact, from the answer given for an identical but complete number sentence, the known fact. For example, from $[5 - 4 = 1]$ we can derive or infer that the answer to $[5 - 4 =]$ is also 1. The commutativity principle allows us to derive the answer to an incomplete addition number sentence from the answer given for a completed addition number sentence that comprises the same terms but in the reverse order (this is also applicable to multiplication). For example, from $[3 + 6 = 9]$ we can infer that the answer to $[6 + 3 =]$, where the position of the terms '3' and '6' have been interchanged, is also 9. Fully understanding the commutativity principle also involves recognising that it is not

applicable to subtraction (or division) number sentences. The final two *derived facts* principles included in numeracy intervention are the $n+1$ and $n-1$ principles. These allow us derive the answer to incomplete number sentences from the answer given for completed number sentences in which one of the terms is larger or smaller by 1. For example, from $[5 + 3 = 8]$ we can infer that the answer to $[5 + 4 =]$ is 9, because $[5 + 3 + 1 = 8 + 1 = 9]$.

For those who are competent in mathematics, these *derived facts* principles can seem too obvious or at least intuitive. However, research shows that many of those children who are low-attaining in mathematics often fail to use *derived facts* effectively and, instead, tackle each new number sentence from scratch (Dowker 1998). Providing remediation, however, is not straightforward. Because the *derived facts* principles are known implicitly, because they can seem obvious, they can be especially difficult to explain to anyone who doesn't yet understand them (Catch Up 2009a).

Consideration of the numeracy intervention raises several questions, all of which are relevant to the present study. First, how important for the effectiveness of the numeracy intervention is fidelity to the specified procedures (Jackson 2012)? Second, although perhaps intuitive, is making the mathematics 'simple', by limiting each session to only one component at one number range, the most effective approach? Making things simple for children who are low attaining in mathematics is not without criticism (Houssart 2002, 2004; Mason 2005). For example, 'typical arguments for this approach are persuasive and commonplace.... The irony of these arguments is that if you follow these guidelines low attainment is the inevitable result, as well as the reason' (Watson 2006, p.103). These two questions will be important for the design of the prototype game: how rigorously should the game apply the 'one component at one number range' principle of the numeracy intervention? Third, as has been shown in research on the Numbers Count intervention (Torgerson *et al.* 2013), might children benefit equally or more from the numeracy intervention if they participated in groups rather than individually? The same will be asked of the way in which the prototype game is used.

Finally, the authors of all the interventions discussed here acknowledge that not every child who is low-attaining in mathematics will benefit from any particular intervention, as evidenced by the wide variability of children's achievements in the numeracy intervention, even if it is faithfully delivered (Holmes & Dowker, in press). For some children, because of their anxieties, because of their specific needs, or because they have become disaffected in response to repeated failures, the numeracy intervention on its own can be insufficient. For these children, alternative diagnoses might be necessary (Cohen Kadosh *et al.* 2013). At the very least, and probably for all children low-attaining in mathematics, teachers should use a variety of approaches (Gersten *et al.* 2009), with digital games being one such possibility (Räsänen *et al.* 2009; Wilson *et al.* 2006b): 'given the ubiquity and popularity of ... computer games, it would be worth investigating whether and how computerised games and activities might be used in interventions [to] include conceptual as well as factual and procedural learning' (Dowker 2009, p.18).

In summary, focused intervention for children low-attaining in mathematics has been shown to be effective. In particular, the numeracy intervention has been shown to help children make more than twice the progress that would be expected on the basis of the passage of time alone. However, although mostly effective, the numeracy intervention is not always sufficient such that additional approaches, perhaps in the format of digital games, might sometimes be necessary. Finally, the two dimensions of the numeracy intervention, components of numeracy and levels of achievement, resonate with the focused activities and progress levels found in many digital games.

2.3 COMPUTER GAMES

Research premise 3: *Computer games are very popular and can be highly engaging and motivating.*

Digital games (computer games, video games, console games and mobile app games, rather than physical, board or other games) have been with us for more than forty years, and now appear ubiquitous. Many thousands are available, in a wide range of genres (first catalogued by Crawford 1982) (Table 2.1, p.17).

Table 2.1

Summary of digital entertainment game genres.

	COT* examples	Play duration	Engagement emphasis	Format	Development	Ethics
Driving / sport	<i>Grand Theft Auto</i>	Long	Reflexes	Relatively rigid	Relatively complex	
Maze	<i>Pac-Man</i>	Casual	Thinking	Relatively rigid	Relatively easy	
Physical	<i>Wii Sports</i>	Casual	Reflexes	Relatively rigid	Relatively complex	
Platform	<i>Super Mario Bros.</i>	Casual	Reflexes	Relatively flexible	Relatively easy	
Puzzle	<i>Tetris</i>	Casual	Thinking	Relatively flexible	Relatively easy	
RPG**	<i>World of Warcraft</i>	Long	Thinking	Relatively flexible	Relatively complex	
Shooters	<i>Doom</i>	Long	Reflexes	Relatively flexible	Relatively complex	Problem
Strategy	<i>Angry Birds</i>	Casual or long	Thinking	Relatively rigid	Relatively complex	

* COT = Commercial off-the-shelf games. **RPG = Role-playing game

Following *Pong*³, a digital version of table tennis which in 1970 became the first commercially successful computer game, there soon were action games, including shoot 'em up games; adventure games, which involved exploring virtual worlds or solving puzzles; strategy games, evolving and managing anything from zoos to whole civilisations; role playing games, usually fantasy quests, often played online, sometimes with many thousands of opponent players; platform games, such as those featuring the *Mario Brothers*; and puzzle games, such as *Tetris*. Digital games are available on a wide variety of platforms and in multiple formats. They include complex software packages, such as *The Sims* or *Grand Theft Auto*; massively multiplayer online games that can require many hours of gameplay, such as *World of Warcraft* or *Call of Duty*; physical digital games controlled with whole-body movements, such as *Dance*

³ Games and game platforms mentioned in this thesis are referenced in Appendix B.

Central or *Wii Sport*, played on games consoles such as the *X-Box Kinect* and the *Nintendo Wii*; and casual games, less complex games that can be played in just a few minutes, (Wallace & Robbins 2006), including apps on mobile phones and the Internet, such as *Angry Birds*, *Flight Control*, or *Temple Run*, or the many thousands of games on websites like *Miniclip*.

Defining what actually constitutes a game is notoriously difficult (Egenfeldt-Nielsen *et al.* 2008; Salen & Zimmerman 2003; Wittgenstein 1968). For Huizenga (1955), games constitute a 'magic circle' which separates the experience from that of the real world. For Caillois (1962), games are light-hearted, non-productive activities distinct from play which are circumscribed in time and place and have uncertain outcomes. Focusing on digital games, Prensky (2001a) identifies six common characteristics: rules; goals and objectives; outcomes and feedback; conflict, competition or challenge; interaction; and representation or story. Juul (2011), on the other hand, describes a 'classic game model' which understands games as optional and negotiable rule-based formal systems with variable outcomes, which require players to work to influence those outcomes, and which causes them to be emotionally attached to the outcomes.

While each of these descriptions offer some guidance for the design of a digital game, pointing to key characteristics that might be considered, their differences suggest that attempting to develop a definition is itself 'non-productive'. Instead we should be content to understand games as a range of activities that we would recognise as games, for the reason that they share some 'family resemblances' (Wittgenstein 1968): in this research of a digital game, those family resemblances are understood to include a virtual make-believe environment, rules of play (limitations and constraints), tasks that require effort, explicit aims and objectives, feedback from actions, scored outcomes, virtual or real competition, and lack of consequences for the real world (Whitton 2007a).

Nonetheless, even though it is not possible to define them, digital games are without doubt popular. Today, leading mainstream digital games are developed and advertised with the million dollar budgets previously associated with blockbuster Hollywood

movies, the franchises of which are themselves more often than not released in a variety of digital game formats; while, in contrast, casual games are often developed rapidly for much more modest budgets, yet can sell in their millions (Reisinger 2010). In the UK, more than two thirds of young people in the UK have access to a digital games console (households in the lowest income group are more likely to have a games console than a computer, OFCOM 2012) and around 95% of children play digital games, although more boys than girls: 96% of boys and 92% of girls, aged 6-9; 98% of boys and 94% of girls, aged 10-14 (Parliamentary Office of Science and Technology 2012). The annual UK market for digital games is around £4 billion (Schutte & Warman 2012). Meanwhile, in the US, around 96% of American teenagers, across the socio-economic spectrum, play games on computers, consoles or mobile phones (Lenhart *et al.* 2008; NPD 2013), making the US market worth in excess of \$20 billion a year (ESA 2013). Finally, across the EU, playing games is one of the most common online activities for 9-16 year olds. 83% use the Internet for playing games, compared with 85% who use it for school work and 62% who use it for messaging (Ólafsson *et al.* 2013).

However, it shouldn't be assumed that the popularity of digital games is universal. Even some figures for the number of young people who play games are based on their only playing at least one hour of games per month (Macchiarella 2013), or on average once a week (Thomas & Martin 2010), rather than every day (although this research is complicated by the large variety of games and the different ages and gender of game players). In addition, previous research revealed that some children prefer doing other things, such as playing outside, with their friends or with Lego building bricks, rather than using digital games. For those children, digital games were seen as fun but not that important (Holmes 2011).

No discussion of digital games can avoid the controversies that have surrounded them, since we first were given the opportunity to kill for fun. The very first digital game, *Spacewar!*, developed in 1962 at MIT, involved the shooting of enemy spaceships (the better known *Space Invaders*, the first shoot 'em up available outside of computer research departments, appeared fifteen years later). Since then, very many popular digital games have been both violent and misogynistic, characteristics which have been

linked to aggressive behaviour, particularly towards women, in those who play them. However, the research remains contentious, partly because of the methodological challenges, with some identifying links between violent gameplay and real-life violence (Anderson *et al.* 2010), while others suggest that any causal link is very weak (Ferguson & Kilburn 2010). In any case, violent game content is rarely a significant motivator for play (Przybylski *et al.* 2010), while violence, as found in many fairy tales, might be important for 'normal' child development (Jones 2008). Digital games are also criticised for other reasons. For example, some do require many hours of sedentary gameplay, which it is argued can lead to childhood obesity (Chaput *et al.* 2010), social isolation and addiction (Van Rooij *et al.* 2010), or poor academic development (Weis & Cerankosky 2010).

However, the overall impact of games on players appears to be small (Przybylski *et al.* 2010), and some health and cognitive benefits from playing digital games have elsewhere been identified (Baranowski *et al.* 2008; Blumberg & Fisch 2013; Green & Bavelier 2012). Digital games can also be highly engaging and motivating. Although people play games for very different reasons, many possible motivational mechanisms have been identified (Iacovides *et al.* 2011; Malone 1981; Ryan *et al.* 2006). For example, games can provide compelling narratives and dramatic tensions, using dynamic interactions, high-quality imagery and sounds. They can also offer optimal challenges, choice over actions and goals, adaptive and rapid feedback, and catharsis from life's pressures by means of an escape to an alternative reality. Playing digital games might also be pleasurable because doing so offers opportunities to discover new information and to acquire new skills and abilities, all without physical risk; or because they can lead to a sense of achievement, mastery, empowerment and enhanced self-esteem when actions leads to results. Of particular interest is the pleasure gained from overcoming adversity, moving from the negative emotions of suspense to the joyful emotions of achievement when a gameplay challenge is overcome (Lindley *et al.* 2008).

It is also argued that games are most engaging when they lead to a state of mind known as flow (Bowman 1982; Prensky 2001a). Where skills and challenges are

balanced, the purpose of the task is clear, and the feedback is immediate and constructive, some players become mentally immersed within the world of the game, they achieve ‘an almost automatic, effortless, yet highly focused state of consciousness’ (Csikszentmihalyi 1996, p.110). Flow is especially interesting for the present study because, according to Csikszentmihalyi, it also involves self-development, it ‘forces people to stretch themselves, to always take on another challenge, to improve on their abilities’ (1992, p.30). In short, flow in digital games can promote learning.

Finally, the motivating impact of digital games has been studied in terms of neuronal mechanisms. It is well known that rewards are associated with the generation of dopamine in the brain and that, within limits, the larger the reward, the larger this motivational signal. However, Howard-Jones (2011) explains that the anticipation of rewards is equally important, and that, perhaps counterintuitively, the use of uncertain rewards, anticipated rewards that might or might not be given, actually increases the overall dopamine release and thus generate a higher motivational signal. The waiting and hoping for reward is a part of the ‘buzz’. This is perhaps why chance, involving for example the roll of a dice, is important for the enjoyment of many ordinary games and contributes to the sense of playfulness (Costikyan 2013).

In summary, digital games which come in many types and many genres, are without doubt popular, although not universally so. Nevertheless, for a range of social, psychological and neurological reasons digital games can be highly motivating, perhaps making them suitable vehicles for motivating children to engage with educational tasks and thus for promoting learning.

2.4 GAMES-BASED LEARNING

Research premise 4: *Computer games have potential for learning.*

The use of digital games for learning, sometimes called games-based learning (GBL) (Squire & Jenkins 2003) or ‘serious games’ (Abt 1979), has over recent years become the focus of much attention. There has been a great deal of advocacy (Gee 2004b;

Prensky 2001a; Shaffer 2006) but also extensive research, summarised in numerous systematic reviews including, most recently, Boyle *et al.* (2013), Connolly *et al.* (2012), and Perrotta *et al.* (2013). Many have argued that digital gaming can provide players with significant and possibly unique opportunities for learning.

The 'affordances' of games, for example in providing instant feedback, in requiring 'active' learning, or in simulating particular types of real-world activities, can make them especially well suited to some kinds of educational tasks not offered by many other modes of learning. (Byron 2008, p.155)

Although often unsubstantiated and overly-confident, for example 'studies have proven empirically the efficacy of game-based learning over conventional methods' (de Freitas & Maharg 2011, p.20), much of this research has been affirmative. Nevertheless, GBL remains relatively uncommon in the classroom (Wastiau *et al.* 2009; Williamson 2009).

Even casual observation of children playing digital games inevitably leads to the conclusion that, as they do so, very often they are learning (Vygotsky 1933). For many, children's play is an essentially constructivist activity, the proto-natural form of learning, and learning is intrinsically playful (Bruner 1960; Caillois 1962; Sutton-Smith 2001). Play is 'the paradigm of education as it represents the natural field of experience in which a child builds the basis of his/her whole knowledge' (Farné 2005, p.172). For Gee, entertainment computer games are themselves 'learning machines', because their designs comprise various principles of learning (Gee 1999). The learning might be as simple as how to use the physical controls to manipulate the virtual space, how to go up, down, forward and backwards. It might involve learning about the benefits and disadvantages of cooperation, either with in-game avatars or with real people in shared game environments, or the learning of fine visual/motor coordination and faster decision making (Granek *et al.* 2010; Green *et al.* 2010; Pelletier & Oliver 2006). Nevertheless, although this learning might be limited, it is learning: it 'may be more incidental than intentional, more broad than deep, but it nevertheless does constitute learning' (Facer *et al.* 2003, p.201). GBL aims to build on and move beyond these foundations, to replace these weak learning outcomes with learning outcomes more useful for and aligned with the demands of formal education.

GBL adapts and applies for educational purposes the mechanisms of digital games. For example, by responding directly to the input of the player, allowing the player to take action and affect outcomes, digital games can reinforce learned behaviour or encourage the player to rethink. They can also be designed to adapt immediately to the skills of the individual, just as teachers do, raising the bar, increasing the difficulty, for players who move rapidly through the challenges; reducing the pace or difficulty for players who are progressing more slowly (Shute & Zapata-Rivera 2008; Vandewaetere *et al.* 2011). Digital game worlds can also be designed to simulate, and render safe, features of the real world (Murray 1998), giving learners a more authentic experience than is possible with books or other media: players get to do and experience things situated in a virtual world that connects to their real lives, not just to read about or watch them. Finally, entertainment games also often include increasing levels of difficulty, with a key aim of the player being to 'level up' during gameplay to higher and higher levels (Adams & Rollings 2006; Salen & Zimmerman 2003; Schell 2008), which is very similar to the approach adopted by the numeracy intervention.

However, digital games are most often promoted as effective learning vehicles because, when properly designed, they can be fun, engaging and highly motivating (Iacovides *et al.* 2011; Malone 1981; Ryan *et al.* 2006), which it is argued leads almost inevitably to learning (Garris *et al.* 2002; Hoffman & Nadelson 2010; Prensky 2001a), another unsubstantiated assumption which has been contested elsewhere (Whitton 2007b; Wouters *et al.* 2013). Whitton, for example, found no evidence of a connection between the enjoyment of entertainment games and games to support learning, and argued that any motivational benefits of GBL do not alone justify its use (2007b).

Using digital games to support formal learning is still controversial (Bourgonjon *et al.* 2013; Dickey 2013; Williamson 2009). While some have argued for a substantial games-based revision of education provision (de Freitas & Maharg 2011), many have objected to the very notion that computer games may have a part to play in the classroom, fearing that the intention is to replace teachers, to trivialise the serious project that is formal learning, or to constrain educational provision to screen-based brain-training rather than quality learning experiences (Hollingworth *et al.* 2009).

Others have shown that digital games can simply be difficult to implement within the constraints of a typical classroom, and that teachers are often inexperienced in how they work or might be used to support learning (Kenny & McDaniel 2011; Pivec & Pivec 2008; Williamson 2009).

‘Drill and practice’ games, software that encourages children to practice educational content by offering them animated rewards in response to correct answers, remain very common (for example, *Neurogames*, Reed 2010), and the evidence is that they can play a useful role (Holmes 2011): ‘drill and practice software in mathematics has proved extremely popular with teachers and pupils. Learners are happy to spend time on such activities, in and out of school; and think of this as “play” or “a game”’ (McFarlane *et al.* 2008, p.10). However, because these games use a behaviourist pedagogy and often ‘combine the entertainment value of a bad lecture with the educational value of a bad game’ (Squire & Jenkins 2003, p.8), drill and practice games are often dismissed as ‘chocolate-covered broccoli’ (Bruckman 1999) or ‘edutainment’ (Buckingham & Scanlon 2004) in which many children have little interest. Facer *et al.* suggest two possible reasons: either children are protecting their leisure time, or such games do not compare well with entertainment games (2003).

Drill and practice edutainment games might also be considered ‘gamified’ learning. Gamification (Kapp 2012; Werbach 2012) or ‘gameful design’ is ‘the use of game design elements in non-game contexts ... a software service layer of reward and reputation systems with points, badges, levels and leader boards’ (Deterding *et al.* 2011, p.1). The mechanics of digital games are repurposed to heighten the motivation and loyalty of those involved in a range of activities, from exercise to shopping. Leader boards, for example, build upon the positive impact of social competition on engagement in digital games (Howard-Jones & Demetriou 2009; Vorderer *et al.* 2003). They can have a large motivational effect: ‘while it’s fun to obtain a high score on a video game, it is just as fun to let others know you are the one who received the high score and to imagine being on the top of the leader board’ (Kapp 2012, p.34). Leader boards, in game and non-game contexts, also provide players both a measure of their current performance and a clear medium-term goal for them to pursue. The gamification of learning,

distinct from GBL, has been applied dramatically to classrooms (*World of Classcraft*, Young 2013) and an entire school to create highly immersive, game-like learning experiences (*Quest2Learn*, Q2L 2010).

More recently, the literature has considered the use of commercial-off-the-shelf digital games (COTS games) being repurposed for classroom learning. Examples include the use of the fantasy computer game *Myst* in listening, speaking and writing lessons (Rylands 2010); *Dr Kawashima* 'brain training' console games in primary school classes (Miller & Robertson 2010); and *Wii* games to support disengaged learners (Douch *et al.* 2010). However, the use of COTS games in the classroom is far from straightforward. Even when teachers are experienced in using them, know how they are played, how long they take to play, and how they might contribute to desired learning outcomes, they can be difficult to use effectively. Their pedagogy might not be relevant, such that it has to be squeezed into the curriculum. And, if it is relevant, it might not be accurate: they have been designed to entertain and thus often interpret liberally their subject matter (Jenkins 2002).

While it is argued that all 'good' games lead to learning (Gee 2004b), less attention has been given to the development and use of digital game gameplay to support the learning of specific educational content (notable exceptions are Egenfeldt-Nelson 2006; Facer 2004; Huizenga *et al.* 2009). In other words, there are few examples of digital games designed to facilitate and encourage the learning of, rather than the revision or practice of, clearly delineated and pre-defined educational content by means of a game's gameplay (the look and feel of the game, its narrative, the challenges it provides, its mechanisms and its rules, Crawford 1982). Rather than the learning of specific educational content being a happy coincidence of gameplay (as with COTS games) or gameplay being a reward for successful practice of pre-learned educational skills (as in edutainment), grounding the learning in the gameplay aims to exploit the immersive nature of entertainment games.

However, in GBL that does use the mechanisms of entertainment games to incorporate the learning in the gameplay, instead of facilitating the learning of specific educational content the aim is more often to raise awareness of content, often outside

the curriculum, for example *Time to Eat* which promotes sensible eating habits to young people who have diabetes (Pollak *et al.* 2010). Alternatively, such games focus on the so-called ‘soft skills’, such as communication, collaboration and problem solving (Ju & Wagner 1997), which many argue persuasively are needed most for children, to prepare them for future life (Levy & Murnane 2005).

From another perspective, learning through the gameplay might also be contrasted with games in which the learning takes place either before or during the gameplay (Table 2.2). In edutainment the learning opportunity, answering a worksheet-style task, usually occurs *before* the gameplay which is the reward for a correct response but is usually unrelated to the learning (for example *Neurogames*, Reed 2010, in which an animated squirrel is the reward for correctly answering a mathematics question). This is a behaviourist approach with delayed rewards.

Table 2.2

Learning before, during and through the gameplay.

Learning takes place...			Example games
Before the gameplay			
Questions followed by unrelated reward animation.	Behaviourist approach with delayed rewards.	Worksheet style practice.	<i>Neurogames</i>
During the gameplay			
Questions integrated into unrelated gameplay.	Behaviourist approach with immediate rewards.	Worksheet style practice in an engaging context.	<i>Timez Attack</i>
Through the gameplay			
Knowledge construction situated in the gameplay.	Constructivist approach.	Virtual context for exploring learning content.	<i>Time to Eat</i>

In rather more sophisticated games, the learning takes place *during* the gameplay but still that gameplay is usually unrelated to the learning (for example *Timez Attack*, West 2010, in which mathematics questions appear as unrelated obstacles to be overcome in order to progress within a virtual battle). This is a behaviourist approach with immediate rewards. Learning *through* the gameplay, on the other hand, situates the

learning content in the virtual context of the digital game's world, and it does so by means of authentic gameplay tasks (for example, in *Time to Eat*, the game involves feeding a virtual pet who, like the intended players, also has diabetes). This might be considered a more constructivist approach.

Immersing the learning of educational content in the gameplay aims to exploit the various mechanisms of entertainment digital games to help children learn that content. To win the game, you need to cross the chasm; to cross the chasm, you need to build a bridge; to build the bridge, you need to learn the physics of the game environment. In such a game, players learn the physics of the game in order to play and win the game; they do not play the game in order to learn the physics, even though that is the covert aim of the educational game developer. Immersing the learning into digital gameplay also effectively situates that learning in a context with which the child is potentially familiar, building on the understanding that learning is always grounded in context (Brown *et al.* 1989).

In summary, games and games-based mechanisms and approaches are widely thought to have potential for education, although GBL has not been widely implemented in classrooms. Nevertheless, extensive research has demonstrated a variety of ways in which games might be appropriated, to increase motivation, to relate the subject more to the individual's life outside school, and to promote learning. What however is not yet clear is whether learning is facilitated more by approaches in which the learning takes place before, during or through the gameplay.

2.5 GAMES-BASED LEARNING FOR CHILDREN WHO ARE LOW-ATTAINING

Research premise 5: *Computer games-based learning might be especially suitable for children who are low-attaining.*

GBL has most often been researched with mainstream learners, for whom traditional teaching is already usually adequate. For these children, GBL might be fun and possibly effective but it perhaps is not essential. However, children who are low-attaining, who

are failed by a system that sometimes adopts a one-size-fits-all approach, often need to be motivated to re-engage with their learning, and digital games have been identified as a possible vehicle (Sanger *et al.* 1997). Alternatively, such children might need additional or situated approaches to help them understand (Dowker 2009; Vaughn *et al.* 2012). Bryant and colleagues, for example, have identified several features of high quality intervention necessary for children who are low-attaining in mathematics: sequenced sub-skills, instruction on prerequisite skills, multiple practice opportunities, small groupings, feedback, procedural strategies, and progress monitoring (2008). Many of these features might potentially be operationalised in a digital game.

Nevertheless, there are few examples of GBL research that consider the use of digital games to support children who are low-attaining. Useful examples are: Laurillard & Baajour (2009) which involved the design of a computer game, for dyscalculic children, that had little in common with entertainment games; Holmes (2011) which used a case study approach to investigate how digital games designed to support 'struggling readers' in school were used at home; and Räsänen *et al.* (2009) and Wilson *et al.* (2006b) both of which investigated digital games for children who were low-attaining in mathematics. Laurillard and Baajour (2009) concluded that their game became a 'useful adjunct' to the teacher and provided opportunities for self-paced practice but, without prompts from the teacher, it failed to elicit mathematical language from the children. Holmes (2011) emphasised the motivational characteristics of digital games, which can be important for children who have learning difficulties, and noted that the children believed they had progressed, which is thought to be a prerequisite for learning (Lynch *et al.* 2006; Zimmerman 2000).

Wilson and colleagues devised and researched an adaptive game for the remediation of dyscalculia: *The Number Race* (2006a). The Number Race aims to address a core deficit in number sense, 'the ability to represent and manipulate numerical quantities non-verbally' (Wilson *et al.* 2006b, p.2), and is based on the idea that the development of number sense begins with subitisation, the ability to estimate numbers of dots. It is a minimal game, with little similarity to entertainment digital games, that involves 'intensive training' to strengthen links between symbolic and non-symbolic representations of

number. Wilson and colleagues conclude that the children in their study made progress in several areas, number comparison, subitisation and subtraction, which was unlikely to be caused by simple motivation to engage, and thus the game might help young dyscalculic children. However, they also note that ‘the principal difficulty observed was that after about 10 hours of use (an average of 420 trials), children tended to become bored with the software’ (2006a, p.10). They then discussed how the game should be amended so that children might be prepared to use it more frequently, without acknowledging how difficult it might be to arrange for a game requiring more than 10 hours of use to be incorporated into a school timetable.

Räsänen and colleagues (2009) adopted a quasi-experimental approach to contrast the effectiveness, for children with low numeracy skills, of The Number Race and another game, Graphogame-Math. Graphogame-Math, which the researchers devised for typically developing pre-school children rather than older children who were low-attaining in mathematics, aims to help children discover the relationships between the number system and arithmetic by giving them multiple opportunities to learn the correspondence between small sets of objects and numbers (no screen shots were provided). The outcomes of the experiments were, however, equivocal. While they found moderate intervention effects in a number comparison task that were statistically significant, the effect sizes had a wide confidence interval (from negative to strong positive). Meanwhile, only 4 of 20 calculated effect sizes comparing gains between the intervention and control groups were statistically significant. However, interestingly, particularly for the present study, they conclude that ‘the question of whether the medium itself had any effect on learning ... should be revised to one of how media can be designed to improve learning, as well as to better understand the mechanisms of learning’ (*ibid.*, p.18).

In summary, while the limited research does so far suggest that GBL might be especially suitable for children who are low-attaining, further research is clearly needed. This premise is thus the final catalyst for the present study: an investigation into the design and use of a digital game for children who are low-attaining in mathematics, that implements principles of the numeracy intervention and of GBL. However, the contention here is that these principles on their own are inadequate. A game that aims

to support children who are low-attaining in mathematics also needs to consider learning theory and relevant aspects of the cognitive sciences.

2.6 INSIGHTS FROM LEARNING THEORY AND THE COGNITIVE SCIENCES.

Research premise 6: *Few examples of GBL are grounded in learning theory.*

Despite the recent interest, both from the research community and from commercial developers, few examples of GBL are explicitly grounded in learning theory. Instead, developers typically just acknowledge that entertainment computer games provide powerful learning opportunities which might usefully be repurposed for the classroom, and draw on commonsense understandings of motivation and feedback (Becker 2000; Becta 2003, 2006). Digital games are considered potentially effective vehicles for learning simply because they are fun and engaging and because they can provide immediate and tailored responses to the player's actions. When a decision is made in the virtual environment, something happens straightaway: a door opens, a trap is released, something indicates how close you are to winning (Prensky 2001a; Vasilyeva *et al.* 2007).

The premise of this research, that digital games might be used to support children who are low-attaining in mathematics, also began with motivation and feedback. However, the design of the prototype game went beyond the motivation/feedback rationale, to consider how the game could be constructed to best facilitate learning, how it should work, and what approach it should take. A review of the literature identified various learning theory and examples of psychology and neuroscience research with potential for the proposed prototype game: implicit theories of intelligence, uncertain rewards, guided discovery learning, practice and repetition, the spiral curriculum, and modes of representation.

However, having been considered in detail, the first two of these, implicit theories of intelligence (Dweck 2000) and uncertain rewards (Howard-Jones 2009), were both rejected as objects of this study. Very little of Dweck's theoretical framework has fed

either into GBL (the closest is Brainology, an online instructional program that teaches brain science and study skills to help students develop a growth mindset, Dweck 2008) or into interventions to support children who are low-attaining in mathematics. Similarly, whereas chance plays a key role in the challenge and enjoyment of many games (consider, for example, the use of dice in board games such as ‘snakes and ladders’, Costikyan 2013), unexpected or uncertain rewards are rarely featured in digital games designed to promote learning (Holmes *et al.*, in press; Howard-Jones & Demetriou 2009). This is probably because, in educational contexts, uncertainty tends to be associated with lack of knowledge rather than chance, and uncertain rewards are thought to be unfair and thus de-motivating (Hock-Koon 2013). It was also recognised that involving either of these research frameworks properly, investigating whether challenging fixed-mindsets might lead to resilience in the face of difficulties or how uncertain rewards might lead to improvements in learning, might distract from addressing the principles of the numeracy intervention. The theory of uncertain rewards was, however, useful for the design of the reward system (virtual coin collection) for the prototype game.

The remaining theories, guided discovery learning, practice and repetition, the spiral curriculum, and modes of representation, appeared to be highly relevant to a design-based investigation of a prototype game for children low-attaining in mathematics and so were considered further.

Guided discovery learning

The behaviourist understanding of learning as the acquisition of often domain specific knowledge and skills is challenged by the cognitivist emphasis on the understanding of concepts, reasoning and problem solving, applicable across domains, which it is argued might best be achieved through discovery. Discovery learning, most often associated with Bruner (1961) and Papert (1980), is thus constructivist. Children are understood to actively construct their own knowledge through engagement with and discovery of aspects of the world around them, without any explicit instruction (Alfieri *et al.* 2011). Discovery involves an internal reorganisation of previously held ideas to accommodate

newly encountered ideas. The knowledge gained through discovery is thought to be more useful and better learned than anything explained, demonstrated, or taught by a teacher. From this perspective, the traditional classroom is seen as too didactic or artificial. Instead, learning should be achieved 'as the child learns to talk, painlessly, successfully and without organized instruction' (Papert 1980, p.9), with tools such as computers functioning as 'objects to think with' (*ibid.*, p.11).

However, pure discovery learning is unsuccessful if the learner fails to come into contact with the relevant information or if, having done so, fails to make the necessary connections or to construct 'accurate' knowledge (Kirschner *et al.* 2006). Even though children do discover how to talk and walk without explicit instruction, it does not necessarily follow that discovery learning applies to the learning of specific or curriculum based content.

Although it seems reasonable to expect learners to be able to construct their own understandings with minimal assistance because they do so on a daily basis in the context of everyday activities, perhaps the content and context of formal education are extraordinary ... and consequently require more assistance to arrive at accurate constructions, understandings, and solutions. (Alfieri *et al.* 2011, p.12)

Discovery learning 'may fail to promote the first cognitive process, namely, selecting relevant incoming information. In short, when students have too much freedom, they may fail to come into contact with the to-be-learned material' (Mayer, 2004: 17). Even Bruner (1961), whose work is most often cited by the discovery learning movement, counselled that discovery cannot be made *a priori* or without at least some guiding theory or knowledge of the domain, making it less useful for independent learning. Explicit instruction can, in any case, sometimes be more effective (Klahr & Nigam 2004). Guided discovery learning (Laurillard 1995), or enhanced discovery learning (Marzano 2011), on the other hand, offers a pragmatic synthesis between didactic delivery and pure discovery: 'the effects of unassisted-discovery tasks seem limited, whereas enhanced-discovery tasks requiring learners to be actively engaged and constructive seem optimal' (Alfieri *et al.* 2011, p.13).

Instead of a single narrative dictated by the teacher, or freedom to experiment with all possibilities, learning is facilitated and scaffolded by the teacher by means of dialogue, guidance, advice, feedback, and explanations (Pea 2004). Scaffolding involves the adult structuring elements of the task that are beyond the child's immediate competence, providing a pathway through the learning (Wood *et al.* 1976). Guided discovery learning with multimedia, which might include digital games, is summarised by Buckingham and Scanlon as an approach in which

the learner is not compelled to follow a single narrative line originated by the teacher (as in the drill-and-practice packages), or alternatively to wander or experiment with possibilities of their own free will (as in the exploration and reference packages). Guided discovery learning involves collaboration and dialogue between teacher (or, in this case, software) and learner. It depends on the agreement of a shared goal, and the supply of guidance and feedback from teacher to student. (2003, p.124)

The issue for the present study is whether digital gameplay might be designed as an object to think with, by which the child is encouraged and guided to discover for themselves the principles of a particular numeracy component.

Repetition and practice

Despite the intention to explore in this research the potential of learning through gameplay, which has been identified as a constructivist approach, repeated practice with immediate feedback is nevertheless something that many learners who are low-attaining find particularly helpful (Kuhn & Stahl 2003; Torgesen 2005), especially when the practice is a complement to the learning, rather than a substitute for it (Delazer *et al.* 2005). Although 'learning by practising is no longer the cutting edge of learning theory [and] the use of technology to support practice is rarely seen to be innovative' (Luckin *et al.* 2012, p.37), it is nevertheless acknowledged as a technique that enables learners to build a foundation of core knowledge in which higher order learning might be grounded. Interestingly, however, despite Gee's acknowledgement that practice is essential for learning (2004b), most digital games designed for learning emphasises the encounter with things to be learned and the active construction of knowledge rather than the retention and recall of that knowledge (Rohrer & Taylor 2006).

Research in neurology reaffirms common-sense understandings (consider the hours of practice put in by, among others, golfers and concert pianists): repetition and feedback can help ensure that learned skills become automatic and without error, thus freeing working memory for other cognitive demands (Feldon 2007; Meyler *et al.* 2008; Shaywitz & Shaywitz 2008). This understanding is reinforced by fMRI studies which show a shift in brain activity following practice from more frontal areas of the brain, associated with working memory and processing, to more parietal areas, associated with longer-term memory and automatic retrieval (Delazer *et al.* 2003).

The importance of automaticity for foundation level mathematics has also been reaffirmed by various research (Jackson & Coney 2005; Mestre 2002). Willingham (2009) summarises the importance of memorising, or making automatic, mathematics facts. First, to free working memory; second, to avoid having to rely on error-prone calculation methods; third, because higher-order mathematical processing often involves multiple lower-order facts; and fourth, because lack of automaticity has been shown to be an important cause of children's difficulty with mathematics. Automaticity thus needs to be extended beyond factual knowledge (for example, facts about addition) to include procedural knowledge (the ability to use automatically mathematical operations), both of which also must be underpinned by fluent conceptual knowledge (the understanding of mathematical operations) (Kaufmann 2004; National Mathematics Advisory Panel 2008). With each of these, children who are low-attaining in mathematics often have considerable difficulty (Ashkenazi *et al.* 2009; Dowker 2005a; Woodward 2006).

Multiple opportunities for practice, supported by opportunities for constructivist knowledge building, guided instruction, and conceptual reasoning, have been identified as essential for achieving mathematics automaticity. However, inevitably, there are at least three distinct aspects of practice, each of which might be important for children who are low-attaining: deliberate, distributed, and retrieval practice. Deliberate practice involves presenting tasks in the child's zone of proximal development (Vygotsky 1978) which might be mastered by concentrating on critical aspects of what

is to be learned, using repetition and feedback (Ericsson 2006). This approach has been shown to be necessary for learning but insufficient (Campitelli & Gobet 2011).

Moreover, the timing of the practice, whether massed in a single session or distributed over multiple sessions, has also been shown to be important (Cepeda *et al.* 2006). In over-learning, once the child has mastered a particular skill, they immediately then continue to practise the same skill. This is the approach typically expected by many mathematics textbooks, where multiple tasks of the same type, variations on a theme introduced in previous pages, are presented for children to work through for them to gain practice in the taught skills (Rohrer & Taylor 2006). However, distributed practice, where practising the same skills is divided across a number of sessions, hours or even days apart, has repeatedly been shown to be more effective for learning (Donovan & Radosevich 1999).

Finally, the mode of practice has also received much attention, with some researchers arguing that standard repetition is considerably less effective than repetition by retrieval or testing: 'tests do much more than measure learning; they also enhance learning' (Storm *et al.* 2010, p.244). Retrieval is frequently not just a regurgitation of information from memory but rather an active reconstruction of knowledge, making connections between what is being asked and various items previously encoded and now recalled. Retrieval events are thus more powerful learning opportunities than the original encoding events, such that testing as pedagogy rather than as assessment has much potential (Black & Wiliam 1998; Karpicke & Blunt 2011; Storm *et al.* 2010).

Spiral curriculum

Learning by repetition and practice might be most effective if it is part of what Bruner described as a spiral curriculum: 'a curriculum as it develops should revisit [basic ideas] repeatedly, building upon them until the student has grasped the full formal apparatus that goes with them' (1960, p.12). According to this approach, instruction should begin with the child's current developmental level and should involve them systematically revisiting the same broad conceptual/procedural processes at increasing levels of detail and sophistication, with each successive encounter grounded in the previous one.

A good curriculum needs to spiral around the great ideas, principles, and values of a field. Thus, our initial learning, which by definition will necessarily be basic and incomplete (but hopefully still accurate), will be revisited later in this spiral curriculum.... A spiral curriculum builds on initially learned concepts, which are usually just the beginning of comprehension or simply memorized facts or procedures, and develops them into higher levels of thinking. (Gentile 2004, p.16)

Topics are revisited, moving from the simple to the more complex, exploring the same topic at deeper levels; while new learning is related to previous learning, reinforcing and becoming intertwined with what is already known, thus achieving deeper understanding (Harden 1999). However, although intuitively appealing, the application of the spiral curriculum in mainstream mathematics has been heavily criticised. The argument is that the spiral approach inevitably treats topics superficially, limiting opportunities for children to achieve mastery of any particular topic, while preventing progress being made with new material (Gamoran 2001; Hook & Litzcke 2005): 'exposure to many concepts rather than emphasis on a few key concepts may lead to a superficial understanding of mathematical skills that are critical for learning high level math concepts' (Snider 2004, p.34).

However, rather than being used in a full curriculum, a spiral approach might instead be more applicable within a sequence of learning moments. For example, it might be productive for children who are low-attaining in mathematics to repeatedly and systematically revisit the components of numeracy, beginning with small numbers then progressing onto larger numbers to ensure that they have fully grasped the relevant concepts and/or procedures (this is the approach adopted by the numeracy intervention). The contention here is that a spiral approach might be suitable for children low-attaining in mathematics if embodied within a digital game by means of a spiral of both repetition and progression within the gameplay.

Modes of representation

Building on the work of Piaget, Bruner (1966) also argued that learning consists of three progressive stages based on the way in which information is stored and encoded

in memory: enactive, learning through action, by doing; iconic, learning by means of images; and symbolic, learning through language, by means of words or numerals:

Any domain of knowledge... can be represented in three ways: by a set of actions appropriate for achieving a certain result (enactive representation); by a set of summary images or graphics that stand for a concept without defining it fully (iconic representation); and by a set of symbolic or logical propositions drawn from a symbolic system that is governed by rules or laws for forming and transforming propositions (symbolic representation). (Bruner 1966, p.44)

Bruner's modes of representation thus may be conceived as three ways of representing domains of knowledge, or as three systems of processing information, or as three stages of learning. Unlike Piaget's age-related stages, these modes of representation are only loosely sequential, each stage merges into the next. The theory thus suggests that the learning of new material might be most effective if it progresses from iconic to symbolic representation, by means of enactive learning.

Although not explicitly, Bruner's modes of representation have long been part of the mathematics classroom; with the learning of arithmetic beginning with mathematical play, and progressing through pictorial representations, before emphasising the symbolic representations needed for computation. For example, Cuisenaire rods or Numicon shapes are often used with young children for them to represent and physically manipulate numbers (the enactive mode): 'objects such as number rods are seen as physicalized 'stepping stones' that assist the student in forming analogies between their own experiences and the world of mathematical abstractions' (Eisenberg 2002, p.3). Patterns of pictures are often used in textbooks and worksheets and patterns of dots are used in assessment of dyscalculia (Butterworth 2003) (the iconic mode). And school mathematics quickly progresses to a use of numerals (for example: 1, 2, and 3) and mathematical operators (for example: +, -, and =) in number sentences (for example: $1 + 2 = 3$) (the symbolic mode).

However, Tall (2003) argues that Bruner's modes of representation are not directly applicable to the learning of mathematics. He offers a re-interpretation: mathematical understanding comprises the embodied, which combines Bruner's enactive and iconic

modes; the symbolic-proceptual, the role of symbols in arithmetic, algebra and symbolic calculus; and the formal-axiomatic, starting with selected axioms and making logical deductions to prove theorems. Whether or not that re-interpretation is useful for higher-level mathematics, for children working at lower levels, particularly for those who are low-attaining, it is nevertheless the transition between iconic and symbolic representations that can sometimes be a stumbling block (Bruner 1964). This difficulty might be, at least in part, because the use of objects only results in a sharper distinction between informal and formal mathematical knowledge (McNeil *et al.* 2009).

At best, [physical objects] might serve as hints, or highly flawed metaphors, for the true mathematical concepts that they represent, while at worst, they can be downright misleading, drawing students' attention away from the realm of abstraction to the worldly realm of the senses. (Eisenberg 2002, p.3)

In a virtual environment, such as that of a digital game, Bruner's modes of representation cannot be so clearly distinguished; if only because, within a computer game, almost everything exists as images. Nevertheless, if one is prepared to suspend disbelief, to accept the virtual world as if it were physical for the duration of the game, Bruner's modes of representation do suggest certain ways of developing possibly effective learning opportunities. For example, it might be useful to allow the child to interact physically with objects on the screen, with 'interact physically' understood in a virtual sense, dragging the objects around the screen to simulate constructing mathematical problems in the physical world using concrete objects. Secondly, before requiring the child to use symbolic notation, it might be useful to begin with concrete representations of quantities, objects on screen that represent numbers by virtue of their size that are combined in mathematical problems, even if the concrete representation is again virtual. And thirdly, it might be useful to prioritise the transition between iconic and symbolic within the game, in order to give support for those children who find this transition especially difficult.

2.7 SUMMARY

The six premises discussed in this chapter together constitute the rationale and starting point for the present study. The original motivation for the study is the fact that there are many children in our schools who are low-attaining in mathematics, which has important consequences for the individuals and for society. Moreover, while appropriate intervention for these children can be effective, particularly if that intervention is based on the componential view of numeracy, the evidence is that some children might also need alternative or additional support, to help them both re-engage with learning and better understand the mathematics. The literature, and this researcher's prior experience and research, suggested the potential of digital gameplay as a medium through which the needs of these children might be partly addressed; particularly if that gameplay implemented principles of the numeracy intervention and was grounded in learning theory.

The research premises therefore lead to the two overarching but deliberately open research questions introduced in Chapter 1: How might a prototype digital game be designed to support children who are low-attaining in mathematics? What happens when such a game is used in schools? The following chapter discusses how these questions were approached.

Methods

As discussed above, this investigation was grounded in a sequence of six premises, beginning with the recognition that there are some children who are low-attaining in mathematics for whom conventional intervention is insufficient, and ending with two contentions: that digital GBL might be especially suitable for those children, and that few examples of GBL are grounded in learning theory. In fact, before this investigation, as confirmed by the literature search discussed in Chapter 2, there existed no intervention-based digital games for children low-attaining in mathematics. Meanwhile, previous research had reaffirmed that the way in which a game is used to support learning and the game's design are co-dependent and thus of equal interest (Houssart & Sams 2008; McFarlane *et al.* 2002; Williamson 2009).

For these reasons, a design-based research approach was adopted (Brown 1992; Collins 1992; Design-Based Research Collective 2003), the aim being 'to develop theories about both the process of learning and the means designed to support that learning' (Gravemeijer & Cobb 2006, p.18). For this research, this was operationalised as an investigation into both the design and use of a digital game that implements principles of an effective mathematics intervention and is grounded in learning theory.

Theory is the key component: 'educational design research *uses* theory, along with intervention findings, craft wisdom, inspiration, and experience as *inputs* to create interventions that solve real problems [and] *produces* theoretical understanding as an *output*' (McKenney & Reeves 2012, p.39). A DBR approach is increasingly common in the research of learning technologies (Anderson & Shattuck 2012), while its potential for research centred on a digital game designed to support learning has already been

demonstrated elsewhere (Barab *et al.* 2005; Cheng *et al.* 2010; Squire 2005). The novelty here is the focus on supporting children who are low-attaining rather than typically achieving and the specific learning theory in which the study has been grounded.

Given that design-based research has only a short history and is still relatively uncommon in the literature, before discussing how it was applied in this study, the design-based research approach will first be considered in some detail.

3.1 DESIGN-BASED RESEARCH

Although its general principles are mostly agreed by the design-based research (DBR) community (van den Akker *et al.* 2006a; Design-Based Research Collective 2003; McKenney & Reeves 2012), DBR is actually not a singular approach. Rather, it is a collection of approaches that share a common desire to make educational research more relevant to educational practice (a desire not unique to DBR, *cf.* Lewin 1946; McIntyre 2005), while increasing the theoretical robustness of educational design practice. As a consequence, various names are used interchangeably in the literature (including 'design science of education', Collins 1992; 'design experiments', Brown 1992; and 'educational design research', van den Akker *et al.* 2006a). 'Design-based research' (Design-Based Research Collective 2003) is preferred here because the name suggests design as a medium of research rather than just an object.

The DBR approach was first outlined in two papers, by Ann Brown (1992) and Allan Collins (1992), both of which called for the development of a design science of education. Both researchers believed that education research should go beyond the laboratory, to be situated in the contexts where learning actually takes place. They also recognised that education is complex and thus requires multiple approaches, with different learning designs being investigated for their effects; and they both argued for an approach to education research that is grounded in learning theory and that also aims to generate or refine learning theory. There are now multiple although

overlapping definitions (*cf.* Cobb *et al.* 2003; Dede 2004; Phillips 2006), summarised by McKenney and Reeves. DBR is:

a genre of research in which the iterative development of solutions to practical and complex educational problems also provides the context for empirical investigation, which yields theoretical understanding that can inform the work of others. Its goals and methods are rooted in, and not cleansed of the complex variation of the real world. (2012, p.7)

In an influential collection of essays, van den Akker *et al.* (2006b) characterise DBR as interventionist, iterative, process orientated, utility orientated, and theory orientated. DBR involves an education intervention for use in the real world, which is developed by means of iterative cycles of design, intervention, analysis and reflection. It is process orientated because it focuses on understanding and improving interventions rather than laboratory-style evaluations; and it is utility orientated because the usefulness of an intervention is prioritised over standardised assessments. Finally, and key to its claim to be a worthwhile research approach, it is also theory orientated. The design is both grounded in theory and aims to contribute to theory building.

The Design-Based Research Collective's 'five characteristics of good design-based research' (2003) provide a similar framework. (i) DBR involves continuous cycles of design, intervention, analysis and reflection (Gravemeijer & Cobb 2006). (ii) It intertwines the goals of designing learning environments and developing proto-theories of learning; it is a circular or spiral process, in which designed learning environments both embody and inform conjectures about learning (Sandoval 2004). (iii) It leads to emergent theories that might contribute to future research; it does not merely tune or evaluate what works (Cobb *et al.* 2003). (iv) It relies on established methods of data collection and analysis, with different methods being more or less appropriate and complementary at different stages (Gorard *et al.* 2004). And (v) it accounts for how the design is situated in authentic settings such as real classrooms, rather than in classrooms carefully re-configured to ensure valid results, while recognising that all aspects of classroom life are highly interdependent, that they are synergistic, and need to be treated as part of a systemic whole (Brown 1992).

DBR involves conventional methods of data collection and analysis, qualitative and quantitative, with different approaches appropriate at different stages. However, DBR was partly conceived in contrast to research that focuses on ‘frozen’ technology: how a pre-existing technology is being used, or how ‘effective’ it is at a particular point in time, rather than how it might be designed or improved to help support learning (Bereiter 2002; Collins *et al.* 2004). A summative evaluation, for example, might be obvious for a study centred on a learning technology such as a game designed to support learning. However, while such an approach, converting proxies of real life into data for quantification and statistical analysis, is valued by many (Hargreaves 1997; National Research Council 2002; Oakley 2006), many others are critical (Hammersley 2002; La Caze & Colyvan 2009; Olson 2004): ‘success or failure of an innovation cannot be evaluated simply in terms of how much students learn on some criterion measure’ (Collins 1992, p.6). The argument is that a quantitative approach can only comment upon that which has been counted, or at least it prioritises that which can be counted over and above that which demands interpretation. This is especially problematic in an educational context, given that such contexts are inevitably messy and always in flux (Berliner 2002; Gherardi & Turner 2002) and particularly that there is as yet no universally agreed simple model of learning (Illeris 2007).

Such an approach, often characterised as the application of a ‘gold-standard’ medical model, which itself relies upon a set of contested assumptions (Greenhalgh 1996), also tends to ignore much of what scientists and experts actually do: the iterative development of ideas and the prioritisation of intuition and tacit knowledge over rigid adherence to rules (Brooks 2012; Doherty 2000). When applied to learning technologies, it can become an attempt to develop ‘evidence-based’ approaches for ‘effective’ technologies, a black-box or quasi-laboratory approach that requires a pre-existing technology (there was no such technology in this case, and therefore nothing available for study) and variables that are easy to measure, which can compromise the technology’s relationship with its context. In any case, ‘no significant difference’ is all too frequently the outcome of such research (Daniel 2002; Reeves 2005).

As Collins argues (1992), research into education technologies also needs to consider complementary questions around, for example, implementation in practice, effect on teacher and student attitudes, and sustainability. In fact, any learning that occurs does so as a consequence of the interplay between the learner, the teacher, the educational content, and the educational medium (Dickey 2013). Accordingly, DBR is conceived, in contrast to pure basic research exemplified in the work of physicists and pure applied research exemplified in the work of engineers, as belonging to Pasteur’s quadrant of ‘use-inspired basic research’ (Stokes 1996).

Cycles of design, intervention, analysis and reflection

Because no one study will be able to answer all relevant questions, DBR (like other ‘design sciences’ such as architecture, car manufacturing or fashion, Anderson & Shattuck 2012), typically involves repeating cycles of design, intervention, analysis and reflection: ‘an iterative process of “successive approximation” or “evolutionary prototyping” of the “ideal” intervention’ (van den Akker 1999, p.8). As summarised in Reeves’ schematic (Figure 3.1), DBR begins with an analysis of the problem to be addressed and a clarification of the intended learning goals.

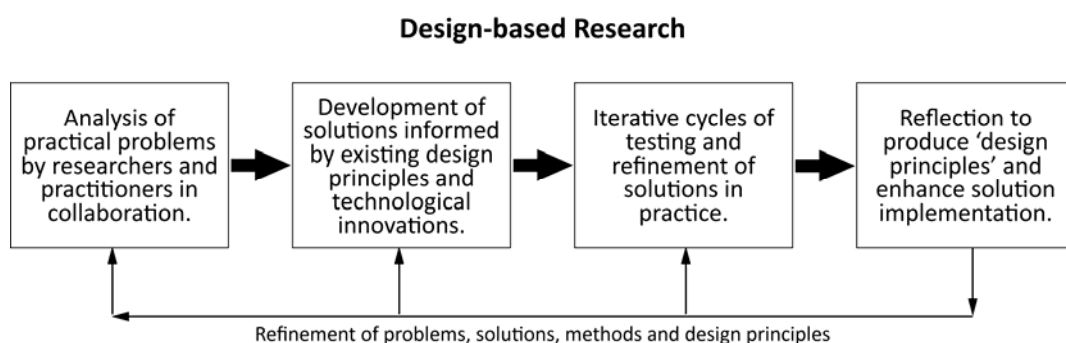


Figure 3.1

A design research approach in educational technology research (Reeves 2006, p.59).

A prototype for an appropriate intervention grounded in theory is then derived from the literature, the input of practitioners, and the tacit or craft knowledge and experience of the researchers and any developers. It is in essence a theory-guided

bricolage adapted from a variety of sources (Hebdige 1979; Lévi-Strauss 1966; Turkle & Papert 1992). This designed intervention is then empirically researched in the context for which it is intended, the research is authentically situated, in a sequence of cycles, with outcomes and reflection being fed back into second and subsequent iterations.

The spiral cyclical character of DBR is illustrated by Gravemeijer and Cobb (Figure 3.2): 'at the heart of [DBR] lies a cyclic process of (re)designing, and testing instructional activities and other aspects of the design.... [which serves] the development of the local instruction theory (2006, pp.24, 28). In other words, DBR comprises a spiralling relationship between the study of the developing design as it is implemented in practice and reflexive thought, with each cycle being dependent on the outcomes of the previous cycle. The process begins with conjectured local instruction theory, what the researchers expect the intervention to reveal in the context in which it is researched, with the conjecture being derived from the literature and tacit experience, and works towards empirically grounded local instruction theory, domain specific theory which is not necessarily widely generalisable but that can inform design or teaching in other situations (Gravemeijer 1994).

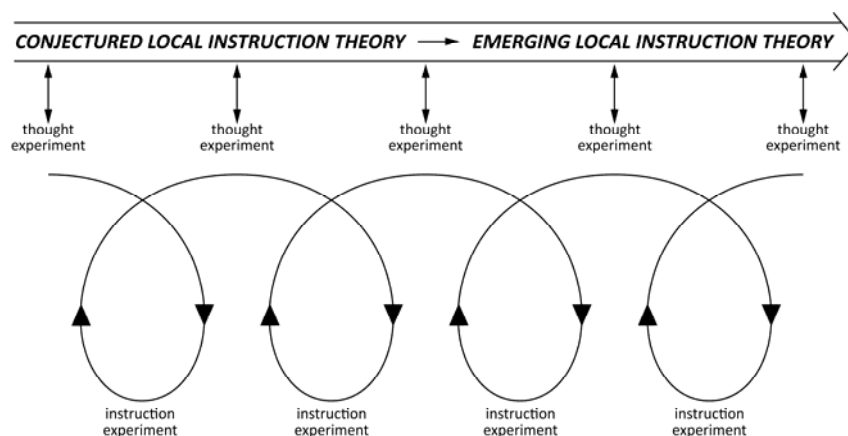


Figure 3.2

Reflexive relation between theory and experiments, based on (Gravemeijer & Cobb 2006, pp.28–29).

Emergent theories of learning

DBR thus aims to contribute towards the development of emergent theories of learning, ‘warranted theory’ (Edelson 2006), understandings of how the intervention functions and is used in context by practitioners and children, by means of the process of intervention design and implementation. DBR makes a ‘practical contribution in the form of the intervention, plus theoretical understanding ... about the phenomenon in question that is abstracted from empirical findings, and contributes to a body of knowledge that is useful to others outside the research setting’ (McKenney & Reeves 2012, p.19). To ensure its contribution is worthwhile, DBR goes beyond mere description, fine tuning, or evaluating what works, to explain and make predictions. The starting conjectural local instruction theory (for the present study, games-based learning theory, principles of the numeracy intervention, and insights from learning theory and the cognitive sciences) functions as an explicit but developing interpretive framework. And while it does not aim to generate decontextualized principles or universal grand theories (Anderson *et al.* 2010; Gravemeijer & Cobb 2006), the theory must itself contribute both to enhanced learning design and future research. In terms of the present study, the generated theory must both inform the design of digital games for children low-attaining in mathematics, and provide an understanding of how and why such a game might function and be useful.

Authentic contexts

DBR is also essentially collaborative (Collins 1992). It prioritises the involvement of participants, children, teachers and sometimes other stakeholders, as co-researchers and co-designers rather than simply as objects of research, extraneous variables to be controlled for, or recipients of research outcomes (Gravemeijer & Cobb 2006; Jitendra 2005; Kafai 2005). It involves studying the responses of students and teaching staff to the features of the design suggested by and grounded in the theory (Walker 2006). Accordingly, it is grounded in authentic classrooms rather than classrooms carefully re-configured to ensure repeatable results. The aim is to permit high ecological validity, so that the intervention might properly ‘migrate [to] average classrooms operated by

and for average students and teachers, supported by realistic technological and personal support' (Brown 1992, p.143). In other more conventional approaches, poor implementation or improper use of an intervention under study is often thought to obstruct or invalidate the research. Whatever the outcomes, it is not possible to determine the cause of the success or the failure, the intervention or its implementation, or whether there were other confounding variables. This is why considerable efforts are often put in by conventional researchers to ensure, sometimes with mixed success, that the intervention under study is delivered exactly as intended (Jackson 2012). In DBR, on the other hand, the setting is 'allowed' to be entirely realistic, with all its inevitable messiness, and the intervention's use in that complex environment, 'successful' or otherwise, is itself a core research object: 'being situated in a real educational context provides a sense of validity to the research and ensures that the results can be effectively used to assess, inform, and improve practice in at least this one (and likely other) contexts' (Anderson & Shattuck 2012, p.16).

Problems and criticisms

Inevitably, DBR is not without problems or criticism. Problems centre on the fact that design-based research is not yet mature. Its boundaries are yet to be fully delineated, its methods yet to be fully tested (for example, the approach is renowned for generating large amounts of data, too little of which is needed to answer the research questions, which are themselves often evolving targets), and its criteria for success are yet to be universally agreed (Dede 2004). Criticisms centre on questions of objectivity, generalisation and validity. The vested interests of researchers have long been an issue for education innovation research (Collins 1992; Selwyn 2012): 'if a researcher is intimately involved in the conceptualization, design, development, implementation, and researching of a pedagogical approach, then ensuring that researchers can make credible and trustworthy assertions is a challenge' (Barab & Squire 2004, p.10). However, DBR goes some way towards addressing these concerns by focussing on theory generation through the lens of the design and use of the innovation in context, while avoiding attempts at binary evaluation. Nevertheless:

To ensure that they are scientifically rigorous, it is incumbent on those carrying out design studies to create a culture of science that includes ruling out competing hypotheses, that fosters scepticism about knowledge claims (including their own), and that encourages powerful tests of rival conjectures. (Shavelson *et al.* 2003, p.27)

However, such a challenge misapplies the rules of the natural sciences to what intends to be a design science, more in common with engineering and architecture (Collins 1992), and fails to recognise that DBR has as its goal the development of theory to guide future research and instructional design, rather than the assessment of particular interventions in limited circumstances. Thus, it is instead incumbent on those carrying out DBR to ensure that their studies are rigorous, ecologically valid, transcending of immediate context, and trustworthy (Barab & Squire 2004; Collins 1992; Gravemeijer & Cobb 2006).

DBR and the present study

A review of the methods literature, together with previous research experience, identified the DBR approach as being especially appropriate for the present study. The research premises (Chapter 2) constitute the conjectural learning theory, which contributed to cycles of design, intervention, analysis and reflection. The intention was to design a prototype digital game originally grounded in the conjectural theory, then to research that prototype in authentic contexts, real classrooms, amending it in response to input from the children and teaching staff. The decision to adopt a DBR approach also informed the research questions discussed in Chapter 1, which move beyond whether or not the prototype game is effective in and of itself, to investigate how it is used in the classroom, how it might be made more appropriate to the needs of teachers and useful, and what its use reveals about any learning that it facilitates. In short, the aim of the present study, as is typical of DBR, is to contribute to theory building, an understanding of the innovation as used in real classrooms that does not necessarily aspire to context free generalisations but which might inform the future development of instructional designs.

3.2 RESEARCH DESIGN

The DBR approach adopted here is an emerging research design (Creswell 2008) which began with an analysis of the problem to be addressed, clarification of the intended learning goals and research orientation, then involved three research cycles of design, intervention, analysis and reflection. Throughout, the aim was to ensure the research remained focused but free to develop in response to early findings: ‘the emerging theoretical and practical insights and, in some cases, even the research design, adjust course based on the empirical data’ (McKenney & Reeves 2012, p.15).

The specific methods used in each research cycle (for sampling, data collection, and analysis and reflection) are detailed in the relevant chapters. Here, however, first the three research cycles, then the overall approach to sampling and data collection, will be summarised.

Three cycles of design, intervention, analysis and reflection

There were three cycles of design, intervention, analysis and reflection. The first research cycle involved the initial design of a theory-based prototype game which was researched in one school. Children were withdrawn from their usual school routines to play the game, making this in effect an exploratory, low-fidelity laboratory study. The second research cycle involved a second iteration of the game based on the outcomes of the previous cycle. This was researched in-depth in three more conventional school contexts, with teaching staff using the game as and when they saw fit. The third and final research cycle involved a third iteration of the game based on the outcomes of the second cycle. To be as realistic an implementation of the game as possible and to help achieve theoretical saturation, this iteration of the game was researched online with twenty-four schools. The three research cycles thus developed from a small scale laboratory-like implementation to a large scale ‘authentic’ implementation; it began with an exploratory study, was followed by an in-depth study, and finished with a confirmatory study (Figure 3.3, p.50).

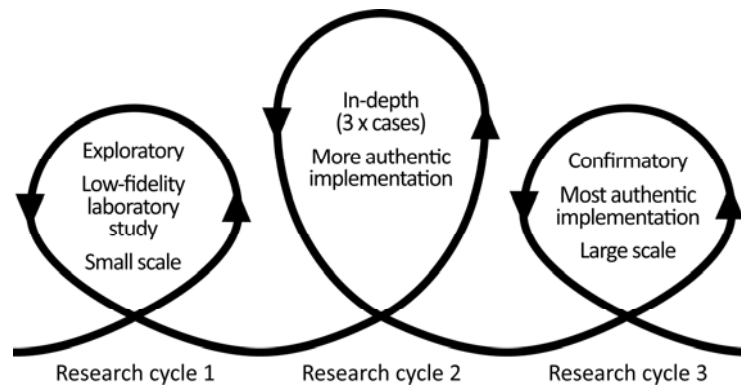


Figure 3.3

The three research cycles: from exploratory to confirmatory, low-fidelity to 'authentic', small scale to large scale.

The three research cycles were, therefore, as suggested by Brown (1992), 'analogous to the alpha, beta, and gamma phases of software development':

The alpha, or developmental, phase is under the control of the advocate, and by definition it must work for there to be any later phases. It works, though, under ideal supportive conditions. Next comes the beta phase, tryouts at carefully chosen sites with less, but still considerable, support. Critical is the gamma stage, widespread adoption with minimal support. If this stage is not attempted, the shelf life of any intervention must be called into question. (Brown 1992, p.172)

First research cycle

The first research cycle, the alpha phase (Figure 3.4, p.51), here comprised the design of a working digital prototype game, rather than a low-fidelity prototype, and its use in a single school by a small number of children. The purpose of this research cycle was essentially exploratory, and to provide a foundation for the next research cycle. As suggested by the literature, and as will be discussed in Chapter 4, the design of the prototype game drew on principles of the numeracy intervention, insights from learning theory, and GBL theory. It was thus a 'theory-guided bricolage' (Hebdige 1979; Lévi-Strauss 1966; Turkle & Papert 1992). A key assumption of the game's design was that a fully-working final version, if made generally available to schools, would be delivered online, and schools would purchase access to the game to complement their other provision for children low-attaining in mathematics. However, this initial prototype game (coded and designed, after

extensive discussions with the researcher, by Doug Lapsley, an experienced developer of digital GBL) existed only as a collection of files on a standalone laptop computer, and required the researcher to select and run the various modules.

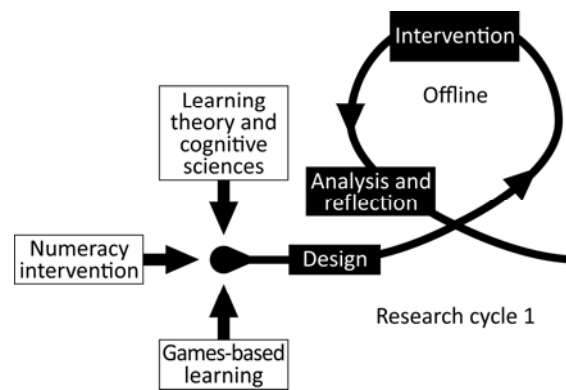


Figure 3.4

First research cycle of design, intervention, analysis and reflection (alpha phase).

In this first research cycle, to ensure ‘ideal supportive conditions’ (Brown 1992, p.172), the intervention (the empirical research of the use of the prototype game) was facilitated by the teacher with primary responsibility in the school for children who were low-attaining in mathematics; and the children’s use of the prototype game was supervised by the teaching assistant who usually delivered to them the numeracy intervention (the sampling used is discussed below). The game functioned effectively as both the instrument and object of the research. However, as noted, the first intervention was in effect a low-fidelity laboratory study: children were taken out of their usual routine to play the game, the game was delivered offline, on a standalone computer, not online as a final version would be delivered, and the researcher was a participant-observer (Jorgensen 1989) who provided wherever necessary face-to-face support (starting the game, guiding the gameplay and providing mathematical and technical support).

Second research cycle

The second research cycle, the beta phase (Figure 3.5), was both more authentic and more in-depth. It involved the amendment (indicated by the dotted line) of the prototype game in response to the outcomes of the first research cycle, and its use in three ‘carefully chosen’ (Brown 1992, p.172) schools: a town centre school, a suburban school and a rural school. This was thus a purposeful sample of schools (sampling is discussed in more detail below).

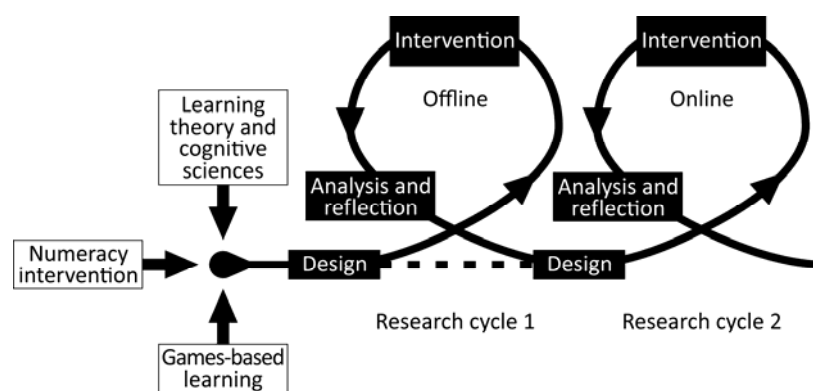


Figure 3.5

First and second research cycles of design, intervention, analysis and reflection (alpha and beta phases).

This research cycle thus adopted a collective case study approach, rather than an intrinsic or instrumental case study approach (Stake 2005), because ‘no case ... preserves all the features of the whole. It is a fragment with a distinct location that shapes its character’ (Gomm *et al.* 2000, p.108). The three schools thus functioned as ‘bounded’ cases, which, while emphasising the wholeness of the system, allowed attention to be focused on those aspects that were especially relevant in each case (Stake 1995). Such an approach was particularly appropriate for the present study because it involved asking ‘why’ and ‘how’ questions in situations over which the researcher had low control (Yin 2008). This second iteration of the game was also ported to the Internet, so that it might be played on any computer with Internet access, and the teaching staff and the children whom they nominated were given password-protected access. The use of a password allowed the system to identify each player and thus record and track individual progress.

Teaching staff at each school involved in the second research cycle were given complete control of the game, to decide independently of the researcher if, when, where and how they did use it. Learning about those decisions became itself an object of the research. Meanwhile, the researcher only observed each child's use of the game on three or four occasions, not every time that they played it, and then did not engage directly with the children but watched from a distance the unfolding interactions between the children, the adults and the game. This approach, moving the observation from being participatory in the first research cycle towards being relatively unobtrusive in this second research cycle (Webb *et al.* 1966), aimed to address the fact that the presence of the researcher in a small private space can change the dynamics such that the original situation, the object of the observation, no longer exists: it becomes unavailable to the act of observation.

The intervention was more authentically grounded in real learning contexts. However, the teaching staff were instructed in how the game implemented the numeracy components and might be accessed, the researcher managed the participants' online access to the game and provided telephone support and guidance throughout, and the researcher was present albeit 'unobtrusively' during some of the gameplay. As a consequence, the research context of the second intervention was still some way away from the assumed context of a final version of the game. Nevertheless, this approach allowed the prototype game to be researched in three contexts, similar but with important differences. It generated large quantities of data, and gave various opportunities for the experiences and opinions of the participants to be considered, which informed the final iteration of the game for the final intervention.

Third research cycle

The third research cycle, the gamma phase (Figure 3.6, p.54), involved 'widespread adoption with minimal support' (Brown 1992, p.172). The prototype game was again amended in response to the outcomes of the previous research cycle, and was then researched online with twenty-four schools. This third research cycle served two core purposes. First, it afforded a last opportunity to reinforce or refute outcomes of the first

two research cycles, to help achieve a sufficient level of theoretical saturation (Corbin & Strauss 1998) and to provide some validation through the triangulation of data from different sources and an additional method (Denzin 2009; Rhineberger *et al.* 2005). Second, it involved the prototype game in a context much closer to the assumed context of a final version of the game, so that the impact of that context on the participants' attitudes to the game and on its usefulness in the classroom might be considered).

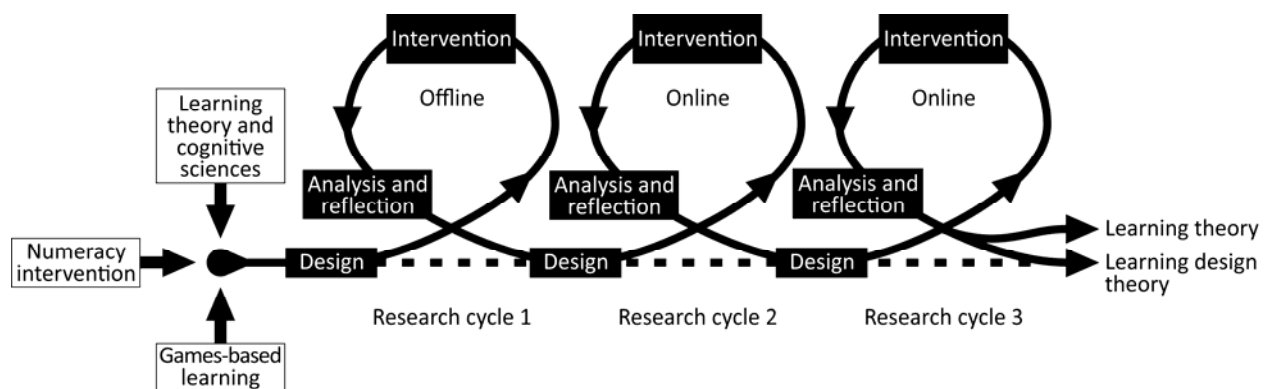


Figure 3.6.

The three research cycles of design, intervention, analysis and reflection (alpha, beta and gamma phases).

It is in this sense that the final intervention aimed to be more authentic. Full control of the prototype game was handed over to the education charity that owns the numeracy intervention, the principles of which were implemented in the game. The charity then made the game freely available to teachers and classroom assistants who had completed training for the numeracy intervention. In turn, those school staff used online management tools, developed to support the game, to provide children in their care who were low-attaining in mathematics with access to the final prototype, as and when they thought it appropriate to do so. The management tools also enabled the teaching staff to monitor online the children's achievements and progress. The outcomes of the third research cycle aimed to contribute both to learning theory and to learning design theory.

Research questions

As discussed in Chapter 1, the study thus set out to address two overarching but deliberately open research questions: How might a prototype digital game be designed to support children who are low-attaining in mathematics? What happens when such a game is used in schools? These questions were open because of the minimal guidance provided by previous research, but also because DBR studies are emerging designs.

Each cycle of the research only addresses a part of the study's overarching aims and is based on the outcomes of the previous cycle, which means that the research questions inevitably evolve during the research process (Creswell 2008). Consequently, as is typical of a DBR study, the research questions are reconsidered, reformulated and made explicit at each cycle of the research. The resultant sub-questions, posed in each research cycle and discussed in the relevant chapters, build towards answering the study's overarching central research questions, rather than being identical to them. The aim is to ensure the research remains focused but free to develop in response to early findings (van den Akker *et al.* 2006b).

Sampling

Details of the sampling used in each research cycle are discussed in the relevant chapters. Here the overall approach to sampling will be considered and the different approaches used in each research cycle will briefly be compared.

While the importance of appropriate sampling is frequently acknowledged, 'the apparent conclusions of our research are determined less by the social reality under investigation and more by the nature of the sample we use to collect data' (Gorard, 2001, p.9), there is more agreement about what qualitative sampling should not involve than what it should involve (Curtis *et al.* 2000). This is partly because the list of possible approaches to sampling is extensive. Miles and Huberman, for example, provide a typology of sixteen types, including maximum variation, critical case and snowball (1994, p.28). Most appropriate for a DBR study, however, are those characterised as either theoretical, designed to generate theory which is grounded in the data (Eisenhardt 2002;

Glaser & Strauss 1967) or purposeful, selecting a sample that fits with the starting theoretical framework, ‘informed a priori by an existing body of social theory on which research questions may be based’ (Curtis *et al.* 2000, p.1002). Both perspectives were involved in this study because they effectively overlap: ‘theoretical sampling is purposeful selection of a sample according to the developing categories and emerging theory’ (Coyné 1997, p.628). For the present study, children became involved because they had been identified by their teachers as low-attaining in mathematics, and teaching staff became involved because they had responsibility in school for those children.

The first research cycle was facilitated by a trainer from the education charity, who identified children and teaching staff, at a secondary school in Northamptonshire, who were willing to be involved in the research. This was therefore a purposeful sample, in the sense that the participants were suggested for particular reasons but were not atypical in any obvious respect. The children had been identified as low-attaining in mathematics and were already involved with the numeracy intervention, and they were also old enough to converse in depth about their experiences playing the prototype game and therefore capable of making a useful contribution. It was also a convenience sample, because it was facilitated by someone familiar with the numeracy intervention. The sample comprised a total of four children, one teacher and one teaching assistant (Table 3.1). However, while small enough to make this cycle of the research manageable, this number of participants was also large enough to involve some heterogeneity, to be broadly representative (of children low-attaining in mathematics and the staff who supported them), and to generate sufficient ‘exploratory’ data.

Table 3.1
Participants by research cycle.

Research cycle	Setting	Adults	Children
1	1 school	2	4
2	3 schools	7	15
3	24 schools (online)	29	72
Total	28 schools	38	91

Sampling for the second research cycle took place in two stages. First, three feeder primary schools for the secondary school involved in the first research cycle were purposefully sampled (Curtis *et al.* 2000). To ensure some variation, one school was located in the town centre, one in a more suburban location and one in a rural location. Second, individual participants were selected and invited to be involved in the study by their school, not by the researcher, using a variety of criteria important to the school including the children's achievements, timetabling and staff availability. Fifteen children were selected because they had been identified as low-attaining in mathematics and the school believed they might benefit from participating in the study, seven teaching staff were selected because they had responsibility for supporting the selected children (Table 3.1, p.56). The overall aim was to involve the teaching staff and children who were most likely to have used the prototype game had it not been part of a research study but had been introduced to the school for a more conventional reason.

The sampling for the third research cycle was again purposeful and self-defining. As noted, control of the prototype game was handed over to the education charity, who invited around 90 teaching staff who had attended training for the numeracy intervention to get involved. Twenty-nine teaching staff from twenty-four primary schools across the UK responded to the invitation and were given online access to the prototype game's management tools, and 72 children played the game (Table 3.1, p.56).

Data collection

Details of the methods used for data collection in each research cycle are discussed in the relevant chapters. Here the overall approach to data collection will be considered. DBR often employs several methods of data collection, all of which are intended to build upon and to inform the design at the centre of the study and to contribute towards addressing the research questions and building theory (McKenney & Reeves 2012), 'if the results of different methods converge (agree, or fit together) then we can have greater confidence in the findings' (Gillham 2000). However, a common criticism of DBR is that it can generate unworkable amounts of data or data that do not contribute usefully to the research questions (Dede 2004). This is partly because at the

start of a design-based study, and as it evolves until the research has fully focused, the data collection net is often cast widely. The current study involved a range of qualitative data collection methods, which became progressively more focused through the research cycles: observations, field notes, interviews, questionnaires, audio and screen capture, data capture, and some document analysis (Table 3.2).

Table 3.2

Data collection methods used in the three research cycles.

Research cycle	Data collection methods	Notes	Participants	
			Adults	Children
1	Observation	Participant observation	✓	✓
	Field notes	Written notes taken during and immediately after the observation	-	-
	Screen capture	Gameplay	-	✓
	Audio recording	Conversations centred on the gameplay	✓	✓
	Interviews	Semi-structured Face to face Audio-recorded Pre- and post-intervention	✓	✓
	Questionnaires	Paper-based Lickert scale responses and text answers Pre- and post-intervention	✓	✓
	Document analysis	Catch Up Numeracy progress books (individual records of achievement)	-	✓
2	Observation	Non-participant observation	✓	✓
	Field notes	Written notes taken during and immediately after the observation	-	-
	Interviews	Semi-structured Face to face Audio-recorded Pre- and post-intervention	✓	✓
	Questionnaires	Paper based Lickert scale responses and text answers Pre- and post-intervention	✓	✓
3	Interviews	Semi-structured Telephone Audio-recorded Pre- and post-intervention	✓	-
	Questionnaires	Online Lickert scale responses and text answers Pre- and post-intervention	✓	✓
	Gameplay data	Numeracy component, time to play, errors made etc.	-	✓

Observations

Observations were made in each of the first two research cycles. The first research cycle involved participant observation (Jorgensen 1989). The researcher guided and supported the gameplay, and was involved in the interaction. Participant observation has the advantage of allowing the researcher to be close to whatever is being observed, enabling them to notice details; however, as noted earlier, it has the disadvantage of the researcher impacting on what is being observed, changing the dynamics such that the original situation, the object of the observation, becomes unavailable to the act of observation. In addition, and more pragmatically, it can also be difficult to write useful field notes while participating. In this research, participant observation was used only in the first, mostly exploratory, research cycle, where being able to provide guidance and to ask questions during the observation was especially useful.

In the second research cycle, the observation became less obtrusive (Webb et al. 1966), with the researcher watching the interactions between the classroom assistant, children and digital game from some distance (a few feet) away. This had the advantage of allowing the researcher to observe more objectively what was taking place, without interfering, and also to be able to achieve a useful overview. The disadvantages, particularly when observing groups of children working at the same time, included missing the beginning of some noteworthy interactions and sometimes missing dialogue particularly when quietly spoken. In addition, it was never really possible to be entirely separate from the scene being observed. Occasionally, the teaching staff would speak directly to the researcher, asking what they would like to see (the response was always for them to continue as they would do if the researcher was not present). At other times, the children would speak to the researcher as if they were a member of teaching staff. On these occasions, the conversation was kept brief but positive and the child was asked to direct any questions to the teaching assistant.

In each research cycle, the observations were recorded by means of hand-written field-notes (van Maanen 1988), supplemented with additional notes made once the observation sessions were finished. In the first research cycle, in which the researcher

had full control over the game, computer screen capture software (*Camtasia Studio 6*) was used to capture the on-screen activity and to audio-record the conversation between the child, the teaching assistant and the researcher.

Interviews

All of the participants involved in the first two research cycles, and the teachers in the first cohort involved in the third research cycle, were interviewed. They were asked about, for example, their knowledge of computer games, their attitudes to mathematics, and their experiences using the prototype game. These were semi-structured interviews based around a list of pre-written questions (Appendix C), derived from the research questions, in which 'the interviewer is free to probe and explore within ... predetermined inquiry areas' (Hoepfl 1997, p.52). The interviews were audio-recorded. Throughout, the researcher was aware that while interviews are 'a conversation, the art of asking questions and listening [they are] not a neutral tool ... this method is influenced by the personal characteristics of the interviewer' (Denzin & Lincoln 2005, p.643) and by 'the accuracy of respondent's memories, people's response memories, people's response tendencies, dishonesty, self-deception and social desirability' (Punch 2005, p.176). In short, sometimes interviewees misremember things, sometimes they say what they think the interviewer is keen to hear, and sometimes they simply make things up; such that the interviewer's job is to interpret the interview, however in a way that explicitly acknowledges their starting beliefs.

All interviews conducted with children took place in the presence of a member of their school's teaching staff. This was to address research ethics, child safety and the safety of the researcher (Cuskelly 2005; Lewis & Porter 2004). It also inevitably means that the children might have modified their responses to questions because, in the presence of a member of teaching staff, they thought it important to give what they thought to be the 'correct' or 'required' answer. However, having acknowledged that possibility, the children mostly seemed to ignore the presence of the supervising adults and all appeared to express their personal opinions to the researcher. This observation is reinforced by the huge variety of both positive and negative responses given by the

children, with the negative responses including many criticisms of the game and its functionality.

Questionnaires

A variety of survey-style questionnaires were also used, developing across the research cycles, reflecting the fine-tuning of the research orientation in response to the empirical data. Questionnaires were included because, although not neutral or straightforward, they can ask relatively standardised questions of a range of participants, affording the possibility of some general inferences and useful comparisons (Oppenheim 2000). They asked similar questions to those covered in the interviews, thus also providing some data triangulation, necessary because ‘answers given as a result of the method used are *artefacts* of that method (Gillham 2000, p.4).

In the first research cycle, before and after the intervention, participants completed paper-based questionnaires involving both Lickert scale responses and open text answers (Appendix D). To mitigate any literacy difficulties, the questions were read out for the children by the researcher and they either spoke their responses which were recorded for them or, when appropriate, pointed to a Lickert scale of five faces, sad to happy (Appendix E). The advantage of delivering questionnaires in this way is that the questions stimulated additional discussion with the participants. However, as will be discussed in Chapters 4 and 5, the questions included in the questionnaires and the participants’ responses proved not to be especially fruitful.

The third research cycle involved pre- and post-intervention online surveys⁴ (Evans & Mathur 2005), with the teaching staff being asked to support the children as they completed the questions. These questionnaires built upon questions covered in the interviews, thus also providing some data triangulation, necessary because ‘answers given as a result of the method used are *artefacts* of that method (Gillham 2000, p.4). As with the interviews, the possible impact of the interviewer’s or the adult’s presence

⁴ Created using the Survey Monkey website (www.surveymonkey.com).

when answers were given needs to be acknowledged. For example, when online questionnaires were completed by children supported by teaching staff, it is impossible to know how much of the child's response was moderated by the adult. However, having acknowledged the possibility, the variety of negative and positive responses again suggests that the children's responses given in the questionnaires are reasonably trustworthy.

Gameplay data

The final research data was captured automatically by the prototype game's system. This gameplay data included the time at which the game was played, the time it took to complete a session, the errors made, and the amount of time taken to complete each numeracy level for each component. This data lent itself to descriptive inferences, which enable the researcher to 'get a handle on' or summarise complex data sets of multiple variables (Hinton 2004), and provided proxy indicators of each child's progress.

Analysis

While the aim of the data collection is to provide thick descriptions of the participants' interaction with the prototype game, the aim of the analysis and reflection is to determine a parsimonious and logically coherent understanding of the data (Eisenhardt 2002), to feed back into the interpretive framework and inform a new iteration of the prototype game (Gravemeijer & Cobb 2006), and to contribute to well-warranted theory (Collins *et al.* 2004; Edelson 2006).

As noted above, it is incumbent on those carrying out DBR to ensure that their studies are rigorous, ecologically valid, transcending of immediate context, and trustworthy. At the analysis stage, this involved recognising that research is essentially a cooperative activity, not a neutral tool (Gomm 2008), such that analysis must avoid treating data 'at "face value", as if personal accounts granted the analyst direct access to a realm of the personal' (Atkinson 2005, p.5). Interviews, for example, are often influenced by the respondents' implicit agendas including sometimes simply a desire to please the interviewer (Punch 2005; Silverman 2009). Analysis also involves being

explicit, about the researcher's theoretical starting point and the methods, and acknowledging that 'as observers and interpreters of the world, we are inextricably part of it; we cannot step outside our own experience to obtain some observer-independent account of what we experience' (Maxwell 1992, p.283). Analysis is instead a hermeneutic process, an essentially creative act, a dialogue with the object of analysis, 'like a real conversation [although the object of analysis] does not speak to us in the same way as does another person. We, who are attempting to understand, must make it speak' (Gadamer 1960, p.370). Finally, the analysis should build on the ecological validity of the data, to ensure that outcomes are descriptively valid, they describe what actually happened, interpretively valid, they represent accurately what the observed phenomena meant to the participants, theoretically valid, they permit an internally consistent theoretical understanding, and internally generalisable, generalisable within the community group (Maxwell 1992).

In this study, the analysis comprised an iterative process of categorisation and interpretation, based on data coding, data sorting and data reduction. For the interview data from the first two research cycles, analysis involved the following steps:

(i) The interviews were transcribed and imported into the qualitative analysis computer software *NVivo 8* (QSR International).

(ii) The interviews were then displayed in the software, read closely and encoded using the software's 'nodes' functionality (Appendix F). Drawing on Dey (1993), Miles and Huberman (1994) and Saldaña (2013), this involved each section of the first interview, sometimes a single phrase and sometimes several consecutive phrases which appeared to belong to or to build upon a single thought (and were thus often grouped in the transcription as a paragraph), being marked up with an appropriate descriptive tag or conceptual label, a 'code'. In short, the 'single thought', a phrase or consecutive phrases, functioned as a heuristic coding unit. As suggested by Glaser and Strauss (1967), the initial codes were all drawn from, or emerged from, the interview data (for example, 'disadvantages of games', 'talking' and 'adult/child relationship') rather than being pre-specified (although it should be acknowledged that all coding is inevitably

coloured by pre-knowledge, subjectivities, and prejudices, Saldaña 2013). Frequently, a single section or overlapping sections were encoded with more than one code (for example, one phrase might be encoded both as 'implementation' and 'timetables'). Interviews read subsequently were coded using the same initial codes or else they suggested and were marked up with new codes. In this process, subsequent interviews tended to suggest fewer and fewer new codes, until it appeared that all key aspects of the interviews had been successfully encoded and no new codes were required.

(iii) Once all the interviews had been encoded, the large number of codes that had been generated were sorted, sometimes split but mostly grouped together in broader analytic categories, second-order concepts, based on themes or patterns suggested by and inferred from the close reading of the interviews and the encoding process. These analytic categories focused on issues such as the children's and adults' attitudes to the prototype game, in terms of its attractiveness to motivate engagement and effectiveness in supporting the children's numeracy, and their use of the game, how it was implemented in school and whether the game was played by individual students or in groups. Common patterns and themes in the interviews, such as the use of the game to facilitate dialogue, were then interpreted and compared with the literature (Denzin 2002; Miles & Huberman 1994) and with the original data, 'the central idea is that researchers constantly compare theory and data – iterating toward a theory which closely fits the data' (Eisenhardt 2002, p.20). Here, data interpretation was iterated towards a theoretical interpretation of the design and use of a prototype digital game for children low-attaining in mathematics, which emerged from the data and involves its use as an artefact that supports both individual and collaborative learning.

For the third research cycle, coding and analysis involved a slightly different approach. As noted earlier, a key purpose of the third research cycle was to reinforce or refute outcomes of the first two research cycles, to help achieve a sufficient level of theoretical saturation (Corbin & Strauss 1998) and to provide some validation through the triangulation of data from different sources and an additional method (Denzin 2009; Rhineberger *et al.* 2005). Accordingly, the analysis of the third research cycle's interview and questionnaire data involved comparing it with, and integrating it into,

the analytical categories generated in the analysis of the first two research cycles; the aim being to determine whether the data supported or contradicted the earlier analysis and, simultaneously, whether any new codes were necessary. An example of a new code suggested by the third research cycle, which had not been suggested by either of the first two research cycles, is 'the Matthew Effect'.

Research ethics⁵

Any study involving children requires careful attention to research ethics (BERA 2011). This is especially important for research involving children who have learning difficulties and who are therefore potentially more vulnerable (Nind 2009). Accordingly, to begin with, this study adopted Beauchamp and Childress's four principles of ethical research (2001): that the research should aim to improve the world, that it should do no harm, that the benefits should outweigh the costs, and that it should be respectful of the persons involved. The study aimed to design a resource that might improve the learning of the participating children, by grounding the design of a prototype game in a review of the literature and incorporating features that aimed to be of benefit to the children. Potentially harmful outcomes were avoided by, for example, ensuring that the prototype game did not include any violent or aggressive content and was gender neutral, and by keeping the time taken to play as short as possible (to minimise time using a computer and time missed from mainstream classes).

Ensuring that an ethic of respect was adopted towards all the participants began with obtaining informed consent⁶ (Cameron & Murphy 2007). However, obtaining informed consent from children is not straightforward. Various strategies were used to ensure as far as possible that the children were genuinely willing to be involved, and were not just acquiescing to please the adults. First, the teaching staff were asked to use their experience of working closely with the children to identify only those who they

⁵ Research ethics approval is included at Appendix G.

⁶ Participants' information is included at Appendix H. Participants' consent is included at Appendix I.

believed would be happy to be involved. Second, the parents of the children who had expressed an interest in taking part were given written information in good time and were asked for their permission for their children to be involved. Third, the project was explained face-to-face by the researcher to each individual child who participated in the observed sessions and interviews, and they were again asked if they were happy to take part.

Other ethical issues that need to be considered when working with children who have a learning difficulty include capacity to withdraw, confidentiality, and representing the perspective of the child (Cuskelly 2005; Lewis & Porter 2004). Accordingly, consent was viewed as an ongoing process (Cameron & Murphy 2007): in the observations and interviews, the children were reminded that they could leave at any time and return to their mainstream class; the schools and participants were all anonymised and individual outcomes were kept confidential; and the children's views about the prototype game were asked for and, wherever possible and appropriate, addressed in a subsequent iteration of the game.

As noted above, the second and third research cycles involved the participants using the Internet, which raises the additional complexity of Internet-based research ethics (Ess & AoIR 2002). However, these Internet research ethical considerations usually focus on content created by Internet users who did not intend or expect that content to be analysed for research purposes; whereas the participants in this study were fully aware that their performance in the game and their questionnaire responses were contributing to a study. In addition, the Internet functioned only as the medium not an object of this research. Rather than creating content, the children only used the Internet to access the game and questionnaires, much as they already accessed in school other online educational resources, with the teaching staff assuming their usual responsibility for ensuring that the children were safe while they were online. Finally, the access to the game and questionnaires was password protected to ensure confidentiality. Given this context, the research ethics strategies outlined above (in particular, obtaining informed consent before the participants were asked to access

the Internet, Varnhagen *et al.* 2005) were, as confirmed by Buchanan (2011), otherwise sufficient.

Declaration of interests

The numeracy intervention (Holmes & Dowker, in press), the principles of which were implemented in the prototype game, was co-authored by this DPhil candidate on behalf of the charity Catch Up (2007). Until December 2011, the research reported in this thesis was partly funded by the Esmée Fairbairn Foundation via the Catch Up organisation. In addition, the charity Catch Up have indicated that they intend selling a modified version of the final prototype game.

Potential implications for the analysis and interpretation of results are considered in the discussion chapter (Chapter 7). This is important as conflicts of interest, if not properly declared and considered, can compromise research integrity (BERA 2011).

Research cycle 1

This chapter discusses the study's first research cycle of design, intervention, analysis and reflection of a theory-based prototype digital game for children who are low-attaining in mathematics. It comprises the initial design of a prototype game, grounded in the numeracy intervention and learning theory, which was researched in one school with a small number of children. This was in effect an exploratory, low-fidelity laboratory study.

Research questions

As discussed in Chapter 1, the study's research questions ask how a prototype digital game might be designed to support children who are low-attaining in mathematics, and what happens when such a game is used in schools. This first research cycle begins the process of addressing these two central research questions by considering three sub-questions. The first sub-question focuses on the initial design of the prototype game, grounding that design in the theory discussed in Section 2.6:

- 1.1 How might insights from the numeracy intervention and learning theory inform the design of the prototype digital game?

The second and third sub-questions focus on the experiences of children and teaching staff who used the initial prototype game and their feedback, in what was in effect an exploratory, low-fidelity study:

- 1.2 What are the responses of a sample of children who are low-attaining in mathematics and the teaching staff who support them to the prototype game?

1.3 How might the prototype game be amended to make it a more useful classroom tool?

The study was 'exploratory' because it was the first attempt to ascertain what happens when the game is used by children, with the aim of orientating the following research cycles. It was 'low-fidelity' in the sense that the children were withdrawn from their usual class specifically to participate in this study, and because the prototype game only existed on a single laptop computer (rather than being accessed online).

4.1 DESIGN

The design of the first iteration of the prototype game, its appearance and gameplay, aimed to implement principles of the numeracy intervention and insights from learning theory. It also drew upon four additional sources: established principles of effective digital game design (for example, Adams & Rollings 2006; Gee 2004b; Schell 2008); lessons derived from some well-received examples of GBL identified in the literature review (for example, Barab *et al.* 2005; Blunt 2009; Habgood 2005); and both the researcher's and developer's experience, skills and tacit knowledge of games design. This first iteration existed as a set of *Adobe Flash* files stored on the researcher's laptop computer. The process from research premises to prototype game was complex, hence the discussion of this first iteration of the game requires some detail.

Genre

An assessment of the characteristics of the many overlapping game genres identified in Chapter 2 (including shooters, puzzle, strategy, driving, sport, maze, platform and RPGs), suggested a promising approach for the prototype game: a hybrid puzzle / platform game, a game in which a character negotiates a series of puzzles set in a two dimensional digital environment comprising a series of multi-level platforms.

The genres other than puzzle and platform were rejected as possible candidates for the prototype game for a variety of reasons. For example, the shooters genre was rejected because of the ethical implications and the precautionary principle (Stirling

2007): 'if there are reasonable scientific grounds for believing that a new process or product may not be safe, it should not be introduced until we have convincing evidence that the risks are small and are outweighed by the benefits' (Saunders 2000, p.1). The evidence is that violent video games can lead to increased aggressive behaviour, decreased pro-social behaviour and physiological desensitization to real-life violence, and are thus inappropriate in classrooms (Anderson *et al.* 2010; Carnagey *et al.* 2007; Gentile *et al.* 2004), even if shown to be potentially effective for learning (Gentile & Gentile 2008; Habgood 2005).

The maze format was rejected because of its relatively rigid format. It was difficult to determine how it might support both the necessary educational content and identified theoretical approach. The strategy and driving/sport genres were rejected because of their relatively rigid formats, but also because of their relative complexity. They would require more resources than was available for this research project. As a final example, the RPG (role-playing game) genre was rejected because of its long-form nature. RPG games typically take many hours to play and thus are potentially more difficult to integrate into classroom timetables, and because of their 3D complexity and high cost of development.

The 3D immersive environment typical of many RPG games, rather than the RPG genre itself, was initially considered a strong potential candidate approach for the prototype game. 3D immersive environments have been used successfully in the commercial development of GBL to support mathematics (such as *Timez Attack*, West 2010). In addition, highly flexible and relatively inexpensive 3D game engines which allow the relatively quick development of 3D immersive games have recently become available (such as *Unity 3D*, Labschütz & Krösl 2011), and 3D GBL has been shown to have considerable merit elsewhere (such as *Quest Atlantis*, Barab *et al.* 2007). However, the 3D approach was finally rejected for this research because of the still relatively complex development process which put it beyond available resources.

A hybrid puzzle / platform game thus emerged as the best candidate game genre for the prototype game in this research. Puzzle and platform games may sometimes be relatively long-form but are frequently casual in design (for example, *Angry Birds*). The

casual game approach was preferred for various reasons. Firstly, children, particularly those who are low-attaining, often have relatively limited attention spans: minutes rather than the hours that can be required by long-form games (Ashkenazi *et al.* 2009). Secondly, because of the heavy demands of classroom teaching and issues around timetabling, long-form games, again because they can require hours of play, are likely to be more difficult for teaching staff to integrate successfully into classroom practice (Williamson 2009). Thirdly, the numeracy intervention individual sessions last only 15 minutes, and it is likely that teaching staff would want to use digital games as part of, rather than all of, a session (Evans 2008). And finally, casual games usually require fewer resources than long-form games, making them more affordable and practical to develop.

Puzzle games also typically emphasise thinking and strategy, giving them potential for facilitating learning, while platform games typically emphasise ‘reflexes and coordination’, and hence favour adrenaline-induced fun. However, there are many examples of both genres that involve both thinking and reflexes (for example, *Tetris*). A prototype game which draws on both genres might thus provide a similarly diverse playing and learning experience. In addition, both the puzzle and platform genres are relatively flexible in terms of style and gameplay, making them potentially open to incorporating learning objectives, and relatively straightforward to develop, making them achievable within the resource constraints of the research. Finally, the puzzle and platform genre are ethics-neutral, which is to say that while any puzzle and platform game might include questionable content, such content, unlike with shooters, is not a necessary part of either genre and thus might be avoided.

Design framework

In the context of the game’s genre, Schell’s four basic elements (2008) provide a useful preliminary although inevitably overlapping framework for understanding digital games. The four elements are: mechanics, that is the procedures and rules of the game (hereinafter referred to as gameplay mechanics); story, the sequence of events that unfolds in the game; aesthetics, how the game looks and sounds; and technology, the coding and algorithms. Given that the coding and algorithms are not a focus of this

research, this element will not be considered here in any detail. However, for digital games that are designed to support learning, rather than solely for entertainment, this framework needs to be extended – firstly, to include educational content, the subject matter that the game seeks to address, and educational objectives, the learning outcomes that the game seeks to facilitate; but most importantly, to include learning and pedagogy, the approach to learning and teaching taken by the game, within the gameplay (hereinafter referred to as gameplay learning).

Content and learning objectives

As discussed in Chapter 2, the content of the prototype game was derived from the numeracy intervention. Four principles of the numeracy intervention were identified as having potential for translation into a digital game designed to support children who are low-attaining in mathematics. These were: the componential approach to numeracy, the levels of attainment, the learning objectives, and the focus on only one numeracy component at one level of attainment in any one session.

For the first of these principles, three components of numeracy were identified, each of which had been highlighted by teaching staff as presenting particular difficulties in the classroom. As discussed in Section 2.2, one was identified in each of the three categories of numeracy: *remembered facts*, an example of factual knowledge; *estimation*, an example of procedural knowledge; and *derived facts*, which involves both conceptual and procedural knowledge. For the second principle, the earlier research suggested that the games should focus on the numeracy intervention's first six levels of attainment. However, for this exploratory cycle, it was decided to implement only the first three levels (number ranges 1 to 5, 1 to 8, and 1 to 10). Accordingly, for the third principle, the learning objectives were for the participating children to become secure in each of the components addressed by the prototype game, to have automatized *remembered facts*, *estimation* and *derived facts*, with numbers up to 10. This was operationalised as answering correctly twelve tasks on first attempt at each level of attainment. Finally, the fourth principle suggested that the child should be required to focus on only one numeracy component at one level of attainment in any one gameplay session. For all these reasons, nine separate sub-

games were developed, one for each combination of component of numeracy and level of attainment (Table 4.1).

Table 4.1

Sub-games, game levels, numeracy Levels and number ranges, as implemented in the prototype game.

	<i>Remembered facts</i>	<i>Estimation</i>	<i>Derived facts</i>
Sub-game	1	4	7
Game level	1	1	1
Numeracy Level	1	1	1
Number range	1 – 5	1 – 5	1 – 5
Sub-game	2	5	8
Game level	2	2	2
Numeracy Level	2	2	2
Number range	1 – 8	1 – 8	1 – 8
Sub-game	3	6	9
Game level	3	3	3
Numeracy Level	3	3	3
Number range	1 – 10	1 – 10	1 – 10

A pool of numerical tasks was created for each level within each component. For *remembered facts* Level 1, the numerical tasks included: $4 - 2 = ?$ (each term and the answer being within the number range 1–5). For *estimation* Level 2, the tasks included: $4 + 2 = ?$ (with 5, 6 and 7 being deemed ‘acceptable’ estimates). For *derived facts* Level 3, the tasks included deriving the answer to $3 + 7 = ?$ from the given number sentence $7 + 3 = 10$.

Story

The story and aesthetics of the prototype game were designed to reflect as closely as possible the approach taken by games in the selected genre, platform games (such as the *Super Mario Bros.* franchise developed by Nintendo). While other GBL (such as *Quest Atlantis*, Barab *et al.* 2007) follow game genre such as RPG and emphasise story (Frasca 2003; Jenkins 2004), the prototype game, building on the language of platform games, adopts a rather more prosaic narrative. Accordingly, in the prototype game the story is a very simple quest. The player is on a journey through a virtual landscape,

dealing with obstructions and collecting coins along the way. The aim is to get to the game end as quickly as possible while collecting the highest possible number of coins.

Aesthetics

The graphics were created by the developer and similarly drew on the language of platform entertainment games. It comprised a cut-away view, 'much like an ant farm is viewed in a glass tank' (de Byl 2009, p.6) of three layers of two dimensional space, which move across the screen at different rates (a technique known as parallax scrolling) to give a *faux* three dimensional experience (sometimes referred to as 2.5D). The background layer comprises a moon hanging over a simple cityscape; the mid-ground layer comprises a range of grey hills, in which are situated various pieces of park furniture; and the foreground layer comprises a pathway and various obstructions (Figure 4.1).

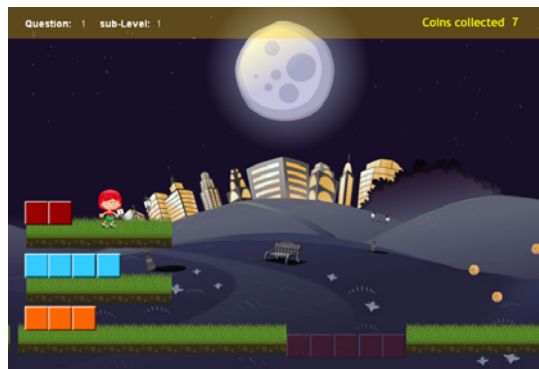


Figure 4.1

Remembered facts Level 1 start screen.

The foreground layer also includes a quantity of gold coins which are floating in space. The background and mid-ground layers were designed to be attractive but relatively neutral. The foreground layer was designed to include all the mechanics of the game. At the end of the path on the foreground layer, the far right-hand end of the virtual screen which is only revealed once the player has made sufficient progress, is a finish line and flag.

Gameplay mechanics

The relationship between the various principles and insights incorporated in the prototype game is over-determined. Any one constituent part sometimes affects many aspects of the gameplay, mechanics and learning, while each aspect of the gameplay might draw on more than one constituent part.

For example, the numeracy intervention specifies that, in any particular session, to minimise cognitive overload, learners should only be asked to work within a limited number range within just one component of numeracy. When the learner is secure with the numbers in a number range covered by a level of attainment for a particular component, they move onto the next number range, while staying within the single component. Digital entertainment games also often include increasing levels of difficulty, although in the form of game levels. A key aim of the player is often to 'level up' during gameplay to higher and higher levels (Adams & Rollings 2006; Salen & Zimmerman 2003; Schell 2008). Given this synergy between game levels and numeracy levels of attainment, the prototype game also incorporated game levels.

However, whereas in entertainment games the level of difficulty depends on the gameplay, how the game is played (often using a technique known as 'dynamic difficulty adjustment', Hunicke & Chapman 2004), in the prototype game the level of difficulty depends on the number range covered by the level of attainment, the level's learning content. As a consequence, game levels, separate sub-games, were devised for each level of attainment for each of the three components. Each game level only included numbers within the given level of attainment's number range. For example, game level 1 for each component only used numbers within the number range of the numeracy intervention's Level 1 (numbers from 1 to 5, Table 4.1, p.73).

Remembered facts sub-games

Game level 1 of the first component included in this research, *remembered facts*, comprises a horizontal grass path punctuated by a series of gaps which the avatar is initially unable to cross (Figure 4.2a, p.76).

**Figure 4.2**

Remembered facts Levels 1, 2 and 3 start screens.

Each gap is of a pre-specified size, within the number range of numeracy Level 1, with the size being indicated by the inclusion of an appropriate number of shadowy square blocks. To the left of the gap is a stack of three rectangular blocks, the playing pieces, each one again divided into squares to indicate its size. The player has to determine the length of the gap, then select two playing pieces which together will fill the gap, thus enabling the avatar to cross. Sometimes the gap is filled by adding two blocks together; sometimes it requires the player to deduct one block from another. This version of the game assumes that the player is able to draw on their experience elsewhere of playing similar-looking platform games to determine for themselves how they should proceed: to move the avatar through the space, dealing with the obstructions and collecting coins along the way.

Remembered facts game level 2 (Figure 4.2b) again comprises a grass path punctuated by gaps, of sizes within the number range covered by numeracy Level 2, but this time the gaps are vertical and have to be negotiated using ladders, again made of individual units. In game level 3 (Figure 4.2c), progress is impeded by a door which has to be opened with a key. Three keys are available, each located at the bottom of a hole. Above, a calculation within the number range covered by numeracy Level 3 is animated using blocks, the given answer indicating which key is needed. For example, if the blocks animate $5 + 4 = 9$, the player has to choose the key from the hole that is 9 units deep.

Estimation sub-games

Estimation game level 1 (Figure 4.3a) comprises a set of clouds and fans, with progress being impeded by a gap in the clouds. The player has to estimate which of the columns of fans will 'suck' the cloud sufficiently to close the gap approximately (operationalised as plus or minus 10 percent of an accurate answer). Following the approach of the numeracy intervention, all of the *estimation* game levels only include addition number sentences. Subtraction is not included. *Estimation* game level 2 (Figure 4.3b) features a balance which, when the pans are level, fills a gap in the path. The player has to estimate which blocks to add to the left hand pan in order to balance it with the already laden right hand pan. Again, to cross the gap, it is only necessary to balance the pans approximately. Game level 3 (Figure 4.3c) features a climbing net, which can be pulled up, via a pulley system, to allow the avatar to climb to the higher level and continue. The player has to climb the ladder and choose the appropriate handle on the pulley line. Again, it is sufficient for the player to give an approximate/estimated answer.



Figure 4.3

Estimation Levels 1, 2 and 3 start screens.

Derived facts sub-games

The *derived facts* game level 1 (Figure 4.4a, p.78) landscape is divided into two. On the left, an animation shows which of a series of tubes is the same size as the sum of two blocks added together. On the right, a similar arrangement allows the player to calculate the answer to a second pair of animating blocks by deriving it from the given

answer for the first pair of blocks. This level features a random selection of the four *derived facts* principles featured in the numeracy intervention (Section 2.2). The *derived facts* game level 2 landscape (Figure 4.4b) includes two gushing water pipes which impede the avatar's progress. Animated blocks indicate how the first pipe may be blocked. The player has to derive the solution for the second pipe from the answer given for the first pipe. Finally, the *derived facts* game level 3 landscape (Figure 4.4c) works in the same way to the previous level, but with spewing volcanoes instead of gushing water pipes.

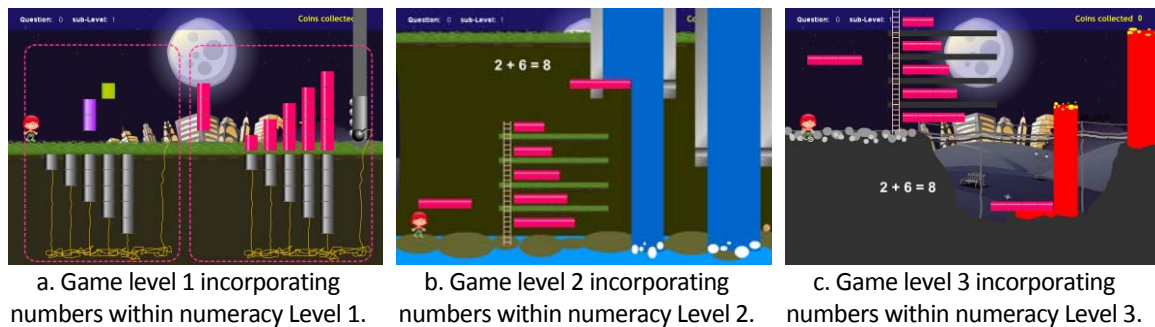


Figure 4.4

Derived facts Levels 1, 2 and 3 start screens.

Avatar

Also following the conventions of entertainment platform games, a virtual character, a 'proxy persona' (de Byl 2009) or 'avatar' (Morningstar & Farmer 1990), represents the player in the game. The avatar is able to move forwards, which from the player's perspective means from left to right, through the space depicted in the foreground layer. However, progress is impeded by the inclusion of various obstructions, depending on the gameplay, the particular numeracy component and the level of attainment. The avatar can also move backwards with some limits, from right to left but not beyond the start of the space dedicated to the current task; and it can move upwards, by jumping, and downwards where the virtual space permits, pulled by the game world's virtual 'gravity'. All movement is activated by the keyboard's arrow keys.

The aim of each game level is for the avatar to be moved quickly through the landscape, negotiating successfully the various obstructions, in the form of numerical

puzzles, and collecting as many gold coins as possible. If the player attempts to bypass the obstruction, their avatar disappears briefly (in the language of platform games, the avatar ‘dies’) then reappears at the start of that task; the more often the avatar dies, the longer it takes to complete the task. Success is measured in terms of the time taken, and the number of coins collected, both of which are reported on the game screen.

Gameplay duration and response to error

To fit with the casual game approach, to maximise the usefulness of the prototype game in real classrooms and to take account of the relatively short attention span of children who are low-attaining, the prototype game was developed so that a meaningful amount of gameplay required no more than around 10 minutes to complete. Previous research (Holmes 2011) suggested that players should play only one game level in any one session, which in turn would comprise around 10 numeracy tasks. The game engine was then programmed to present tasks in a random order, drawing from the pool of available tasks for the given game level.

In many examples of GBL the player only gets one opportunity to answer a question and, if they make an error, rather than receiving feedback telling them the correct response, they are simply presented with a new question. The prototype game used an alternative approach. Firstly, the game was designed to allow the player to attempt the task as often as they liked, trying out any possible solutions, building on their existing knowledge and skills, until they identified one that worked. Although failure still had an impact, on the time taken to complete the level, it was no longer critical. Secondly, the game engine returned tasks not answered correctly on the first attempt to the pool of available tasks, to be asked again before the player finished the level: giving them additional practice and the opportunity to confirm that they had learned from their previous error.

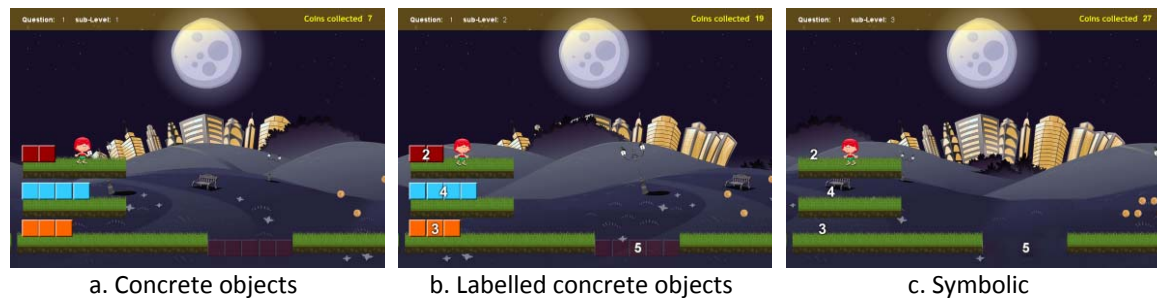
Gameplay learning

Apart from the componential approach to numeracy intervention, what most clearly distinguishes the prototype game from others designed to support children who are

low-attaining in mathematics is that, as discussed in Section 2.4, it aims to facilitate learning *through* the gameplay (rather than learning *before* or *during* the gameplay, Table 2.2, p.26). In the virtual context of the prototype game, the player is presented with a series of practical problems. If they wish to move through the landscape quickly, in order to achieve a fast time and to amass a large number of coins, in other words if they want to play and win, how do they negotiate the various obstructions? There is just a gap in the path, for example, that has to be crossed, a gap of a predetermined size, and various building blocks that might be combined in order to do so.

A second feature which distinguishes the prototype game is the way in which it builds upon a virtual interpretation of Bruner's three 'modes of representation' (Section 2.6): enactive, learning by doing; iconic, learning by means of images; and symbolic, learning by means of words or numerals. The enactive mode is implemented by the way in which the player has to move 'physically' their avatar and choose and move props, 'concrete' objects, in order to proceed through the game – with 'physically' and 'concrete' understood in the virtual context of the computer screen.

Over and above the fact that the game is experienced in the form of animated images, the iconic mode is implemented by first presenting the players only with the concrete objects. There is only a physical gap that needs to be bridged and blocks that may be employed to do so; there are no numerals to be seen (Figure 4.5a, p.81). In other words, rather than manipulate symbolic notations independently of any concrete reality, they have to answer a concrete mathematical problem, albeit in the virtual context of a digital game. Once the player has constructed the solution to the given task, which blocks together enable their avatar to cross the gap, a transition into the symbolic mode is implemented by presenting exactly the same task a second time, but now with the concrete objects being labelled with numerals that describe their size (for example, a gap five units long is labelled with a '5') (Figure 4.5b, p.81). Finally, the symbolic mode is strengthened by presenting the same mathematical task a third time but now involving only the numerals; the concrete objects are no longer shown (Figure 4.5c, p.81).

**Figure 4.5**

Implementing the transition between iconic and symbolic.

In this way, the game might be said to synthesise elements of both constructivist and behavioural approaches to learning: ‘it is not that behaviourism, or constructivism, is wrong; indeed, they are both right in their core ideas but they are incomplete and, on their own, make an inadequate basis for design’ (Burkhardt 2006, p.131). In the prototype game, the players begin by constructing knowledge for themselves, by means of the manipulation of concrete objects which has a real impact on the world of the game, which is then reinforced through a series of repeated but increasingly abstract levels of practice: the player moves from iconic, pictures, to symbolic, numerals, via enactive, actions, for every given task, mirroring Bruner’s developmental process.

This approach thus also draws on insights from the other theory identified above, repetition and practice and the spiral curriculum (Section 2.6). Having first constructed their knowledge, the prototype game requires the player then to practise what they have learned, within each set of three sub-tasks. They address the authentic task, they consolidate the skills and knowledge required by the particular component of numeracy, and they reinforce the relationship between the concrete objects and the numerals, the iconic and the symbolic. Then, once a task has been completed successfully, the player is required to repeat the process, to practice it again, but this time with different number sentences within the same number range. If the sub-task is not completed successfully, the task is returned to the question pool. Finally, once a game level has been completed successfully, the player then repeats the process at a

higher game level, spiralling upwards: working with the next highest number range, mirroring the numeracy intervention levels of attainment, within different gameplay.

4.2 INTERVENTION

This first intervention was essentially exploratory. Its purpose was to guide the following cycles of the research, including the further design of the prototype game, and to begin developing an understanding of the game's use. The prototype game thus functioned as both an object of the study and the medium, the research instrument. A specific aim was to ensure that the design of the game involved some of the children for whom it was intended, to design with the users rather than for them (Facer & Williamson 2004).

The intervention involved 4 children and 2 adults at one school (Table 4.2), over two school weeks.

Table 4.2

Research cycle 1: intervention participants.

Participants	Total
Schools	1
Adults	2
Children	4

Context

The study took place in July 2011 at Orange Hill⁷, a secondary school in Lane End, Northamptonshire. Although the game was designed mainly for primary school children, the study took place in a secondary school because previous research had shown that children of secondary school age contribute particularly helpfully to discussions about games designed to support their learning (Facer & Williamson 2004;

⁷ Throughout this thesis, all school names and locations have been anonymised.

Holmes 2011). It was facilitated by Sue⁸, a Catch Up Numeracy trainer and Orange Hill's Literacy Coordinator, who takes responsibility for the management of literacy and numeracy interventions at the school.

Lane End is a small commuter town in the middle England county of Northamptonshire (population c. 18,000), which predominantly comprises families in NS-SEC analytic classes 1 – 3 (Office for National Statistics 2010), elsewhere summarised as 'well-off families with mortgages' (ACORN 2010). Orange Hill is the town's only secondary school. It has approximately 1,200 children, aged 11 – 18 years, of whom around 6% have a Special Education Needs statement or are on School Action Plus (where the average across England is 8.5%); around 5% are eligible for free school meals (England: 16%); and 1% of the children have English not as their first language (England: 12%). Approximately 80% of children achieve 5 or more A*-C grades at GCSE, including English and mathematics (England: 58%). The DfE characterise 11% of the children at Orange Hill as 'low-attainers', children who were below the expected level for most children when leaving primary school (England: 18%). Of these 'low-attainers', 67% at Orange Hill made the expected progress in English (England: 48%) while 48% made the expected progress in mathematics (England: 27%). All data is derived from the Department for Education (2010; 2011c; 2011f).

In summary, Orange Hill has a broadly average number of children who have special educational needs but, because of its location, a much lower number of otherwise disadvantaged children (children eligible for free school meals or with English not as their first language). In terms of its examination results, Orange Hill is a high-achieving school, out-performing the national average at GCSE by a considerable margin, and enabling a high proportion of previously low-attaining children to achieve the expected progress for their age in English and particularly in mathematics.

At Orange Hill, the numeracy intervention is delivered to children in Years 7 and 8 (aged 11 to 13 years), with suitable candidates being identified on entry to the school.

⁸ Throughout this thesis, the names of all participants have been anonymised.

Three sources of information are used: the children's Key Stage 2 SATs results, which of them are working at Key Stage Level 3 or below; qualitative information provided by primary schools, have they identified any children who they believe might need additional support; and assessments administered in the children's first term at Orange Hill, which of them are working in mathematics at a level more than six months behind their Chronological Age.

In the two years during which the numeracy intervention had been used at the school, children who had received the support had made progress in line with national results (Holmes & Dowker, in press). The positive impact of the numeracy intervention on the participating children had been noted by teaching staff elsewhere in the school, such that the intervention was seen as contributing positively to the support the school provides to children who are 'low-attainers' in mathematics. It was partly for these reasons that the school agreed to participate in the current research, to support the potential development of a resource that complements the numeracy intervention.

Sampling

A purposeful sample was used to select children who might most usefully contribute to this research cycle, and who might thus be asked to participate. Initially, eight candidates were proposed by the school staff: children who might be willing to participate and who the staff believed might benefit from participating in the study. Two broad selection criteria were used to select four participants, all of whom were willing and interested to use a prototype game designed to support their mathematics and to contribute to the study (parental permission was given for each of the children, and the children all gave their informed consent). Firstly, which of the children receiving numeracy intervention support at Orange Hill had relatively severe numeracy difficulties for their age – the purpose being to ensure the inclusion of children who had numeracy difficulties roughly commensurate with those experienced by primary school children who are low-attaining in mathematics. Based on the characteristics of the numeracy intervention levels discussed above and previous research (Holmes & Dowker, in press), this was operationalised as working predominantly at or below Level 6 in the numeracy intervention. Secondly, which of these children play computer

games, whether at home or at school, for entertainment or to support school work. Given that most children in the UK do play computer games (Parliamentary Office of Science and Technology 2012), and that the prototype game drew on the language of entertainment computer games, it was important that the children participating in this first intervention had some awareness of such games – so that they are at least approximately representative of the target audience and are able to make useful comparisons.

Methods

This intervention included several complementary data collection methods (Table 4.3): semi-structured interviews of all the participants, documentary analysis, a questionnaire, field-notes taken during and after participant observations, capture of on-screen activity during the gameplay, and audio-recording of the conversation centred on the gameplay.

Table 4.3

Data collection methods used in the first research cycle.

Data collection methods	Notes	Participants	
		Adults	Children
Observation	Participant observation	✓	✓
Field notes	Written notes taken during and immediately after the observation	-	-
Screen capture	Gameplay	-	✓
Audio recording	Conversations centred on the gameplay	✓	✓
Interviews	Semi-structured Face to face Audio-recorded Pre- and post-intervention	✓	✓
Questionnaires	Paper-based Lickert scale responses and text answers Pre- and post-intervention	✓	✓
Document analysis	Catch Up Numeracy progress books (individual records of achievement)	-	✓

The intervention proceeded as follows. Interviews were conducted with Sue, the teacher who has primary responsibility in the school for children who are low-attaining in mathematics, and with Kath, the teaching assistant who usually delivers the

numeracy intervention, about each of the participating children (both members of staff gave their informed consent). Subsequently the children were interviewed about their experiences of learning mathematics and of playing computer games (parental permission had been given for each of the children to be involved; and the study was explained to the children, who all consented to be involved). Semi-structured interview guides were used for all interviews (Appendix C), and the interviews were recorded. Answers given were often followed up with supplementary questions.

After having been interviewed, the children completed a questionnaire about their attitudes to learning. Questions were read out for them and they gave their responses by pointing to one of five faces, sad to happy, arranged as a Lickert scale (Appendix E). The children's numeracy progress books (which record progress achieved in the numeracy intervention) were also examined, in order to gain an understanding of their individual achievements for the components of numeracy in question.

The prototype game was then introduced to each of the participating children, who played it once or twice on different days, during their usual numeracy intervention individual sessions, while being supervised by Kath and observed by the researcher. As this was an exploratory phase, the observation was essentially participatory (Jorgensen 1989), with the researcher guiding the play while watching how the interaction between the child and the prototype game unfolded. Sometimes the guidance was necessary because it was unclear to the participating child how they might play the game; other times it was necessary because the software did not function exactly as intended. Observations were recorded by means of field-notes, supplemented with additional notes made once the observation sessions were finished. Screen capture software (*Camtasia Studio 6*) was used to capture the on-screen activity and to audio-record the conversation between researcher, participating child and teaching assistant. On subsequent visits, follow-up interviews were conducted with each of the participating children, about the prototype game and their experiences playing it; and of Kath, about her observations of the children before, during and after they played the game.

The aim was to develop a ‘thick description’ of the learners and how they interact with the prototype game (Gravemeijer & Cobb 2006), to begin to understand in the broadest sense how the game might make a contribution, and what this begins to tell us about the learners and learning-through-gameplay. All of the interview data were transcribed and imported into the qualitative analysis computer software *NVivo 8*, where it was coded, categorised and sorted according to common patterns (Denzin 2002; Miles & Huberman 1994) and themes were allowed to emerge. A parallel but more informal process was undertaken with the observation field-notes and the screen and audio data. The questionnaire responses, however, were less helpful. Although some superficial information could be gleaned, most of the questions proved to be too specific (for example, ‘How worried are you when you find mathematics too difficult?’, Appendix D) and the responses too inconsistent to warrant them being incorporated in this study.

Outcomes

Although the sample in this first intervention was small, four children in total, it proved to be sufficient for this cycle of the research. While there were clear individual differences, the findings of the interviews and observations very often overlapped, such that they provided a level of data saturation that enabled the beginnings of a theoretical understanding and informed the further design of the prototype game.

The staff had no definitive explanations for why the children who participated in this intervention were working below the level of their peers in mathematics. However, rather than ascribing the children’s difficulties to problems ‘internal’ to the children themselves, innate or neurobiological causes, they thought it more likely the difficulties had more prosaic origins. Perhaps they had had repeated or prolonged periods of absenteeism at primary school, due to illness or difficulties at home, or perhaps at secondary school they had simply avoided mathematics lessons, *“the children might not come in because they have maths today or maybe even double maths in one day and they just don’t like it”* (Sue)

Using the numeracy intervention assessments, the staff at Orange Hill were able to identify the children's mathematics deficits, *"which part of mathematics they need to work on"* (Sue), and in the subsequent individual sessions they were able to help the children make considerable progress, *"on the whole, most students do achieve, whether it is in the data [their achievements on standardised tests] or if it's confidence or even motivation.... I can honestly say that I have never had a negative outcome"* (Sue).

Nevertheless, while most of the children *"just seem to be trying their hardest"* (Kath), for some, about a third, their frustrations do lead to some level of disaffection, *"The negative attitudes usually show in the class ... because the work isn't at their level and that's when behaviour seems to kick in.... And if they kick off enough, they might get expelled, which is what they are looking for. They can't cope with what is going on in class so they are trying to think of a way to get out of it. That is the extreme. Others might just have low-level behaviour problems but it still is a form of attention seeking. 'I can't do it...', but instead of asking for help that's the way they go about it"* (Sue).

As part of the mathematics support that she provides to the children, *"I try to give them different ways of doing it even if it's not helping them with their numeracy, it's helping them with their confidence with their maths"*, Kath already makes extensive use of games, a particular favourite being darts.

We do a number of games with the darts like adding – 100's, 10's, units. Throwing the darts, and you have a running score with you. And the student who gets to 50 first. So not only they have to add up the three darts that they throw but they have to add up the whole running score too. You can also do taking away, start from 50 and count down, and you can do the 'times-ing' because you've got the doubles and trebles. The children don't see it as maths, they see it as a competition between me and them. At the end of the day, they just say I beat you and the smiles on their faces – it's just brilliant. (Kath)

The participating children played the prototype game in lieu of their usual numeracy intervention sessions. However, although each child usually receives a regular 15 minutes of Catch Up support twice a week, the amount of time they were able to spend playing the prototype game varied (teachers had kindly given their permission

for the children to miss as much of their timetabled classes as needed, within reason, for the study). In the first session, Kath mostly observed, making only the occasional comment, while the researcher introduced the game levels and gave guidance where necessary. In subsequent sessions, the roles were reversed, with Kath introducing the games, giving guidance and engaging the child in reflective conversation about what they were trying to achieve, while the researcher observed from a relative distance.

Christopher

The first participating child, Christopher, was 12 years old. When he joined the school, he was more than two years behind in both his reading and mathematics. He has been receiving numeracy intervention support for five months and has made considerable progress but he still finds mathematics difficult, particularly when it involves reading. He is currently working at between Levels 3 and 5 across the numeracy intervention components.

Despite his difficulties, Christopher's self-confidence was high *"because he thinks he has done it right even if he hasn't – because he is answering the question that he thinks is there. He is one of the boys that always wants to impress and wants to better himself all the time"* (Kath).

Christopher played three game levels of the prototype game for a total of 67 minutes: *derived facts* Levels 1 and 2 and, on the second day, *remembered facts* Level 2. Although he initially found the way in which the *derived facts* component had been interpreted in the game mechanics difficult to understand, which resulted in a series of random and unsuccessful clicking, after a few words of guidance he was soon working through the level. However, despite this steady progress, he actually appeared to be mostly ignoring the given known fact and each unknown fact was calculated without any reference to the earlier calculation.

The *remembered facts* level he initially found easier and he enjoyed re-discovering that the terms of an addition calculation were commutative, *"you can change it around, do any first, it makes it easier..."* (Christopher). In other words, rather than engaging with the principle of commutativity when playing the *derived facts* levels, where it was

intended, the principle became clearer to him when he was playing the *remembered facts* level – possibly because he was able to engage with the terms of the *remembered facts* calculation in any order that he chose. However, he found those tasks requiring subtraction somewhat more difficult. He first struggled to understand the importance of the order of terms in a subtraction calculation, which is to say he was not secure in the commutativity principle for subtraction (that the terms in a subtraction number sentence are not commutative). Nevertheless, after some attempts and input from Kath, he appeared slowly to ‘re-learn’ and understand the concept, which he was able to re-apply in later subtraction tasks.

Christopher reported that he enjoyed playing the prototype game, even though he found much of the numeracy “*too easy*”. Nevertheless, despite his claim, and despite a higher level of attainment recorded in his progress book, he struggled with some of the numeracy concepts and initially completed many of the tasks incorrectly. His repeated errors, plus the fact that the game mechanism returns tasks that are completed incorrectly to the pool of questions for asking again, meant that he played for more than twice the amount of time per level than had been intended.

Louise

The second participant, Louise, again 12 years old, was according to both Sue and Kath a “*quiet*”, “*intense*” girl who is “*quite hard to read*”. Although she clearly wants to do well, “*she doesn’t want to show that she does*” (Kath). Louise was also described as a “*stubborn*” girl. “*If she doesn’t want to do it, she won’t do it*” (Sue). “*I don’t think she fully takes on board people’s comments when they are trying to help her. She just says ‘yes’ and still does it her way*” (Kath).

When she was first identified as needing additional support in both English and mathematics, Louise had a Mathematics Age almost three years behind her Chronological Age. Since then, having received numeracy intervention support for about six months, she is working mostly at Level 5 in the numeracy intervention components, has made more than a year’s progress in her Mathematics Age, and is “*more willing to give it a go*” (Sue).

Louise, played three levels of the prototype game, over two sessions, for a total of about 42 minutes: *estimation* Levels 1 and 2 and *derived facts* Level 3. Again, the researcher introduced the first game levels, then Kath provided all the guidance in subsequent sessions. Although noticeably shy in the presence of the researcher, once Louise had understood the game mechanics and had been reminded of the principles of estimation, she soon became animated as she worked rapidly through the tasks – she didn't say much, but her increased concentration and the smile at the corners of her mouth suggested that she was having fun. She particularly enjoyed the fact that it did not matter if she got the wrong answer, she could with little consequence easily just try again – making mistakes did not seem to distract her from what she was trying to achieve. This is not to suggest that she clicked randomly. On the contrary, Louise thought carefully about the tasks, took advantage of what the achievements recorded in her Progress book suggested were for her the relatively easy numbers, and increasingly became more willing just to have a go. However, she had less success with the *derived facts* level – at the start, she was not at all sure how to proceed and repeatedly attempted the same doomed strategy. It took three interventions from Kath before Louise was willing to take a different approach, and through the conversation it became clear that it was the game mechanics rather than the *derived facts* principles that were causing the difficulties. Nevertheless, Louise thought that playing the prototype game could help her with her mathematics, because it would motivate her, *"because it will make you want to do a bit more, so it makes you learn more, it makes you better in lessons"* (Louise).

Kevin

The third participant, Kevin, was also 12 years old. He joined Orange Hill late in the academic year, having previously been home-schooled, and was more than three years behind in both his reading and mathematics. He is known for having persistent behavioural problems in class, which are however partly attributed to his difficulties, *"He does kick off within lessons because the work isn't at his level. It's a way of attention-seeking, a way of getting out of class. [He] thinks if I kick off too many times, I get sent out"* (Sue).

As being in a mainstream class can be difficult to manage, both for him and his teachers and classmates, he currently spends most of his days receiving one-to-one support, including numeracy intervention. This has helped him to make some progress, such that he is currently working mostly at levels 3 and 4 across the numeracy intervention components.

Although his classroom mathematics skills are weak, interestingly he is very good at computing with money (*cf.* Nunes *et al.* 1993) but

if I asked him the same question, but without using pounds or pence, he wouldn't be able to work it out as easy – he doesn't realise it's the same question. Once again he is a happy-go-lucky boy, as long as it is at his level. But if it's harder, he won't try and will most probably just walk out of the class room. (Kath)

Kevin, only attended one session of the research during which he played the first *remembered facts* level (unfortunately, he was not available for future sessions as he was withdrawn from the school). Although he enjoyed the game, and said he would like to play again on another day, he did not want to play a second level at that time: the twenty-one minutes it had taken to complete the one level was quite reasonably more than enough for him for one session. Initially, Kevin had to put up with technical problems in the game: the first two tasks that it asked did not work properly. Nevertheless, after this shaky start, he appeared to quickly understand the game mechanics and moved happily through the level.

The subtraction tasks however made Kevin pause, while he deliberated each problem for some moments but, often after having made one incorrect attempt, he would carefully and most often successfully work out how best to proceed. Kevin took around twice as long to complete the level than intended partly because of this careful deliberation but again also because incorrectly answered questions are returned to the question pool before being asked a second time. What was particularly noticeable about his interaction with the game was that his interest appeared to be sustained throughout the twenty-one minutes. Whereas elsewhere he all too easily can become bored and “kick off” (Kath), here he appeared willing to engage with the numeracy learning tasks, despite his many mistakes, and despite thinking that the game was “a

bit babyish, 'cause it was easy" (Kevin). Finally, although he claimed that he had rarely played computer games, Kevin was the quickest of the participating children to understand the game mechanics, how to use the arrow keys to move his avatar effectively, and also the most adept at collecting the coins en route. For Kevin, collecting the coins was something that he did automatically, without much conscious thought, and while he talked about other aspects of the game.

Sara

Kevin's place in the intervention was taken by Sara, 11 years old and the highest achieving child in this research cycle. She was working at Level 6 in almost all of the numeracy intervention components. She was only about 7 months behind in mathematics, when she first began numeracy intervention, but in class she had appeared to be slipping further behind. According to her class teacher, she was a *"nervous child [with] very low self-confidence"* (Sue), both of which were having a negative effect on her progress.

In her individual sessions, Sara makes a considerable effort. She *"takes on board what you have told her. She tries to see that link..., when a lot of the other kids don't really see the link"* (Sue). Her progress in the sessions has increased her self-confidence and allowed her to make similar progress in her mainstream class. *"I think it shows in class as well as she is quite happy to work with her classmates"* (Sue).

Sara played one game level for approximately thirteen minutes: *estimation* Level 1. Kath introduced the prototype to her, explaining the game mechanics and what was needed to be achieved; and after a slow start, while she orientated herself, Sara moved quickly through the tasks. From the way that she rapidly 'attacked' the game, it was clear that she did not need to calculate many of the answers: as her Progress book suggested, for her the calculations were already *remembered facts*, which therefore didn't need to be estimated. It was also clear that, of all the children, Sara had made the strongest connection between the concrete, labelled concrete and symbolic sub-tasks. Having determined a suitable response, what to click, for the concrete objects, she quickly dealt with the subsequent two versions – it was just *"obvious"* (Sara) what

to do. Even though she found the game easy, *“easy as in fun”* (Sara), she thought it had been useful, particularly being able to engage with the physical objects on the screen, *“I thought [the game] really helped with what I was doing ... I think it helps me more [than using pen and paper or counters], because it’s physical and it’s got money to do with it as well”* (Sara).

Genre, story, aesthetics and technology

Although central to the design process, the prototype game’s genre, story and aesthetics received little explicit attention from the participants; which, given that design often only gets noticed when it is not working properly, might be seen positively. When they first saw the game, all of the children did give an instant upbeat reaction, mostly just knowing smiles but an emphatic *“Yes!”* from Christopher. However, this is probably more of a comment on the novel use of a computer game to support the numeracy intervention for these particular children rather than on any intrinsic qualities of this prototype game. Nevertheless, once they had experienced playing the game, its look and feel was commented upon positively by all of the children and, although clearly they thought it was not quite as good the computer games that they played at home, they did acknowledge that it looked similar and was comparable. In addition, the style of the game’s graphics and the inclusion of the avatar and other gameplay objects did make it instantly identifiable for all the children as a game like Super Mario Bros., that is to say as a platform game, a genre with which, despite some claims to the contrary, they were certainly familiar and which thus brought a certain set of expectations: the game’s simple approach to story, how it might be played and how much fun it might provide.

The technology also had an impact on the way in which the game was perceived by the children. The coding of the game functioned mostly as intended although, as expected of budget software in its first phase of development, there were some bugs. For example, some poorly constructed algorithms did occasionally give incorrect responses to the children’s correct answers. These were mostly overcome by the intervention of the researcher and did not impact too seriously on the progress of the games. However, an issue that was raised by the design of the prototype game was the

conflict between systematisation and flexibility. The development of any software aims to systematise as much of the code as possible, while keeping it flexible and open to further development. Balancing these two needs had to be kept in mind throughout the discussion with the developer. Sometimes the balance struck was evidently successful, for example in the way in which the sub-tasks functioned as variants of the one overall task, as instants of a single software module. Elsewhere, it proved to be more difficult, for example to accommodate tasks involving subtraction in gameplay successfully designed for addition.

Gameplay mechanics

It was clear from the observations, the children's expressions and level of engagement, that all of the participating children enjoyed playing the prototype game: their initial positive reaction appeared to be, for the most part, sustained throughout the time that they played. The same was suggested by the interviews. They all said they would prefer playing the game to doing numeracy in class and they all indicated that they would like to play the game again in the future. This reflects the main thrust of much GBL advocacy, that because games are fun to play, they might be used to motivate children to engage with the learning of mathematics: as Louise explained, *"because it will make you want to do a bit more, so it makes you learn more, it makes you better in lessons"*.

Nevertheless, for all of the children, the game mechanics were at once both familiar and confusing. To begin with, the games appear to have successfully implemented key elements of the platform-games genre: the premise of the gameplay, the need to move the avatar from left to right to overcome obstacles and to achieve the end goal, was understood quickly by all of the children without any explicit instruction. And while some were more adept than others, Louise being the least familiar, all of them appeared to be comfortable using the keyboard arrow keys to move their avatar through the virtual space.

They were all also familiar with having to jump their avatar in order to collide with and hence collect the gold coins. They all immediately both understood the game

conventions and knew exactly what to do. For the boys, Kevin in particular, despite him claiming not to play computer games, collecting the coins appeared to take little conscious effort. In fact, the gold coins, represented by no more than little gold coloured discs hanging in the virtual space, were considered by all the children as the most important part of the gameplay, the immediate and highly valued feedback for a successful negotiation of an obstacle, *“I have to collect as many coins as I can”* (Christopher).

In fact, as they played, all of the children clearly derived some pleasure from the game mechanics and looked as if they had entered, at least for a short time, the state of consciousness known as flow (Csikszentmihalyi 1991). That is to say, once they had relaxed into the game, they soon become fully immersed in the virtual world depicted on-screen, playing the keyboards arrow keys much like a pianist to control their avatar and effortlessly collect coins, to the exclusion of anything going on around them in the real world off-screen. This usually continued until it was interrupted, either by an interjection from Kath or the researcher, or by a stumbling block such as a task that they were unable to answer easily or a glitch in the software.

However, in order for the children to achieve any level of flow, the specific way in which the gameplay was realised in this particular game required some familiarisation. For example, although the children recognised that they had to move the avatar from left to right through the virtual landscape, they had to learn that gaps would impede progress while blocks could be used to fill the gaps. Learning that gaps were obstacles was straightforward: if the player tried to cross an unfilled gap, their avatar briefly died. However, the idea that the blocks might be used to fill the gap, and that they could be brought into play by moving the avatar alongside and pressing the spacebar, was not so obvious. Two of the children, Kevin and Sara, soon worked out why and how to select the blocks, but Christopher and Louise both needed some specific guidance. Christopher, for example, not unreasonably but unsuccessfully, tried to select objects using the computer mouse.

There were a range of other issues around the gameplay mechanics that the next iteration of the prototype game would also need to consider. First, there was little to

discourage the children from selecting potential solutions randomly. Kevin, in particular but not exclusively, often preferred to click as many answers as possible rather than look carefully at the problem to determine the best approach. Clicking randomly was often less cognitively demanding and seemed faster in the moment, although it did have a postponed impact on time to complete the game.

Second, the children's clicks became more random and they became far less engaged when the game dragged on too long – which on one level was almost 17 minutes for Kevin, *"Does it keep on going?"* (Kevin), and elsewhere almost 30 minutes for Christopher, *"I would choose the written work because it wouldn't take as long"* (Christopher). To maximise the usefulness of the prototype game in real classrooms, the intention had been for a meaningful amount of gameplay to require no more than around 10 minutes to complete, which suggested one game level per session, each of which would comprise around 10 numeracy tasks. However, two other decisions had compromised this approach: implementing the modes of representation and putting incorrectly answered questions back into the pool. Accounting for each mode of representation (enactive, iconic, symbolic) meant that each task was presented three times, so players were in effect set a total of 30 tasks, three times the original intention. At the same time, putting all incorrectly answered questions back into the pool and re-presenting them until the player had correctly answered them meant that unsuccessful players might be required to play the level indefinitely.

Third, the level of gameplay difficulty. Building on the approach taken in the numeracy intervention to minimise cognitive overload, using low number ranges within single components, the gameplay tasks were similarly designed to be straightforward: for example, simply assemble two ladders to climb to a ledge; select two blocks to balance a scale; select a single block to stop a gushing pipe. This also reflects the approach taken in most entertainment platform games. The children clearly enjoyed these easy wins, but it was difficult to disentangle their numeracy performance from their gameplay performance to determine whether the simple mechanics were sufficiently challenging, whether they were pitched at an appropriate level to maintain the

children's interest over time, *"It was a bit babyish 'cause it was easy"* (Kevin). *"What was easy, doing the maths or playing the game?"* (researcher). *"Doing it all"* (Kevin).

Finally, while it had seemed to make good sense and was relatively straightforward to implement, the direct mapping between game level and number range had unforeseen and unhelpful consequences: it imposed a one-way linear progress preventing the children having a choice of gameplay thus reducing potential engagement, and was inefficient of development resources. While a child continued working at a particular level of numeracy, which could potentially take a number of sessions across several days, they could only repeatedly play the one gameplay, which could thus easily become boring. This would reduce motivation to continue and might also reinforce by association a belief that mathematics is boring, both of which are contrary to the aims of the game's design. On the other hand, once the children had completed a numeracy level successfully, they wouldn't be able to access that specific gameplay again however much they had enjoyed it. The lower levels in particular are often only relevant for a small proportion of children who are low-attaining in mathematics (reported in Catch Up 2009a) and thus might be played only occasionally, but still they required the same allocation of development resources as other levels.

A variety of potential modifications to the game were suggested, both by the children and by Kath. Most of the children's proposals focused on improving the gameplay experience, increasing the fun and thus motivation to play. For example, while Christopher suggested that you should be able to choose your own avatar, *"on my games, you change the cars and stuff and on this one it be good if you could change the people and stuff"*, Louise suggested that there could be music throughout and that the games should provide an opportunity to achieve bonus points – or at least, when you completed a task correctly, the computer should say *"good job"*. Sara agreed that there needed to be a bonus system, although for her the bonuses should be monetary, more coins. She also suggested that the story needed to be given more emphasis and that the experience needed to be more social, *"make it have more people in there and money. So then you could get more money, that money will help you and your friends. And there was people in there that was trapped. The money could help you get the*

people out that were trapped". Christopher agreed that it would be good to have other people in the gameplay, particularly to *"have a friend to help you"*.

Gameplay learning

The gameplay did appear to offer a variety of benefits for learning. To begin with, all of the children were willing to tackle repeatedly tasks that they did not at first answer successfully – an attitude that appeared to increase the more that they played. Without any external encouragement, from Kath or the researcher, the children always refused to give up in the face of difficulty: when they were in the moment, when they were in a state of flow, getting their avatar past the obstruction and collecting coins, playing the game was all that appeared to matter. They would try every strategy that they could think of, they would engage with the mathematics in any way they thought possible, sometimes deliberating out loud, without fear of failure or embarrassment, in order to succeed in the game. This did sometimes involved random clicking, which led Kath sometimes to intervene, to encourage them to *"stop and think"* (Kath); and the children were being observed, so they might have continued just to please the researcher. Nevertheless, Kath remarked that their willingness to try things in the prototype game contrasted markedly with their frequent reluctance to try unfamiliar numerical tasks in class or in their numeracy intervention sessions.

Translating the three chosen components of numeracy into gameplay and in particular implementing them without overlaps proved to be the most challenging part of the design of the prototype game, and was achieved with varying degrees of effectiveness. The *remembered facts* game levels appeared to be the most successful. They provided many easy-to-access opportunities to practise recalling factual numeracy knowledge, which motivated the children to engage with the learning and allowed them to make noticeable progress. What appeared to help was the fact that the task was straightforward, to fill a gap to enable the avatar to proceed, and the mechanics uncomplicated. However, all of the children were observed to be counting the individual units that made up the blocks or ladders needed to negotiate the obstructions and using counting-on or counting-back techniques to calculate their

response. Although counting, in particular finger counting, is recognised as an important stage in the development of numerical competence (Dehaene 2000; McEvoy 1989), here the intention was for the children to draw on previously learned and now *remembered facts*. In addition, the way in which subtraction was implemented in the *remembered facts* game was confusing to the children – such that, at least initially, the game mechanics appeared to prevent them demonstrating their knowledge of subtraction facts. However, once Kath had asked them to reflect on the nature of the question and what was being asked of them, the children quickly understood, that one block might be subtracted from another block, and appeared to have no further difficulty.

The *estimation* game levels were also at first not as productive as hoped but this was mainly because they involved numbers with which Sara and Louise were already quite familiar. As they were easily able to calculate an accurate answer, estimating the answer became an inauthentic task with no other obvious benefit, undertaken only because the game demanded it. Nevertheless, once the children understood that they could proceed through the game by estimating the answers, rather than having to remember or calculate them accurately, they took considerable pleasure, Louise in particular, in moving very rapidly through the tasks. Accordingly, for these children, although there was some use of counting-on and counting-back, their procedural knowledge of estimation appeared to have been reinforced by means of their engagement with the game.

The *derived facts* game levels on the other hand were as problematic as had been anticipated – the *derived facts* principles had proven to be as difficult to translate into a digital game as feedback from teaching staff had suggested they might be (reported in Catch Up 2009a). The approach finally adopted was to present two tasks side-by-side, with animating blocks representing both the completed/known fact and the uncompleted/unknown fact for the current calculation. However, when they played the *derived facts* games, after some random clicking, Christopher and Louise mostly calculated the answer to the unknown fact without any reference to the given known fact. This probably was not helped by the size of the numbers being presented, within

the number range 1 – 10, and was exacerbated by the on-screen position of the two animating calculations. The intended hierarchy of the two animations was unclear, that you should look at the first calculation in order to help work out the second calculation, particularly as once the avatar had reached the unfinished calculation the finished calculation was occasionally off the screen. Nevertheless, with guidance from Kath, *“did you use the first sum to help you work out the second sum”* (Kath), Christopher did understand what was being asked of him and was soon able to make good progress. Kath also made the point that, in the way the game levels were configured, the link with the *derived facts* tasks the children had been tackling in their regular numeracy intervention sessions was not as useful as it might be. She explained that, working with *derived facts* also involved identifying which of the four principles applied in the current circumstances. This was not addressed in the prototype game.

Although all of the participating children said that they thought the tasks presented in the game were ‘too easy’, it needed to offer *“a little bit harder questions”* (Christopher), they did all make frequent errors. However, it was not clear whether the questions were genuinely far below the capabilities of the children, and the errors were a result of the game mechanics getting in the way, or whether the questions were below what the children believed to be their current capabilities, in other words whether they were overly-confident in their own current numeracy skills. A discussion with Kath and a review of the children’s numeracy intervention progress books did not resolve this, although Kath did comment that it *“would have been more useful when the numbers are more appropriate ... so they would need to stop and think”* (Kath). On the other hand, the three children who spent the longest playing the games also said that they found working with the numeracy tasks in the game easier than doing so in their heads or with pencil and paper – although Sara did point out that pencil and paper would be more useful for complex calculations that involved multiple steps, so that you did not forget where you were in the process, *“I write the maths on a bit of paper so I know what I’m doing”* (Sara).

The children were also asked whether they saw playing the games as fun or as work, and whether they believed that the games had helped them learn. The first of these

elicited almost all possible responses: while Louise described her time with the game levels as playing, Kevin thought it was work, and Christopher saw the game *“as work and fun, dead in the middle”*. Nevertheless, all of them believed that they had learned something by playing the game and that it had supported what they did in their numeracy intervention sessions. From the perspective of the researcher, the children’s claims about learning did appear to have some basis, some learning did appear to be happening while the children played. For example, having answered earlier questions incorrectly, all the children appeared to make clear improvement over time: all of the them answered correctly increasing numbers of subsequent questions, increasingly quickly.

The progress achieved by all the children during the relatively short time that they played the prototype game is in line with the notion that repetition and practice can lead to mastery and/or automaticity. This occurred at two levels: gameplay and educational content. Having begun the games not knowing what to do or what was expected of them, the children quickly assimilated the gameplay into their pre-existing game-playing cognitive schema, their knowledge of entertainment platform games and how they are played, and became increasingly adept. This was achieved by the children repeatedly practising the moves necessary to navigate their avatar and progress through the game: as they did so, their use of the keyboard and the movement of their avatar through the landscape became noticeably faster and their collection of coins appeared to become increasingly automatic. Nevertheless, whether or not the children’s growing game-playing skills contributed directly to their mathematical learning remains an open question.

During the observations, it was also very noticeable that all of the children actively enjoyed the rhythm of the repetitions centred on the way in which Bruner’s modes of representation had been interpreted in the design of the game – which suggests that, despite adding dramatically to the time taken to play each level, the approach contributed positively to the learning experience. The children are first presented only with the concrete objects, the physical gap that needs to be bridged and the playing pieces that may be employed to do so. Having interpreted what they see in terms of

their prior gameplay and mathematical knowledge, they then have to act upon the playing pieces to cause them to bridge the gap, to put them into practice, and thus enable the avatar to proceed. The transition from iconic to symbolic is encouraged by re-presenting the same task twice more, once with the gap and playing pieces labelled with appropriate numerals, the final time showing only the numerals. The aim is to provide the children firstly with an opportunity to construct knowledge for themselves, to alter their existing knowledge of number, moving from assimilation to accommodation, by manipulating or acting upon the concrete objects in order to negotiate the obstacle. This is then reinforced through a series of repeated but increasingly abstract levels of practice.

Having determined how best to manipulate the available playing pieces to negotiate the obstacle, either by eye or by counting but with reference to their prior experience, which sometimes they found difficult or time-consuming, and having learned the relationship between the three sub-tasks, all of the children soon began to enjoy the relatively easy wins afforded by the repetition of the task with the additional information provided by the numerals, *“it’s easy because it’s the same!”* (Kevin). Implementing the gameplay in this way also appeared to reinforce for the children the connection between the authentic concrete problems they were trying to solve and the numerical symbols, and vice-versa. Although Christopher at first failed to transfer what he had learned from one sub-task to the next, once he had been encouraged by Kath to slow down and to reflect on what he was trying to do, he spent some time considering his options and had several eureka moments: the connection between the concrete objects and the numbers suddenly became very clear for him, he realised he could use the objects to judge the numbers and the numbers to judge the objects.

The repetitive practice also appeared to have contributed to the improvements that the children made with the numeracy tasks, over time they answered increasing numbers of questions correctly, increasingly quickly and with growing confidence. However, mapping the levels of numeracy to the game levels meant that each time the number range changed so did the gameplay, thus undermining the intention to build a smooth spiral of learning moments. While the children did begin with smaller numbers

before progressing onto larger numbers, revisiting the same mathematical processes at increasing levels of sophistication, it was a staccato approach with perhaps too much cognitive energy spent on the gameplay rather than on the mathematics.

Some suggestions for amendments focused on improving the opportunities for learning provided by the game. As mentioned, despite the difficulties that the children did have with some of the questions, they argued that the questions were “*too simple*” (Sara), that the game needed to “*do a little bit of harder questions*” (Christopher). Kath agreed, “*it needs harder sums, so they need to stop and think.... It would have been more useful if the numbers were more appropriate to their level*” (Kath). In addition, Kath suggested that in the *derived facts* levels, the children should be asked to identify, as they do in their regular individual sessions, which *derived facts* principle they had just applied – perhaps by choosing one of four possible labelled bonus coins.

Other outcomes

Observing the children while they played the game afforded both the researcher and Kath opportunities to understand something of their relationship with learning and with mathematics. For example, their interaction with the game highlighted a series of disconnects between what the children’s self-confidence suggested they might know, what they were expected to know, and what they demonstrated they did know: that is to say, between their self-efficacy beliefs (how competent they thought themselves to be in mathematics), how competent Kath expected them to be, and what they actually achieved when playing the game. Often they found the mathematical tasks more difficult than they or Kath had expected. The less secure they were with the numbers or components, the more mistakes they made and, because each mistake caused the incorrectly answered task to be returned to the pool of questions, the longer the game took to play. This was a key reason, aside from the poor programming decisions, for Christopher taking thirty minutes to play one game: he was not as secure in the numbers covered in that level as his record of prior achievement indicated.

Elsewhere, when playing *remembered facts* Level 2, Christopher also found the tasks involving subtraction more difficult than his record of progress suggested he would.

However, observing him working through the possibilities, sometimes clicking randomly, sometimes re-discovering various misremembered strategies, and listening to him speaking some of his thought process out loud, also gave insight which might otherwise have not been available. For example, having stumbled upon and recognised a successful strategy that allowed him to complete correctly an early task involving subtraction, when he came across another subtraction task he mostly started again from the beginning. Although he had re-discovered a successful strategy for dealing with subtractions, he had not successfully encoded that strategy in memory, and he had to work it out all over again. An observation such as this, of relevance to Christopher's working memory, might be of benefit when trying to determine the most effective support.

Sitting with the children while they played the games also provided Kath various opportunities to learn more about the children and their approach to arithmetic: how they tackled the tasks, what misconceptions they held, which facts they remembered, and with which strategies they were familiar. Initially, she only spoke occasionally. But once she, rather than the researcher, was providing the support, it also gave her opportunities to intervene proactively, "*were you using the first sum to help you work out the second sum?*" (Kath). She was also able to participate in the gameplay, alongside the children, firstly helping them explore how to deal with the game mechanics, then how to figure out the solutions to the given tasks: discussing how to overcome the obstacles rather than how to answer mathematics questions, encouraging them to reflect on what they were doing and on what they had achieved, providing guidance and reinforcing their successes, "*that was good, you remembered that*" (Kath). In a sense, the game functioned most effectively as a fulcrum for social interaction and discussion, providing opportunities to engage the children in conversations about their game-playing skills and their mathematics.

For example, she was able to help Christopher understand that the commutativity principle did not apply to subtraction, as it applied to addition, by engaging him in a discussion about what he was attempting to do in the *remembered facts* level that he played. He had worked out that he could plug a large gap by choosing two blocks in

any order, in other words that the commutativity principle was applicable to addition, “*I can change it around, makes it easier*” (Christopher). He discovered, through trial and error and some comments from Kath, “*why are you clicking that one?*”, that he could plug a small gap by using the difference between two blocks. And, through trial and error and some discussion with Kath, he soon came to understand why the order in which he selected these two blocks mattered, it clearly was not the same as before, “*I can change adding but not when it’s taking away*” (Christopher).

The prototype game also afforded the children the opportunity to demonstrate an expertise and self-confidence to Kath, and to the researcher – to show off their skills, both in terms of gameplay and mathematics. Even when they professed that they were not experienced at playing computer games, as Louise and Kevin did, showing off their proficiency at moving their avatar, collecting coins, and tackling practical problems on the computer screen, gave all the children obvious pleasure. They also enjoyed demonstrating their capabilities with the arithmetical tasks. The children were also adept at subverting the intentions of the game designers. In the *remembered facts* levels, for example, Sara sometimes seemed as if she were moving somehow from symbolic to concrete, using the numbers to describe the objects rather than using the objects to contextualise the numbers. Meanwhile in the *derived facts* levels, the children only occasionally used the known fact to help them derive the answer to the unknown fact, preferring instead to calculate the target number sentence from scratch; and in the *estimation* levels, Louise often simply remembered the answer to the first sub-task, which she then applied automatically to the following sub-tasks without further reflection.

4.3 ANALYSIS AND REFLECTION

This chapter has discussed the first cycle of design and intervention. Despite the small number of participants, the research methods employed during the intervention of the prototype game being used by children (participant observation, screen and audio recording, interviews, document analysis and field notes) generated sufficient rich data to address the research sub-questions.

Research sub-question 1.1

How might insights from the numeracy intervention and learning theory inform the design of the prototype digital game?

Designing a prototype game that brought together principles of the numeracy intervention, insights from learning theory, and established approaches to developing digital entertainment games, proved to be challenging. First, it was difficult to design a variety of activities that addressed each of the three components across the full range of the three levels of attainment and that enabled learning through the gameplay. For this reason, some of the game levels differed only in terms of their graphics. Second, while the *remembered facts* addition tasks were easily understandable, add together two playing pieces to bridge a gap, the subtraction tasks were by comparison contrived, subtract one playing piece from another to bridge a gap smaller than either playing piece. Third, separating the components from one another to minimise cognitive overload was not always successful: the *remembered facts* games often involved estimation, estimating the length of a playing piece or a gap, while some *derived facts* tasks could be answered as if they were *remembered facts* tasks. Fourth, in the *derived facts* games, it was not clear that players should use the given number sentence to help them complete a target number sentence. And finally, mapping the game levels directly to the individual levels of attainment meant that the spiral curriculum of learning tasks, revisiting the same mathematical processes at increasing levels of sophistication, was fragmented.

Nevertheless, despite these important details, the implementation of the identified aspects of the numeracy intervention and learning theory, using the language of entertainment platform games, did function as intended. First, the game, its style and gameplay mechanisms, clearly matched the characteristics of the platform game genre, making it potentially attractive to and accessible for children who are familiar with such games. Second, the implementation of the components of numeracy, divided into the levels of attainment, was broadly successful: the differences between the components were clear; what was expected of the *remembered facts* and *estimation* sub-games was easy to understand; the implementation of the components and levels of attainment combinations into separate sub-games minimised the

cognitive resources required of a player in any one session; and each sub-game provided multiple opportunities for useful practice in the respective skills. Third, the implementation of the game mechanisms enabled learning through the gameplay, allowing the player to construct an answer for the given task that is meaningful for them by trying a variety of approaches. And finally, the game's interpretation of the modes of representation (concrete object, labelled object, symbolic) had potential for supporting children's transition from iconic to symbolic mathematical thinking.

Research sub-question 1.2

What are the responses of a sample of children who are low-attaining in mathematics and the teaching staff who support them to the prototype game?

All of the children responded positively to playing the prototype game, which reaffirms that, as indicated by the literature (Gee 2003; Prensky 2006; Squire & Jenkins 2003), digital games might have a place in motivating children to engage with learning content. In particular, they thought the game was entertaining and a welcome distraction from their usual numeracy activities: they found the graphics attractive and similar to the computer games that they knew from home; they were able to play the game without any explicit instruction; it was fun to control the avatar, jumping to collect coins, which often led to a state of flow (Csikszentmihalyi 1991); and they liked the fact that each task built on earlier tasks, giving them easy wins. The game was also seen as a safe environment for learning: it allowed them to fail without fear of embarrassment or other unpleasant consequences (Martin & Marsh 2003). In contrast to their approach to mathematics elsewhere, in the game the children were willing to try all the tasks as often as necessary. They mostly refused to give up in the face of difficulty and tried every strategy possible, especially when they were in a state of flow. The game also helped to make the mathematics more meaningful for them, because it affected the world in which they were playing: the mathematics was clearly situated in a familiar digital world in which the mathematical thinking had direct consequences, the only way to make progress was to calculate how to bridge the obstacles. In short, the mathematics might be said to have been authentic (Galarneau 2005; Herrington *et al.* 2003).

The game also did appear to facilitate some learning. Through their engagement with the game, and by means of the reinforcement through repetition and practice, all of the children made clear improvements over time: they answered correctly increasing numbers of questions at first attempt increasingly quickly. In addition, they all believed that they had learned something. And, given that they all finished at least one sub-game, only possible once they had answered each task without error, they also did appear to be achieving the game's learning objectives.

There were however a number of issues. At times, the children preferred to use random clicking, rather than to engage properly with the learning content; the children often used counting-on or counting-back techniques to answer the *remembered facts* tasks, instead of remembering previously learned number facts; estimating the answer was often an inauthentic task in the *estimation* games, because the children were easily able to calculate an accurate answer and therefore had no need to estimate; and the *derived facts* tasks were often answered without any reference to the given fact.

While the observations and interviews suggested that both appeared to have merit, it wasn't easy to assess the impact of two key design decisions: the repetition of tasks as concrete objects, labelled objects and symbolic; and the mapping of the levels of attainment to the game levels. The repetitions of each task meant that each game took around three times as long to complete as intended, but the children clearly derived some benefits from the reinforcement of the connection between objects and numbers, and enjoyed the easy wins that the repetition made possible. The direct mapping of attainment and game levels, on the other hand, meant that each time the number range changed so did the gameplay, which fragmented the spiral of learning moments, and was inefficient of resources.

Where the game appeared to be most successful was in affording the teaching assistant multiple opportunities to infer something about the children's learning needs: how they tackled the tasks, what misconceptions they held, which facts they remembered, and with which strategies they were familiar. Observing the children playing the game also highlighted for the teaching assistant a disconnect between what each individual child's records suggested they knew and could do, what the

children believed they knew, their self-efficacy beliefs, and what their performance in the game and the strategies that they used suggested they actually did know. In addition, once the teaching assistant became more involved, once they had encouraged the children to attend more closely to and to reflect upon the tasks presented by the game, once they had engaged the children in discussion about their learning, each child did become noticeably more adept at dealing with each set of mathematical problems and did appear to improve their mathematical understanding within each of the three components. The intervention of the supporting adult was thus instrumental. The approach to numeracy derived from the numeracy intervention and implemented in the games did enable the children to make progress and to achieve the learning objectives but most effectively when the game was used as a fulcrum for social interaction and discussion between the child and the supporting adult. This unanticipated observation became an important focus of the next research cycle.

Research sub-question 1.3

How might the prototype game be amended to make it a more useful classroom tool?

The intervention suggested a number of ways in which the prototype game might be further designed to make it a more useful classroom tool. Naturally, there were a number of programming bugs that needed to be addressed. But more importantly, the children suggested ways in which the game could be more engaging: by allowing you to choose your own avatar, by giving positive verbal feedback, by including music and bonuses, by including friends in the gameplay, by including a timer, and by showing scores on a leader board. The observations and interviews suggested three other key amendments, to the way in which the numeracy was implemented in the game: reducing the number of tasks that needed to be completed, so that playing a meaningful amount of gameplay takes much less time, to make it more attractive for children to play and easier to implement in real school timetables; re-configuring the way in which the *derived facts* tasks were implemented, to help ensure that the principles are properly reinforced; and separating the numeracy levels from the game levels, in order to smooth the spiral of learning moments, to give the children a choice in what they play, and to make more efficient use of the investment in the games' design and development.

Research cycle 2

This chapter discusses the second research cycle of design, intervention, analysis and reflection. It comprises the second iteration of a prototype game, developed in response to the outcomes of the first research cycle, which was researched in three ‘more authentic’ school settings. The outcomes from each school are discussed separately.

Research questions

This second research cycle continues the process of addressing the study’s two central research questions, by considering four sub-questions (two of which were adopted from the first research cycle because they remained relevant). This cycle’s second sub-question considers how the game was actually used by schools (Birmingham *et al.* 2002; Davies & Eynon 2012). It was introduced because for this cycle the game was made available online, which allowed the teaching staff to access it as and when they saw fit. The third sub-question is based on an unanticipated outcome of the first research cycle: the contribution of the game to educationally productive dialogue.

Therefore, the research sub-questions in this research cycle are:

- 2.1 What are the responses of a sample of children who are low-attaining in mathematics, and the teaching staff who support them, to the prototype game?
- 2.2 How was the prototype game implemented and used in the sample schools?
- 2.3 In what ways did the prototype game function as a fulcrum for social interaction and discussion?

2.4 How might the prototype game be amended to make it a more useful classroom tool?

5.1 DESIGN

The design of the second iteration of the prototype game addressed key outcomes of the first research cycle under the following headings: game levels and numeracy levels; leader board and timer; *remembered facts*; *derived facts*; screen layout and task permutations; and customizable avatar and companion.

The second iteration also included a variety of minor technical bug fixes and, more importantly, a change in the game delivery mechanism. The first iteration of the game existed as a set of *Adobe Flash* files stored on the researcher's laptop computer, and so could only be accessed when the researcher was present. Although this had some advantages, for example it enabled the screen capture of gameplay, it limited the children's access and prevented them playing the games at other times. Accordingly, for the second iteration, the game files were ported into an online system which enabled the children to access the games from any computer with Internet access, at any time. The system was also password-protected, to permit the recording of individual children's progress, wherever they happened to play the games: for example, the children could begin playing the games at school, then continue at home picking up where they had left off.

Game levels and numeracy levels

The first iteration of the prototype game interpreted three of the numeracy intervention's components of numeracy. For each of these three components, game levels in the form of sub-games were designed for each of the first three numeracy levels of attainment (Table 5.1, p.113, row 1: 'Iteration 1') (the first iteration was restricted to three levels for each component because it was exploratory). In game level one for any particular component, the child would work with numbers within numeracy Level one; in game level two, they would work with numeracy Level two; and in game level three, with numeracy Level three. However, as noted in Chapter 4, this direct mapping between game level and

numeracy level, despite it appearing to be a logical approach because of the apparent synergy between the two types of level, had unforeseen and unhelpful consequences.

Table 5.1

Numeracy levels and game levels for each component.

Iteration 1	Game levels:	Level 1	Level 2	Level 3			
	Numeracy levels (number ranges):	Level 1 (1 – 5)	Level 2 (1 – 8)	Level 3 (1 – 10)			
Iteration 2 (original intention)	Game levels:	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
	Numeracy levels (number ranges):	Level 1 (1 – 5)	Level 2 (1 – 8)	Level 3 (1 – 10)	Level 4 (1 – 15)	Level 5 (1 – 18)	Level 6 (1 – 20)
Iteration 2 (actual)	Game levels:	Level 1		Level 1 Level 2		Level 1 Level 2 Level 3	
	Numeracy levels (number ranges):	Level 1 (1 – 5)	Level 2 (1 – 8)	Level 3 (1 – 10)	Level 4 (1 – 15)	Level 5 (1 – 18)	Level 6 (1 – 20)

While a child continued working at a particular numeracy level, which could potentially take a number of sessions across several days, they could only repeatedly play the one game level. As they did so, they would become increasingly familiar with that game level's activities and animations, and their engagement would reduce (as shown by Christopher's slow progress through *derived facts* discussed in Chapter 4). Further, once the children had completed a numeracy level successfully, once they had become secure in that number range, they were unlikely to access that particular game level again however much they had enjoyed it. If the questions were without challenge, inevitable as the child was now secure in that number range, the play would become boring. Instead they preferred to move onto the next game and numeracy level combination. Finally, the direct mapping of attainment and game levels also meant that each time the number range changed so did the gameplay, which fragmented the spiral of learning moments. In short, this one-way linear progress effectively prevented the children having a real choice of gameplay, thus reducing potential engagement. It was also inefficient of development resources: the lower game levels are likely to be used infrequently, yet they take as much time and effort to develop as the other levels.

As noted in Chapter 4, it was always intended to extend the second iteration of the game to include six of the numeracy levels for each of the three components: Levels 4, 5 and 6, covering the number ranges 1 to 15, 1 to 18, and 1 to 20. The aim was to increase the range of difficulty to make the games appropriate for a larger group of children, including those who are low attaining in mathematics but confident with numbers up to 10 in the particular components. To accommodate this using the same approach taken in the first iteration, a further nine game levels would be required, one for each new numeracy level for each component (Table 5.1, p.113, row 2: 'Iteration 2 (original intention)'). However, because of the limitations noted above, the decision was made instead to take a different approach, to separate the numeracy levels and game levels from one another (Table 5.1, p.113, row 3: 'Iteration 2 (actual)').

Separating the numeracy levels and game levels was perhaps the most far-reaching design outcome from the first intervention. In this new approach, once the child has completed a game level they 'unlock' the next game level, irrespective of whether they have shown themselves to be secure in the numeracy level. Unlocking game levels is an approach typical in entertainment digital games (for example, in the popular *Angry Birds* franchise). Once a game level is completed, the next one is unlocked, the player 'levels up', thus motivating continuing play. It is assumed that the player's thought process goes something like this: 'I want to unlock the next level, so I must continue playing and complete the current level'; and, 'I've unlocked a new level, I must be good at this, I'll continue playing' (Adams & Rollings 2006; Salen & Zimmerman 2003; Schell 2008). In other words, the various games levels function as what Lodge calls a 'narrative striptease': 'the endless leading on of the reader [player], a repeated postponement of an ultimate revelation which never comes – or, when it does, terminates the pleasure of the text [game]' (1984, p.29).

In the first iteration of the prototype game, completing a game level and completing a numeracy level meant the same thing. A game level was finished when each numeracy task presented to them had been completed correctly at first attempt. Tasks that were not completed correctly at first attempt were put back into the pot of available questions and later asked again (which is one reason why Kevin, in Chapter 4, ended

up playing one game for twenty-one minutes, he found the numeracy tasks in that particular game and numeracy level too difficult to answer at first attempt).

In the second iteration of the prototype game, however, completing a game level and completing a numeracy level meant different things. To complete a game level, the child had to complete a total of twelve tasks (four number tasks each presented three times: as concrete objects, labelled concrete objects, and symbolic), but they could attempt each task as often as necessary. To complete a numeracy level, on the other hand, ten tasks had to be completed correctly at first attempt. As a consequence, progress through the game levels and numeracy levels is disassociated from one another. At the very beginning, only the first game level for each component is unlocked, the other six game levels are locked (as shown by the padlock icons on the menu screen, Figure 5.1a) and cannot be played. However, once the child has completed a game level, they are shown a leader board (Figure 5.1b) and the next game level for that component is unlocked, giving the child a choice of gameplay; but until they have completed a numeracy level, each time they play, whichever game level that they choose, they are given tasks within the same number range (Table 5.2, p116).

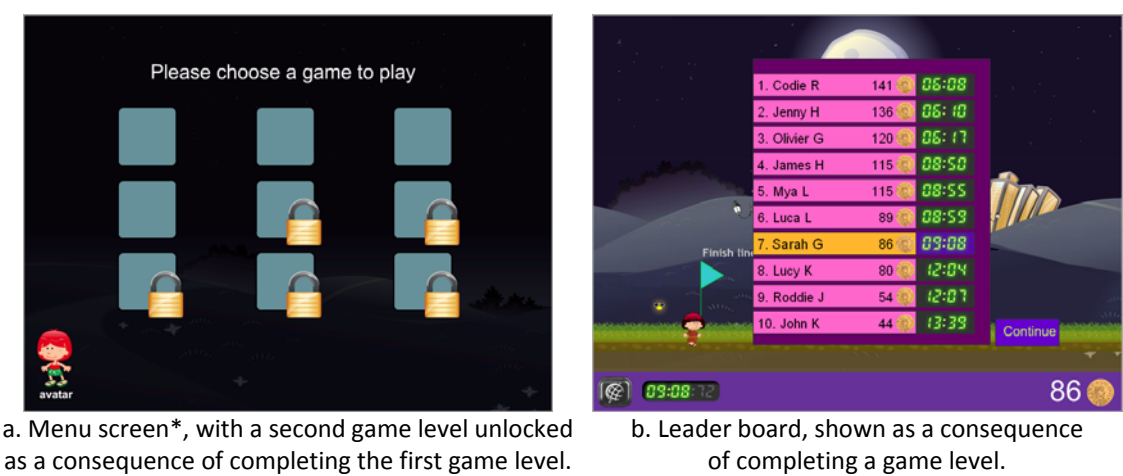


Figure 5.1
Menu screen and leader board.

* On the menu, each square represents a game level and each column of squares represents a component of numeracy. The child can choose to play any of the unlocked game levels, by clicking any square without a padlock. In this example menu screen, the child has completed the first game level for the first component and so has unlocked the second game level for that component.

Table 5.2

Progress through the game levels and numeracy levels.

	Game levels	Numeracy levels
First visit	• Play game level 1. • When twelve tasks have been completed, show leader board (Figure 5.1b, p.115) and unlock game level 2 (Figure 5.1a, p.115).	• Play numeracy Level 1 • If numeracy Level 1 is completed successfully (ten tasks correctly completed on first attempt), show 'you moved up a level' screen (Figure 5.2, p.118).
Second visit	• Play game level 1 or 2. • When twelve tasks have been completed, show leader board (Figure 5.1b, p.115) and, if playing game level 2, unlock game level 3.	• If on previous visit the numeracy level was not completed successfully, play the same numeracy level. Alternatively, if on previous visit the numeracy level was completed successfully, play the next numeracy level.
Third and subsequent visits	• Play game level 1, 2 or 3. • When twelve tasks have been completed, show leader board (Figure 5.1b, p.115).	• If numeracy level is completed successfully, show 'you moved up a level' screen (Figure 5.2, p.118).

Limiting the number of tasks needed to finish a game level to twelve, and allowing the child as many attempts as they needed rather than putting incorrectly answered tasks back into the pot for asking later, also greatly reduced the amount of time needed to complete the game level (which should prevent children having to play a game level for more than ten minutes or so, something that would be appreciated by Kevin). This is possible because the child can complete the game play without also having to complete the numeracy level; if they have not also completed the numeracy level, they will continue with it the next time that they play.

In fact, despite encouraging the children to strive to unlock the next game level, the game levels are in reality no longer the hierarchy that the term 'levels' suggests. They are instead simply alternative sets of graphics and animations, alternative gameplays. Nevertheless, the more that the child plays the game and the more number tasks that they tackle, the more alternative gameplays that they can later choose between (up to three choices per component). In other words, the more engaged they are, the more variation in gameplay there is to help maintain that engagement. On the other hand, if the child chooses, they can repeatedly play their preferred game level, the gameplay

and animations that they enjoy the most, while in the background the system still automatically moves them up gently through the numeracy levels.

While the child plays their choice of game level, the system monitors their success in the number tasks. For each component, the tasks always begin at numeracy Level one, within the number range one to five, and only move up to the next numeracy level once the child has completed correctly at first attempt ten of the twelve tasks. Always starting with the lowest number range gives the child a high likelihood of success, and allows them to work their way up through the numeracy levels to ‘find’ their personal zone of proximal development (Vygotsky 1978) – the point of equilibrium between tasks that they find easy and tasks they find challenging, that they can only achieve with the support of more capable others. Only requiring ten of the twelve tasks to be answered correctly at first attempt allows for minor lapses in concentration and accidental mouse clicks; while ‘completing correctly ten tasks at first attempt’ is taken as proxy for the child being ‘secure’ in that component within that number range.

Once the children have achieved ten of the twelve tasks correctly at first attempt, the next time that they visit the game, the system automatically moves them onto the next numeracy level. In this sense, the second iteration of the prototype game might be called ‘adaptive’ (Vandewaetere *et al.* 2011), in that it ‘monitor[s] important learner characteristics and make[s] appropriate adjustments to the instructional milieu to support and enhance learning’ (Shute & Zapata-Rivera 2008, p.277). Alternatively, it might be considered a small step in the direction of what has been called ‘personalised learning’, an educational system which is configured to meet the unique needs and talents of each individual child (Järvelä 2006; Johnson 2004; Leadbetter 2004).

To exploit the motivating ‘narrative striptease’ effect in respect of the numeracy levels, once a child has completed a numeracy level they are presented with a screen and spoken message that celebrate the fact that they have ‘moved up a level’ (Figure 5.2, p.118). The voice also specifies which numeracy level they have now achieved, and some bonus ‘coins’ (as suggested by Sara, Chapter 4) animate into the bottom bar to increase the total figure. The aim is threefold: (i) to orientate the child, using language

familiar from their regular intervention sessions, reminding them what they have achieved so far, and how much further they still have to go; (ii) to reward the child's achievement, acknowledging that by thinking and working mathematically they have helped themselves to become secure in the current number range and component; and (iii) to motivate the child to want to play again, to achieve the next level and so improve their personal numeracy capabilities still further.

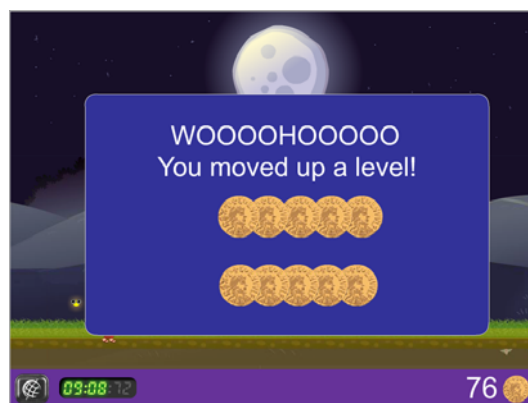


Figure 5.2

'You moved up a level' screen, shown as a consequence of completing a numeracy level.

Leader board and timer

Introducing the leader board mentioned earlier (Figure 5.1b, p.115) was also Sara's suggestion (Chapter 4). She liked the idea of being able to compete with her friends, as she did when playing on her family's Nintendo Wii games console. However, comparing the children's scores openly, even if only in friendly competition, undermines the safe learning environment and raises ethical concerns. For any child, academic progress and individual difficulties are a private matter, and should be shared only with the child's parents and teachers, particularly if that information has been collated by an automatic system over which the parents and teachers have no straightforward control. For children who have been identified as having a learning disability, the especially vulnerable children for whom the prototype game is being designed, sharing information about academic progress and individual difficulties requires even more careful thought. In addition, even if less sensitive information is

shared, such as the number of coins collected or the time taken to complete a game level, in other words game level scores rather than numeracy level scores, there are still practical issues to overcome. What happens for the first child in the school to play that game, or if there is only one child in the school to play the games? In those and similar circumstances, there would be no other scores against which to plot a leader board or compare progress.

Nevertheless, due to the positive impact of social competition on engagement in digital games (Howard-Jones & Demetriou 2009; Vorderer *et al.* 2003), leader boards can have a large motivational effect (Kapp 2012). In addition, incorporating a leader board can also provide players with both a measure of their current performance and a clear medium-term goal (to get to the top of the leader board) for them to pursue. For these reasons, a leader board was incorporated into the second iteration of the prototype game. It displays the child's name, the number of coins they have collected and the time taken to complete the game level (in minutes and seconds), along with similar scores against other names. It was designed to mirror the numeracy levels: the higher the child's current numeracy level, the higher their name appears on the leader board.

In other words, although it might seem otherwise, the leader board reflects the child's progress in the numeracy levels rather than in comparison to other children: despite appearances, it is criterion rather than norm referenced. This is achieved by drawing the other children's names from a pool of pre-specified names, they are virtual not real children, and by generating their scores (coins collected and time taken) dynamically, relative to the real child's score, so that the real child's name is always positioned in the leader board according to their current numeracy level. The key function of the leader board algorithm is to ensure that as the child progresses through the levels of numeracy attainment, so their name moves up the leader board. Meanwhile, the scores of the other 'children' are calculated relative to the real child's score, in order to have names above and below the real child's name.

As a consequence, the ethical and practical concerns mentioned earlier are side-stepped. No children's scores are being made publically available, because the other 'children' listed on the leader board are not real; and the real child only gets to see their own score. For the same reason, it also doesn't matter whether the real child is the only child in that setting to play the game, they will always have virtual competitors against whom to compare their progress. In addition, implementing the leader board in this way gives the child (i) a situated measure of their progress, one with which they are familiar from outside of the school context, their position on a computer game's leader board; (ii) a 'narrative striptease' motivational effect, encouraging them to play again in order to move their name up to the next position on the board; and (iii) an authentic medium-term goal for them to pursue, to get their name to the top. Moreover, it does so by using the informal language of computer games rather than the language of school. However, despite these putative benefits, presenting virtual competitors as real children is nevertheless a deception. The question is whether or not in this particular context such a deception is ethically acceptable (Kimmel *et al.* 2011).

Another additional feature in the second iteration was the timer (which can be seen at the bottom left of the screen shown in Figure 5.2, p.118), which again was suggested by the children in the first intervention. The implemented timer displays minutes, seconds and hundredths of seconds – the hundredths being included only so that there is a rapidly changing counter, to add a mild sense of urgency to the gameplay. The minutes and seconds taken to complete a game level appear in the leader board displayed at the end of that game level.

Remembered facts

As noted in the previous chapters, for the *remembered facts* component the intention was for the children to draw on previously learned and now *remembered facts*, rather than to make calculations. However, all of the children were observed to be counting the individual units that made up the blocks or ladders needed to negotiate the obstructions and using counting-on or counting-back techniques to calculate their

response (Figure 5.3a, p121). Accordingly, in order to prevent this counting-on and counting-back, in the second iteration of the game the graphics for the building blocks and target gaps were amended so that they no longer showed the individual units (Figure 5.3b, p121).

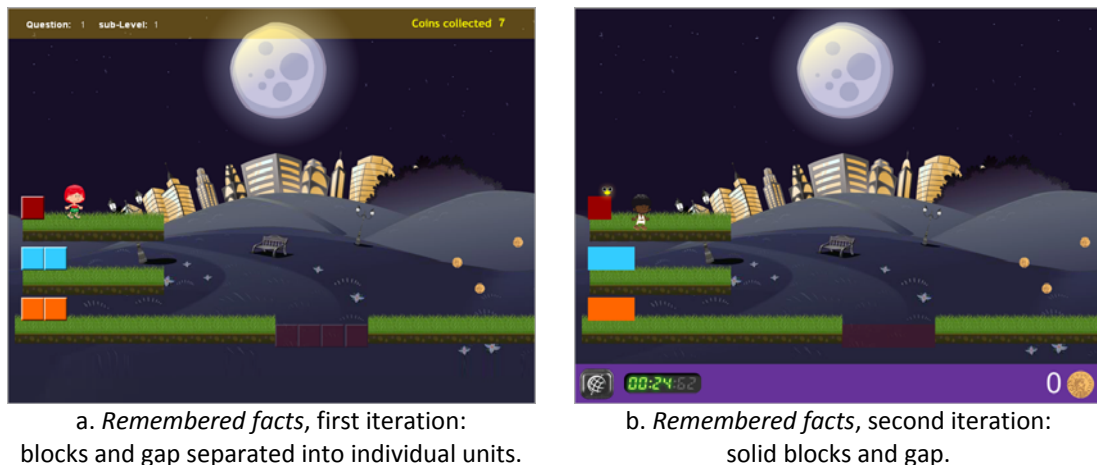
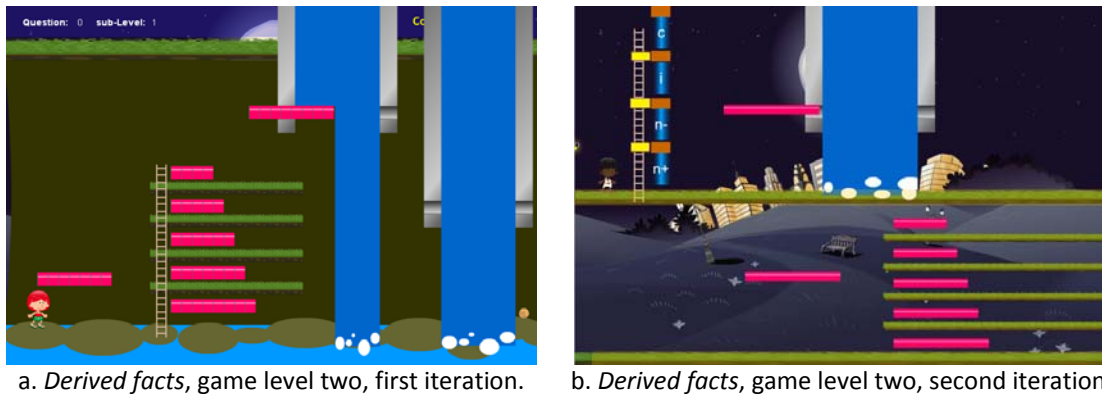


Figure 5.3

Remembered facts, first and second iterations.

Derived facts

As mentioned in Chapter 4, translating the *derived facts* principles into a digital game proved to be as difficult as feedback from teaching staff had suggested it might be. The approach adopted in the first iteration was to present two tasks either side-by-side or one above the other, with animating blocks representing both the completed/known fact and the uncompleted/unknown fact for the current calculation (Figure 5.4a, p122). However, partly because the intended hierarchy of the two animations was not always clear, and partly because the numeracy levels were relatively low for the participating children, they mostly calculated the answer to the unknown fact without any reference to the given known fact. In addition, as with *remembered facts*, the children were observed counting the individual units in the unknown facts, rather than deriving their response from the given known fact. Finally, working with *derived facts* also involves *identifying* which of the four *derived facts* principles applied in the current circumstances, but this was not addressed in the first iteration of the prototype game.

**Figure 5.4**

Derived facts, first and second iterations.

Accordingly, for the second iteration of the *derived facts* game levels, the game layout was rearranged in order to emphasise the hierarchy between the known and unknown animating facts (although this is not clear from the static image shown in Figure 5.4b, it is more so in the fully animated screen). In addition, as with the *estimation* game levels, to prevent counting, the building blocks were amended so that they no longer showed the individual units.

However, the most noteworthy change in the *derived facts* game levels is the introduction of a new barrier that has to be overcome before the child can tackle a main task (visible at the top left of Figure 5.4b). This addition was prompted by Kath, who mentioned that for the *derived facts* component it would be very useful to give the children practice in identifying which of the four principles applied in the given circumstances. She suggested that, after the children had completed a *derived facts* task correctly, they might be given a large bonus virtual coin labelled with the relevant *derived facts* principle. However, in discussion it was agreed that it would be better if the children had to identify the principle before they tackled the task rather than afterwards. The new *derived facts* barrier was introduced to ensure the children did exactly that. The barrier comprises a column of four doors, each representing and labelled for one of the *derived facts* principles: i (identical), c (commutative), $n+$ and $n-$, all terms familiar to children who are participating in the numeracy intervention. In order to pass the barrier, the child first has to (i) consider the known and unknown

calculations that they can see animating beyond the barrier, (ii) identify which derived fact principle is being illustrated, and (iii) climb to, and click to choose, the relevant door. If the child chooses the door that matches the *derived facts* principle illustrated in the animations, the door opens, the avatar can pass, and the child can tackle the given task.

Screen layout and task permutations

Extending the prototype game as described earlier, to include the first six numeracy levels, numbers up to 20, also had an impact on the screen layout: targets and objects now had to be dynamically resized to as much as 20 units wide, rather than the maximum of 10 units required in the first iteration. This is why the *derived facts* target gushing water pipe does not appear in Figure 5.4b, p122; it is off the right-hand edge of the screen, giving the first water pipe sufficient space to resize so that it might accommodate numbers up to 20. Dealing with this practical complication was difficult for the developer. How should they design the screen layout to cope with the larger numbers while ensuring that screen objects can easily, that is to say with minimal screen scrolling, be seen and compared?

Extending the number range also required a different approach to generating the numbers used in each task. With the smaller number ranges implemented in the first iteration, it had been relatively straightforward to write every permutation. Given that the terms and the answer for each number sentence all had to be within the number range, there were relatively few possibilities. For example, for *remembered facts* at numeracy Level 1, that is to say with numbers up to 5, there are twenty possible number sentences: $1 + 1 = 2$, $1 + 2 = 3$, $1 + 3 = 4$, $1 + 4 = 5$, $2 + 2 = 4$, $2 + 3 = 5$, their commutations (for example, $4 + 1 = 5$), and their subtraction equivalents (for example, $4 - 1 = 3$). However, when the number range is extended up to 20, the combinations multiply exponentially, to give a total of 380 permutations. In addition, for each task either one distractor or a range of distractors, depending on the component, had also to be specified, all within the number range for the current numeracy level, while avoiding duplicates and alternative correct but unwanted options (for example, for the

task $1 + 2 = 3$, 4 could not be a distractor because $4 - 1$ also equals 3). As a consequence, for the second iteration, instead of drawing up a comprehensive static list of possible tasks, the developer devised what proved to be a complex algorithm for each component, to automatically generate a random but appropriate number task and appropriate distractors for the current number range.

Customizable avatar and companion

In addition to the suggestions made by the children that have already been mentioned as implemented (the leader board, the timer and the bonus coins), two other new features were also developed specifically in response to requests from the children. The first of these was also, like the earlier suggestions, clearly inspired by the children's experience of entertainment games: the ability for them to configure their avatar, that is to say to personalise their player character by choosing alternative features. Accordingly, the second iteration included a facility to allow the children to customise their player (Figure 5.5).

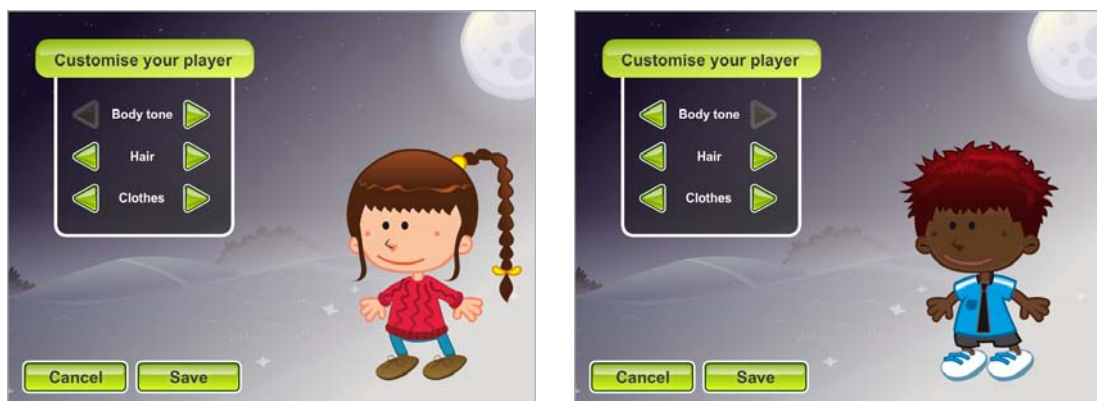


Figure 5.5
'Customise your player' functionality, example customisations.

The available choices included three body tones, twenty-three types of hair, and seventeen styles of clothing, giving over a thousand possible individual permutations. Once the customised player is saved, this is the avatar that the child uses each time that they play the prototype game.

The final feature suggested by the children and implemented in the second iteration was a learning companion (Chan & Baskin 1988; Johnson *et al.* 2000; Kim 2007), “*a friend to help you*” play the game and engage with the mathematics (Christopher). However, because of limitations in available resources, the implementation of the companion was somewhat minimal: it comprised only a small glowing globe (just visible in Figure 5.1b, p.115, above and to the left of the avatar) that did nothing other than follow the avatar around the virtual environment. The original intention was for the companion to offer guidance at appropriate times in the gameplay; resource restrictions meant this had to be left for the final iteration of the game.

5.2 INTERVENTION

This second intervention, which took place in three primary schools, built upon the outcomes of the first research cycle. Unforeseen outcomes of the first research cycle, the critical role of the supporting adult and the importance of the conversation centred on the game, shifted the anticipated emphasis of the second cycle of this research. Rather than continuing to be centred on the game itself and how that game is played by individual children (as discussed in Chapter 4), this second research cycle instead refined that focus to consider how the game was used as a fulcrum for social interaction and discussion between the child and supporting adult.

The intervention involved 15 children and 8 adults, from three schools (Table 5.3).

Table 5.3

Research cycle 2: intervention participants.

Participants	School 1	School 2	School 3	Total
Adults	2	3	3	8
Children	4	6	5	15

Context

The intervention took place between September 2011 and March 2012 at three of Orange Hill's feeder primary schools: Frieth Church of England Primary School (hereinafter, Frieth), Spinfield Primary School (Spinfield), and Lane End Church of England Primary School (Lane End).

Primary schools (schools that cater for children aged 4 to 11 years) were selected because the prototype game was designed to complement the numeracy intervention which is mainly for children who are low-attaining in mathematics of primary school age. Three schools were selected in order to optimise the balance between collecting sufficient data, to achieve a level of data saturation, and achieving sufficiently rich data, 'thick descriptions' which would facilitate a comparative analysis. The three particular primary schools, Frieth, Spinfield and Lane End, were selected because they had good connections with Orange Hill, they had some familiarity with the numeracy intervention, and within the context of Lane End, as described next, they were differentiated. Introductions to the three schools were made by Orange Hill's Literacy Coordinator.

Within the micro-context of Lane End, described in Chapter 5 as a small commuter town which predominantly comprises well-off families with mortgages, the three participating schools might be characterised in terms of the liberally-interpreted designations 'town centre' (Lane End), 'suburban' (Spinfield) and 'rural' (Frieth). Lane End school is situated in the centre of Lane End, in a cul-de-sac of Victorian terraced houses, only about 100m from the main shopping street. It has 200 children. Spinfield is a much larger school, 500 children, which is located in the modern estate of detached and semi-detached professional homes that constitutes the south-western part of the town. Frieth is the smallest of the participating schools, 100 children. It is located in the village of Frieth, about two and a half miles outside of Lane End.

The children who attend the three schools and their achievements (Table 5.4, p.127) broadly match expectations suggested by the way in which each has been designated: 'town centre', 'suburban' and 'rural'. The three primary schools have similar numbers

of children who have special educational needs, numbers close to the national average, but they differ noticeably in terms of other measures of disadvantage (all data derived from the Department for Education 2010, 2011a, 2011b, 2011c, 2011d, 2011f). Whereas only 4% of children at Frieth (the ‘rural’ school) and 1% of children at Spinfield (the ‘suburban school’) are on Free School Meals (FSM), the proxy measure of pupil deprivation collated by the Department for Education, which is considerably lower than the national average, the FSM number at Lane End (the ‘town centre’ school) is 15%, which is virtually the same as the national average. Lane End is also the only school of the three to have a sizeable number of children who have English not as their first language, although still only half that of the national average.

Table 5.4

Participating schools, summary data, 2011.*

	Orange Hill	England	Frieth	Spinfield	Lane End
Children who have a Special Education Needs statement or who are on School Action Plus	6%	8.5%	7%	4%	5%
Children eligible for free school meals (FSM)**	5%	16%	4%	1%	15%
Children who have English not as their first language	1%	12%	0	1%	6%
Children who achieved Level 4 in both English and mathematics in the KS2 tests (taken at age 11)	N/A	82%	86%	96%	66%
Children who achieved the expected progress in English	N/A	85%	50%	96%	79%
English value added (VA) score ***	N/A	100	99	101	99
Children who achieved the expected progress in mathematics	N/A	83%	71%	97%	58%
Mathematics value added (VA) score ***	N/A	100	99	101	98

* Data derived from the Department for Education (2010, 2011a, 2011b, 2011c, 2011d, 2011f).

** FSM is the proxy measure of pupil deprivation collated by the Department for Education (DfE 2012).

*** The VA scores compare individual children’s progress between KS1 and KS2 with that for children nationally who were of the same level of ability at the end of KS1. Based around 100, the VA score indicates the ‘educational’ value that the school has added on average to the children. (DfE 2011e)

The children's average achievements also differ between the three schools. Whereas the children from Frieth ('rural') and Spinfield ('suburban') out-performed the national average in the English and mathematics KS2 tests taken at age 11, only two-thirds of the children at Lane End ('town centre') achieved the Level 4 standard, which is considerably lower than the national average. The numbers of children achieving the expected progress in English and mathematics showed even greater variability. More than 95% of the children, higher than the national average, from Spinfield achieved the expected progress in both English and mathematics. However, at both Frieth and Lane End, fewer children than the national average achieved the expected progress: with Frieth children performing much better in mathematics than in English, and Lane End children performing much better in English than in mathematics (some of this variability is likely due to a statistical artefact caused by the much smaller number of children in these two schools). Nevertheless, despite this variability in achievements, all three schools achieved about average 'value added' scores (the 'educational' value that the school has added on average to the children, DfE 2011e) in both English and mathematics – which suggests that the lower achieving children at the end of KS2 (when aged 11) in Frieth and Lane End started out, for indeterminate reasons, as lower achieving children in KS1 (when aged 6).

At the time of the intervention, all three of the schools had only recently become acquainted with the numeracy intervention. They each used teacher observations, classroom lessons and informal assessments to determine which children were low-attaining in mathematics for whom the intervention might be suitable: typically, this meant which children were working in mathematics at a level more than six months behind their Chronological Age.

Sampling

Once the participating schools were sampled purposefully, as described above, individual participants were selected and invited to be involved in the study by their school: the teachers because they had responsibility for the classes from which the participating children were drawn; the classroom assistants because supporting the

children in those classes who were low-attaining in mathematics was part of their usual responsibilities; and the children because the schools' Special Educational Needs Coordinators (SENCOs) or Deputy Headteachers or the class teacher had identified them as low-attaining in mathematics and believed they might benefit from participating in the study. Other criteria used by the school when identifying the participants included: school policy, the numbers of children previously identified as being low-attaining in mathematics, timetabling, and staff availability. The aim was to involve in the intervention the teachers, classroom assistants and children who were most likely to have used the prototype game had it not been part of a research study but had been introduced to the school for a more conventional reason.

Methods

The intervention included three complementary data collection methods (Table 5.5): non-participant observations, with field-notes taken during and immediately afterwards; semi-structured interviews of the participants (using interview guides, Appendix C), and a questionnaire (Appendix D) which was used mainly to stimulate in-depth supplementary questions.

Table 5.5

Data collection methods used in the second research cycle.

Data collection methods	Notes	Participants	
		Adults	Children
Observation	Non-participant observation	✓	✓
Field notes	Written notes taken during and immediately after the observation	-	-
Interviews	Semi-structured Face to face Audio-recorded Pre- and post-intervention	✓	✓
Questionnaires	Paper based Lickert scale responses and text answers Pre- and post-intervention	✓	✓

The intervention proceeded as follows. Interviews were conducted with the schools' Special Educational Needs Coordinator (SENCO) and/or teacher who had agreed, on

behalf of the school, for the staff and children at the school to participate in the study (all the individual participants also gave their informed consent, and all interviews were recorded). They were asked about, for example, their reasons for agreeing to be involved, the needs of children who are low-attaining in mathematics, their experience of using game-based learning in the classroom, and their expectations and hopes for the study. Interviews were then conducted with the classroom assistants, one or two in each school, who usually provide numeracy support under the direction of a teacher for children who are low-attaining in mathematics. These classroom assistants were going to be taking responsibility for 'managing' the children's use of the prototype game. The interviews discussed the individual characteristics, needs and numeracy capabilities of the children who would be participating in the study, the classroom assistants' own confidence in providing effective numeracy support, and how that support is implemented in the school. Each classroom assistant was then given a brief introduction to the games (lasting around fifteen minutes): how to access the game, the use of the login and passwords, how the children could access the game at home, the game's key features, and how those features related to the numeracy intervention.

Interviews were conducted with each of the participating children (in the presence of their teacher or classroom assistant) about their experiences of learning mathematics and of playing computer games (parental permission had been given for each of the children to be involved; and the study was explained to the children, who all consented to be involved). The children were then asked questions about their attitudes to learning. This was structured by a questionnaire (Appendix D) and 'smiley face' Lickert scale (Appendix E) which were used mainly to stimulate supplementary questions.

The teachers and/or classroom assistants were asked to use the prototype game over the following weeks with the children for whom they provided numeracy support. There were no restrictions put on how the game could be used; with the agreement of their teachers, the classroom assistants could use the game in ways that complemented their usual support, taking into account any factors that were important in their school (such as timetabling and access to computers), or in any

other way that they saw fit. There were also no restrictions put on the amount of time. Instead, the children could play the games as often or as infrequently and for as long as the teaching staff deemed appropriate. However, based on the outcomes of the previous intervention, it was recommended that only one or at most two game levels were played in any one session. Over the following weeks, email support was provided when required, which in practice meant only occasionally.

In various visits to the schools, the children's use of the games and the interactions between the classroom assistants and the children were observed. Unlike in the first intervention, which used participant observation, here every effort was made to remain somewhat separate from the scene being observed in order not to impact too much upon it: there was no intervention and no conversation with any of the participants during the session being observed. However, given that all the participants were aware that they were being observed, inevitably the observation must have had some impact on what was being observed, although nothing substantive was noted. Observations were recorded by means of field-notes supplemented with additional notes made once the sessions were finished.

Once it was clear from email conversations that the school staff believed the children had spent enough time using the games, the schools were visited again and follow-up interviews were conducted with each of the participants, children and classroom assistants, about the prototype game and their experiences of it. Follow up interviews were also conducted where appropriate with the teacher and/or SENCO. Finally, analysis of the data proceeded as outlined for the first research cycle.

Outcomes 1: Lane End

At Lane End, designated here the 'town centre' school, the use of the prototype game was overseen by Ben, a teacher and the school's SENCO, who was assisted by Hannah, a classroom assistant. Four children, all of whom were known to be low-attaining in mathematics, participated: Kaitlin and Sam, both of whom were in Year 6 (aged between 10 and 11 years old), and Christian and George, Year 5 (aged between 9 and 10).

Ben found it difficult at first to arrange for the children to be able to use the games, *"it's just the logistics of us fitting it in, not to do with the game but to do with personalities in the school; I'll say it needs to be done and [my colleagues] ignore me"* (Ben). Budget constraints meant that fewer classroom assistant hours were available to support activities outside of the classroom, while his own SENCO hours had also recently been cut. The solution was to arrange for the children to use the games as a group activity, in the ICT suite, for about ten minutes, three times a week, supervised by Hannah. They were usually taken out of their classes during 'early work' (the fifteen minutes or so following registration, first thing in the morning, during which the teachers prepare their class for the day's learning activities, and the children complete outstanding pieces of class work), *"it's a good time for them to do one level [of the game]..., although they're missing part of their lesson, it's the early work, they're not going to miss teaching time..., although some schools might not be able to get into the ICT suite at that time of day..., personally, I think maths is good first thing in the morning as well, because it gets them set up for the day, as well..., gets their brains working"* (Hannah). This approach was not possible every week, because of other things that were going on in the school, and so Ben occasionally supplemented the children's time with the game, taking them to the ICT suite when he was able to fit it into his other commitments and the children's timetable, *"we can just go into the ICT suite, it takes me two minutes to get the computers going and to get to the website, the children come in, sit down, log in and away we go..., it means we don't have to have buckets of resources lying around"* (Ben). The children were also encouraged to use the games at home.

The ICT suite, where the children played the prototype game, one child per computer, and where all the observations took place, is a large but sparsely furnished room, containing approximately twenty computers sited around the walls and several empty tables in the centre. The children playing the game sometimes had to share this space with other children, who would be engaged on a different task supervised by another member of staff. On these occasions, even though mostly all the children were only whispering to one another, the room could become noisy, partly because of the many computer programmes being used but also because the children's whispers were the loud stage-whispers that you might expect from children who are supposed to be quiet but who are enjoying what they are doing together. At such times, it could be difficult for Hannah or Ben to have a proper conversation with their group of children, who thus concentrated more on their own individual gameplay. Mostly though, especially during the 'quiet time' morning sessions, the four participating children and Hannah or Ben had the room to themselves, which allowed much easier and more free-flowing conversation between all of them.

At the time of the last observation, Hannah also mentioned that she'd like to use the game in the lunchtime library club, *"I think they would choose this game instead of Kung Fu..., not all of them, but a lot of them would..., someone like [Christian], he really enjoys coming out here and doing these games, [Sam] wanted to do it at home, so..., they'd use their free time to do it"* (Hannah). In any case, Ben explained that he intended for the children to continue being withdrawn from 'quiet time' to play the games for some more weeks, for as long as they continued to move up in the numeracy levels.

Kaitlin

At the start of the intervention, Kaitlin was described both as lacking in confidence and being very disengaged, *"when it comes to numeracy, she just shuts down"* (Ben). According to Ben, usually she was unwilling to talk about mathematics, whether in the classroom or one-to-one, which made identifying exactly what she found difficult and her specific needs especially challenging. Nevertheless, when she was asked, Kaitlin

said that she enjoyed doing mathematics, other than when she was called upon to answer out loud in class, where she was often embarrassed by the fact that she could not get the correct answer quickly enough.

Kaitlin enjoyed playing the prototype game, customising her avatar, collecting coins, unlocking the game levels and being able to choose between them. She also enjoyed discussing the games and the mathematics, both with Hannah and with the other children, especially when she was asked by Hannah to help the other children when they got stuck. Kaitlin also believed that playing the game, working with larger and larger numbers, was helping her with her mathematics, *“I think it helps people like us lots, because it helps you with your maths and adding stuff, taking away, and just keep doing levels will help..., if you get that question in class, you get the answer straightaway..., I think it helps you more if you get like higher numbers, it will make your brain work more”* (Kaitlin). Seeing her name move up the leader board provided another boost to her self-confidence, although she could not understand how some of the other names on the board, whom she assumed were real children, could finish the level so quickly (which is to say the leader board algorithm failed to generate wholly credible times). Kaitlin also enjoyed showing off her skills in the game to her brother and mother at home, *“I was doing my maths with my mum and I showed her the games, and she thinks it’s good because it helps with maths; she watched when I played”* (Kaitlin). However, despite her new-found confidence, and her noticeably improved numeracy skills, Kaitlin still has some way to go, *“I know Kaitlin still struggles..., she still doesn’t make the connections”* (Ben).

Sam

Sam also was lacking in self-confidence; a very quiet boy, who also rarely contributed in class. Consequently, Ben would spend large amounts of time with him, looking through his work and discussing it with him. Sam explained that he enjoyed doing mathematics, although he much preferred working out calculations on paper rather than in his head, and he worried when he found the mathematics too difficult. A particular weakness of Sam’s, according to Ben, was his unwillingness to take

responsibility for his own mistakes. For example, when he was unable to solve a mathematical problem he would blame something else *“it’s not me!”* or he would argue that *“I don’t need to learn these things”* (Sam quoted by Ben).

Sam was a keen computer-gamer, who mostly enjoyed playing the games with his mother; he believed that a computer game could help you with your mathematics. He liked the prototype game for all the same reasons as Kaitlin, despite bringing his *“it’s not me”* attitude with him, *“[George] will say, no you do this, and he’ll say, I’ve done that, it doesn’t work, and I’ve watched him and he hasn’t..., it’s very much it’s the game that’s wrong, not me”* (Ben); although with the prototype game at least he was usually keen to learn what to do. Sam also used the game at home, *“which has been working fine, because at home if I get a little stuck I can ask my mum for help or my dad..., sometimes if my mum’s not busy she’ll sit with me and help me, she thinks that it’s quite good that I use it, but if she’s busy and my dad’s busy then I’ll do it on my own..., I prefer doing it with my mum or my dad but sometimes it’s quite good to do it on my own”* (Sam).

While Sam found some of the prototype gameplay difficult to understand and would have liked the game to have included multiplication and division, *“if it were a little harder, it would be even better”* (Sam), he thought that playing had helped him in his classroom mathematics, *“they’re quite fun to do because they’re not too difficult..., playing them a lot helps me remember the answers, they help me remember in my class..., when someone asks me a question, I just think of the game and then think of the answer, the answer comes into my head”* (Sam). Ben agreed that Sam had made good progress, *“His ability to make a judgement has improved, his confidence to say ‘no, that’s wrong’..., in class he’s willing to put his hand up and to engage and talk about numeracy..., now he’s starting to understand, and he’s seen this as a tool that helps him do that”* (Ben).

Christian

Unlike the first two children, Christian when questioned appeared to be very confident in his mathematical abilities. Ben confirmed that Christian was mostly willing to

participate in classroom mathematics but noted that his apparent self-confidence was misleading: usually he would avoid any mathematics that looked even remotely challenging, and very often, when he was unable to avoid the calculations, he was unsuccessful. It was for this reason that Hannah worked with Christian, sat with him and supported his learning, most days in class.

Christian's views about computer games and learning were also notable. While he strongly claimed that game playing most often involved learning, *"you can play games and you can also learn, you get to have fun and you get to learn something"*, he thought that computer games had no place in the classroom, *"because they're playing"* (Christian). All the same, Christian did seem to enjoy playing the prototype game, for the same reasons as the first two children, but also because he liked trying to beat his best times, *"the timer is quite helpful, because then you see it, then you challenge yourself to beat it next time, so that's quite good"* (Christian). He also thought the game levels had helped him with his mathematics, *"they are good because they get brains working, you have to move around where you're going with your fingers, and you learn the calculations in it..., I found the questions harder before but easier now, because I'm starting to get used to them"* (Christian). Ben was impressed by how quickly Christian took to the game, *"Christian is flying through it, his attitude to it..., you can see he's thinking it through"* (Ben), and by how he was learning useful mathematical strategies, *"he can see straightaway from the first [sub-task], this is how you solve this problem, straight onto the second one, it's the same problem again, just slightly different"* (Ben). This, in turn, Ben believed, has had a positive impact on his work in class, *"his attitude has improved..., I've spoken to his teachers and it's interesting to see how he's been doing in class"* (Ben).

George

Although George's learning problems are not severe, they are complex, *"I've never got to the bottom of the issue..., he's not stupid, but very difficult to understand..., he's making progress, but below level, but simple things that we take for granted he seems to struggle with"* (Ben). Ben also believes that the regular one-to-one support George

has received has been a mixed-blessing, *“he knows things, and he knows he knows..., but it’s that adult-assisted learning, sitting next to him for so many years, telling him this is where you need to go, that he almost doesn’t bother..., he knows but he’s waiting until someone tells him”* (Ben). George’s slow progress in mathematics meant that he usually did get adult support in class; he explained that he found mathematics difficult, which made him worry, although when he got the right answers, that made him very happy.

George also enjoyed playing the prototype game, for the same reasons as the other children, especially because of the timer and leader board. He also found discussing the games helpful, *“I asked for help once..., a few times..., it’s good to chat with our friends because if they’re stuck on a question but I know it, we can help each other..., I think that helps people to learn..., if I get stuck, and [Christian] helps me, I like that, and sometimes I help them, and I like that”* (George). In any case, George believed that playing the game had helped his mathematics, *“you look at one question, if you work it out, you keep practising it, until you get it stuck in your head and won’t come out..., practice makes it easier..., this is a good way to practise, I think..., and they’re helping me with my numbers, like eight and nine and stuff like that..., I keep forgetting the answer, playing the games helps me remember the answer..., if I have to do the sum seven plus two, the answer pops into my head, when it pops in my head it makes me feel quite good”* (George).

George did not make as much progress as the other children, his frequent mistakes meant that the game was still serving him low numbers, nevertheless both Ben and Hannah were pleased with what he had achieved, *“I would say with [George], definitely the game has improved his maths, because of the way he works and the way he thinks..., strategies when he approaches the problems are becoming better..., in class he’s now scoring about eighty percent right, and he’s doing up to ten questions, even more sometimes, whereas previously he’d do three or four questions and get the majority of those wrong..., it’s quite a drastic improvement, in some ways”* (Ben). Ben also valued the opportunity to observe George’s learning afforded by the game, *“it’s useful getting him to explain things, because he’s got to engage with me, he usually*

avoids engaging with anyone..., it's instant as well, so I haven't got to sit with him and watch him write, so it's quite nice, it's refreshing..., you can engage with him on a level where previously you'd start pulling your hair out" (Ben). The game also, Ben argued, prevented George waiting for someone else to make decisions things for him, *"with this, there's no escaping, he's got to do it"* (Ben).

Other outcomes

Apart from the occasional crashes, *"it sometimes freezes when you get to the end of the level"* (George), and questions around the mute companion, which if it gave advice *"would help you, because if you get stuck, you don't know what to do"* (Kaitlin), the prototype game was received positively by all the participants. All of the children enjoyed playing the game, *"if I said to them, OK, we're going to go into the classroom and do some numeracy, they'd sigh..., whereas if I say, we're going to go to the ICT suite and [play the numeracy games], they're 'ah, when?'"* (Ben). However, coming out of the classroom was not without issues, *"I think it's nice to come out of class and play the games but it's also good to learn what the teacher says..., sometimes I miss what's going on in class"* (Sam). Nevertheless, all the participants believed that the children's mathematics skills had improved, *"I think it's helping them with the simple concepts so that they can apply to the more difficult calculations later on..., it's getting them confident at the lower levels, plugging gaps"* (Hannah).

The way in which the various features of the prototype game reflected entertainment games was seen as key, *"the fact that they can collect these coins, be part of a table at the end, it's achievement..., it's 'I got to the top of the table', the competitive aspect of it..., just like a Sonic game..., that's what they're used to, with all the collecting coins..., they're prepared to put up with the maths because they're enjoying the game"* (Hannah). Using the entertainment game format also made the repetition, designed to help make the facts and skills automatic, acceptable, *"it's a lot of repetition but they don't know it's repetition, they don't think 'oh no, it's this one again'..., they just feel confident, I know it now, which if you were repeating it on a piece of paper, it really wouldn't work"* (Hannah). The game format also, Ben argued, helped to reinforce the

benefits of a systematic approach, *“when you’re playing a platform game, you pick up skills in level one, and when you get to level two you learn a new skill, and reapply the level one skill..., and when you get to level three, you use level one and level two and you learn a new skill..., that’s life, it’s scaffolding..., I’m using the game as a way of reinforcing the process..., I think, getting the methodology is coming through, being systematic is coming through”* (Ben).

Ben also suggested that the game had helped the children address their fear of failure in mathematics. For example, recently in class, Sam *“put his hand up to answer something, got it wrong and you can see his face drop..., and straightaway he went, ‘no it’s this’ and he told me the answer..., I said to him later, that’s pretty good because you actually recovered and told me the right answer..., you got it wrong, you recognised you got it wrong, then you had the confidence to say, ‘no, this is the answer’..., and maybe that’s a little tiny change, what failure is and how I can get over it..., because with the games, if they don’t get it right, they go straight back and start again..., there’s a consequence, but it’s not a fatal one and it’s not an embarrassing one”* (Ben).

With this group, the inclusion of the three sub-tasks (concrete objects, labelled concrete objects, and symbolic) received a mixed reception. George for one did not like this aspect of the game, *“I think they need to be a teeny bit more mixed up, because I’ve had like, keep having one question, different types, then another question, then it keeps going on, another question, it’s a bit boring..., maybe halfway you could swap to another question”* (George). Others were more positive, *“doing it with the objects helps you to get to do it with the numbers”* (Sam), *“I like the way it’s blocks, then blocks and numbers, that it varies between graphic and actual number there, I like the way that they do that, and I can see what the children understand about numbers”* (Hannah). Meanwhile, of the children, only Kaitlin and Sam appeared to have noticed that *“what they play doesn’t matter because the numbers are going up in the background”* (Ben), that the numbers got progressively higher, the more often they played one of the components, whichever game level they chose, *“once you get used to the numbers, you get the bigger numbers and you get used to them, that’s been*

useful” (Kaitlin); “I think it’s quite good that the numbers get bigger because it helps you learn different maths questions with bigger numbers..., I’m beginning to remember some of the answers” (Sam).

Ben and Hannah both noted what they thought to be important differences between working on numeracy in class and using the games as a group activity, *“when you’re in class, it’s not quite the same..., when they’re using the game, they’re distracted and they’ll just talk about the maths, but if you’re in class with some cubes or something, it’s not quite the same”* (Hannah). On the other hand, Ben found that the games demanded a different teaching approach, *“I can’t model, same as if it were a normal calculation we were doing in a classroom, I would go over and discuss it and I would model...; [with the game] because it’s on the screen, it’s different, it usually starts, ‘well what did you do?’, ‘what was the previous calculation, how did you solve that?’, and then they think, ‘OK I did this, this and this’, and they try to repeat that process..., so it’s getting them to think what they initially did and how that helped them solve this”* (Ben). Inevitably, Ben thought, this impacted on the teacher/student relationship. In particular, it would prevent those children who usually waited for the adult to do the work for them from depending on that level of support, *“it changes that dynamic, that relationship between us..., the object is to solve the problem, but you or the [classroom assistant] will usually write the answer for me..., it takes that away..., they can’t get away from actually working the calculation out themselves..., it’s quite interesting”* (Ben).

Fulcrum for social interaction and discussion

A key outcome of the first intervention was the re-imagination of the prototype game as a fulcrum for social interaction and discussion. The contention here is that while the characteristics of the game, how it implements learning theory in the medium of gameplay, are critical, of perhaps equal importance is the way in which the game facilitates educationally meaningful conversation, between the children, and between the children and the adults.

At Lane End, the pragmatic decision to use the games as a group activity meant that there were lots of opportunity for educationally productive conversation, centred both on the gameplay and on the mathematics. While they logged onto the online system and then played the game, the children chatted, giving each other support, exchanging ideas and strategies. Often the children would talk about the gameplay, the animations, moving the avatar and collecting coins. At other times it would be a conversation about the mathematics: how particular tasks might be answered, what mathematical strategies they had found to be effective, and how the different tasks related to one another. Especially during the observations that took place at the start of the school day, this fragmented conversation continued throughout the session, *“when they’re in here they do like to chat amongst themselves, about what they’re doing, they do like to share, they do like to ‘oh look, I’ve got there first’, whereas if they’re on their own, it’s not quite as much fun, I think..., they have been enjoying the fact that it is a group together”* (Hannah).

Sam, for example, valued being able to ask the others for help, rather than having to ask one of the teaching staff: *“if there’s something you don’t understand, and they understand it, you could ask them..., it’s more helpful than getting a teacher to help..., I was just asking on that when you’re supposed to collect the key, the first time I played it I didn’t understand so I just asked [Kaitlin] what you’re supposed to do and she told me and I got it right* (Sam). On other occasions, the child who earlier gave support might themselves need some support, *“[Kaitlin] for example, had been stuck, I’d rather one of the other ones help her, so they’re learning together, so it’s a peer thing, rather than a teacher coming”* (Ben). Nevertheless, even the children acknowledged that the balance of the conversation, between the game and the mathematics, was important, *“it depends what we’re talking about, if we’re talking about the maths it helps, if we’re talking about something else...”* (Kaitlin).

All the while that the children played and chatted, the adult moved around behind the group, monitoring carefully what they were doing, and interjecting as they saw fit, *“I just try to hover around, I’ll just now and again mention something..., I’m not with them all the time, so they can just get on with it, in their own way”* (Hannah).

Sometimes they offered guidance, *“‘what do you think you should be doing here?’, get them to pause and think for a bit, helping them to progress from there”* (Hannah). Sometimes they asked a child to explain what they were doing or to think through their strategies out loud, *“it’s nice to hear what they are learning while they are doing it, just for them to reinforce it by speaking to me, about what they’ve learned from it..., I think if they can explain something to you then that’s just reinforcing the learning that they’re getting from the game and from the maths questions that they’re doing”* (Hannah). And while some of the children progressed without much support, this gave the adults time to focus on those children who found the mathematics more challenging. George, for example, found the individual attention especially helpful, *“because I was wondering how to do this question when there was no numbers, and [my teacher] said what was the number for the last one..., he was getting me to think a different answer..., it helped me, because if someone gave me another problem like that I would be able to find it easier, to work it out”* (George).

As well as reinforcing the children’s learning, getting them to articulate what they were doing also helped Hannah to understand their thought process, *“the games have helped me learn about the children’s learning, because I’ve talked to them and asked ‘what does that mean then?’ or ‘what is that they are asking you to do, with their calculations’..., I think when the child can tell you what they’re doing, or tell another child..., it’s finding out what’s going on in their mind as well, rather than just see what they’re doing in the game”* (Hannah). Ben had a slightly different approach. He spent more time just observing the children, watching their faces as well as their hands and the screen, as well as asking them about why they worked through the problems as they did, *“they were really getting into it, really taking to it, and I could see the impact and the implications of that..., ‘so do you know what you’re doing?’, ‘yes, I’m doing this, this and this’, it was very interesting to hear what they were thinking”* (Ben).

Outcomes 2: Spinfield

At the second of the three participating schools, Spinfield, designated here the 'suburban' school, the intervention was facilitated by the school's SENCO, Mary. Two other members of staff, Alison and Steve, took responsibility for using the prototype game with the children. During that academic year, Alison and Steve shared the teaching of a Year 3 class (for children aged between 7 and 8), alternating between the roles of teacher and classroom assistant. However, all of the information about the prototype game being used in Spinfield, from the adult's perspective, was provided by Steve. Although Alison participated in a first interview and used the game with two of the children, without giving any reason she chose not to take part in a follow-up interview.

Six children, all of whom were known to be low-attaining in mathematics, participated in the intervention, all from Year 3: John, Evie, Grace, Jason, Darren and Michael (aged between 7 and 8 years).

Unlike Lane End, Spinfield does not have an ICT suite; instead, most classrooms are equipped with a number of computers. The nearest to a dedicated ICT space is the wall-mounted workbench that runs the length of the corridor outside the three Year 3 classrooms, on which are six additional PCs. This is a busy space even during lesson times: staff members are sometimes working at the computers, children are sometimes working with classroom assistants, and the corridor has frequent foot-traffic.

Withdrawing Year 3 children who are low-attaining in mathematics from their classes, to receive thirty minutes of one-to-one numeracy intervention once a week, was a well-established practice at the school, with Steve and Alison taking turns to provide the individual support. Usually adult and child would sit outside the classroom at the workbench, where they would complete various mathematics activities according to the adult's understanding of the individual child's needs and/or what they were being expected to do in the classroom. Given the public nature of the corridor and the level

of ambient sound, during these individual sessions the classroom assistant and child would sit close to one another, their conversation held in hushed voices.

This also mostly characterised the way in which the prototype game was used. The children were taken out of their class in turn, for their weekly one-to-one mathematics support session at the workbench, where they played parts of the game for most of the available half-hour; throughout, the adult gave support and guidance. The children were not given the login and password details needed to play the game at home.

In fact, despite repeated requests, at Spinfield it was only possible to observe one member of staff, Steve, using the games on one day, six weeks after the start of the intervention, with two children, John and Evie. It later transpired that these sessions used the game only for the researcher's benefit; by that time, at Spinfield, the game had long been abandoned. During these two observed sessions, and unlike at Lane End where the game play was often accompanied by much excitement and animated conversation, Steve and the child sat close to one another, working and speaking very quietly, voices slightly raised only when they found something particularly frustrating. Steve got the game going then watched the child play, interjecting only when the child was unable to proceed, which happened sometimes because of the mathematics but mostly because of difficulties with using the game itself; perhaps the children were less familiar with platform games, than the children from Lane End, because of their younger age. More than once, Steve was unable to work out what was needed, so the game was abandoned and another one selected from the menu.

Steve

Steve's expressed intention was to use the prototype game each week, over a period of a couple of months, during one-to-one sessions. However, for a variety of reasons, each child only ended up playing the game once or twice, *"to be honest with you, after a few weeks of having a go, I stopped using it..., it was disappointing for us because we were all keyed up"* (Steve).

According to Steve, the main problem at Spinfield was that the game simply did not work, *“I’ve not enjoyed using it, because of lots of problems about the way it runs, freezing, the children have found that frustrating as well..., they get half-way through a programme, then it will freeze..., they have to go back to the beginning..., so that’s the first turn-off really, because if you’re going to use something like that, it’s got to work..., my colleague [Alison] has been using it as well, completely different day and time from myself, and found the same issues”* (Steve). Unfortunately, despite numerous emails offering support, the problems experienced by Spinfield were not reported until the follow-up interview, when it was too late to address them.

It is not easy to find in retrospect a definitive cause of the problems experienced at Spinfield. It may well have been due to software coding issues. In fact, a day or so after their initial meetings, both Lane End and Frieth reported that they had experienced difficulties getting the prototype game to work. This turned out to be a server code issue which prevented the *Flash* application loading. However, given that the code was fixed within a day and neither Lane End nor Frieth reported any further difficulties, it is unlikely that this was the cause of the ongoing problems experienced at Spinfield. There was also the bug mentioned by Lane End, that at the very end of a game level, rather than *“half-way through”* as mentioned by Steve, the screen occasionally froze. However, while such a problem is understandably irritating, it did not prevent the children at Lane End, the previous school, playing the games frequently over several weeks.

Other possible technical causes included the configuration of the individual computers, the school internal network, and Internet access. The configuration of a computer may well have prevented the game running at all, but it is unlikely that it would have caused the intermittent problems reported by Steve, *“it wasn’t crashing every time, sometimes it would go right through..., it would give them their position, eight or six or whatever they were [on the leader board], so sometimes we got through”* (Steve). The network problems, however, may have contributed. The SENCO and Steve both reported that throughout that term there had been problems on the school network and also in accessing the Internet, *“to be fair, I think at that time we had problems with connection in school, even classrooms getting on the Internet, that didn’t help”* (Steve).

On the other hand, the difficulties experienced with the game might be attributable to the attitudes, knowledge, and skills of the adult. This is not to shift 'blame' onto Steve or Alison, any failure is more properly attributed to the game and the way in which it was presented to the school; rather it is to acknowledge that the success of any intervention is likely to depend as much on those involved with implementing and delivering it, both their individual characteristics and the training and support that they have received, as it does on the various characteristics of the intervention itself. Understanding any school intervention, whether a comprehensive programme or digital game, thus also requires some understanding of the needs of the teaching staff for whose use it is intended.

In the first interviews, both Steve and Alison said they had little experience of playing computer games for themselves, *"I don't understand how all these programmes work, and I don't think I want to"* (Steve); and although Alison said she enjoyed occasionally using computer games as part of her teaching, Steve had never done so, *"I don't play computer games with children in my school because they tend to do it on their own, don't they?"* (Steve). Nevertheless, both of them thought that computer games designed specifically to support children who have difficulties with numeracy might be useful, *"definitely"* (Alison), which is why they agreed to try the prototype game, *"because if it helps them, I would like to do it"* (Steve).

However, the observations suggested, and the follow-up interview confirmed, that Steve was unfamiliar with the conventions of platform game play, with how to play this particular game, and with the demands and approach of the numeracy intervention. The staff had also not taken on board the recommendation to play only one or at most two game levels in any one session; instead, while acknowledging that *"that half-hour with that child is so important, to make best use of it"* (Steve), Steve said that, in the few sessions when they did play the game, they usually played it for most of the available half-hour.

In any case, Steve did not like the prototype game's simplified approach to graphics, which had been based by the developer on the style adopted by many games in the

platform genre, *“the graphics are quite dull, boring graphics..., I think it’s because children are exposed to so much, aren’t they now, on computer programmes..., to me it seemed like the 1980s, when they first came out with computer games, not smooth running on the screen, that’s my impression of it, dated in a way”* (Steve). He also couldn’t understand why the children were so interested in collecting coins, again a typical feature of platform games, *“it just seems, they’re just collecting them, all these coins, to drop down, but what’s the point of it all?”* (Steve).

Furthermore, despite his fifteen-minutes introduction to the prototype, how it worked and might be used, the supporting documentation that was provided and his confident assurances, it was clear from the follow-up interview that Steve had not fully understood how to play the game. Again, this is not to apportion any blame to Steve but rather to acknowledge once more the critical importance of training and/or support for the successful implementation of an intervention. He, for example, was unsure how to move the avatar, and therefore how to interact with the various on-screen tools or how to respond to the numeracy tasks, *“some of the tools that you use to construct the bridges don’t seem to always work and go into the right place, and I can’t understand why they don’t work, and I can’t give answers to the children because I don’t know why they don’t work”* (Steve). He also thought the prototype game failed to give the kind of prompts that other games use to motivate children, *“a little more information about how they’re doing would be quite useful..., ‘well done’, or ‘correct’, so that they know they’ve got the things right”* (Steve), something that he thought the game could do by getting the mute companion to talk.

Steve also did not fully understand the separation of the game and numeracy levels, how game levels are unlocked, and how numeracy levels progress in the background according to the child’s success in the numeracy tasks, *“they found the problems easy, and I think they find it monotonous then, because I know the idea is that it’s repetitive, to build those skills but they still wanted to move on and do something different..., they’re supposed not to be able to unlock the next programme, aren’t they, until they’ve completed, but sometimes they seemed to be able to get on..., and I let them,*

because if they were getting fed up of what they were doing, 'let's go onto something else'" (Steve).

Moreover, as was suggested in the observations and reinforced in the interview, neither Steve nor Alison were especially familiar with the numeracy intervention. According to Steve, they were surprised to learn that the prototype, initially introduced to them as a game to support children who had difficulties with numeracy, did not cover all or most aspects of numeracy as they understood them; that instead it only included three of the very narrow components of numeracy featured in the numeracy intervention and then only with numbers up to twenty. In particular, for this reason, and having had no experience of working with children around the *derived facts* principles (commutativity, identical, $n+$ and $n-$), they found the *derived facts* game levels almost incomprehensible, or as Mary, the school's SENCO, put it, *"they found the concept [of derived facts] quite tricky"*.

However, Steve's most important criticism of the prototype game was that the children learned little from their experience, *"I'm not sure if they were learning anything from the games..., my gut feeling is no they weren't"*. And while he thought that the games *"could play a useful part, a small part, if they were enhanced..., it would be wrong to spend half an hour using the game..., it's not a substitute for one-to-one"* (Steve). Finally, when asked to summarise his impression of the game, Steve confirmed, *"I can't think of anything positive..., out of choice, I wouldn't use it"*.

The children

Steve and Alison stopped using the game after only a few sessions, and each child ended up playing the game only once or twice, because of the various problems that they had encountered and *"because the children have said 'can we do something different'..., they were getting fed up at what they were doing, 'let's go onto something else'"* (Steve). However, the children's opinions, elicited in individual interviews conducted under Mary's supervision, do not appear to square completely with Steve's description. All six of the children said that they enjoyed playing the game, and all of them said that they would like to play the game again. Naturally, the children may well

have just been trying to be helpful, but their responses to repeated questioning around whether or not they had enjoyed the games, together with the negative responses that they gave for other questions, suggests otherwise.

The Spinfield children enjoyed the same game characteristics as had the children from Lane End. They liked configuring their avatar and moving it around the game space, running, climbing, and jumping, *"I liked choosing my own character, you had to choose the colour and the hairstyle"* (Evie); the games *"were fun, climbing over bridges and climbing up stuff"* (Jason), *"I like the jumping part and I liked how you moved..., I thought it was just fun"* (Grace). They also enjoyed solving the problems, particularly when they got the right answer, the games *"were like really good..., it was figuring, to find out the other block, I needed to make it"* (Michael), *"they're really good..., lots of puzzles"* (John), *"it was nice to get the right answer"* (Darren). They especially liked collecting coins, and seeing their names on the leader board, *"I liked the running where you have to catch the coins"* (Evie), *"I liked jumping and the coins and getting the ladder to get the coins at the top..., I liked what you had to do to get to the coins"* (Jason), *"my favourite was collecting the coins, seeing the higher amount and time, I moved up..., it was quite a mystery to see how many points you got"* (John).

Nevertheless, the children did have some criticisms (even if some of which appeared to be contradictory), *"I didn't like the jumping, a bit pointless really"* (Evie), and *"it's really annoying when you fall off and die"* (Jason). In fact, the children who were observed playing the game did appear to 'die' rather frequently, which is to say that they often tried to cross a chasm without making any attempt to use the building blocks, without applying any mathematical thinking. It took some time before both they and Steve worked out that, to progress, they would need to bridge the gaps by adding or subtracting the available materials, selecting blocks by pressing the space bar, *"you had to try and get across this hole, without falling in it, but every time I tried to get across it, I fell in it, then the character died"* (Evie). On the other hand, only one of the children mentioned that the game froze, *"the games, they would sometimes pause"* (Jason), which suggests that not understanding how to navigate the gameplay was for the children a more important, although still not very important, cause of frustration.

John also mentioned that the coin collecting was less than ideal, *“you can’t actually do anything with the coins, I guess it’s just a game, and I don’t think you can buy anything..., if I could buy things to change my character, I would say that would be quite good..., you could go to a shop and buy new costumes, some maybe guns to help you shoot..., or it sends out a rope with a little hook on the end”*. Jason had similar ideas, *“it would be good if you could buy a car or something, or a motorbike”*. In addition, both Jason and Michael said that they would have liked the mute companion to have offered some guidance as they played, *“it would be good if there was some writing on the screen..., and it would be good if [the companion] could read it out to you”* (Michael).

The Springfield children were divided about whether or not they had learned anything from playing the games, *“I was playing and learning, because it was quite fun and I realised it was learning too..., I’d rather learn it in a game”* (John); *“I didn’t learn anything, not sure why”* (Evie); *“I was learning lots, like the number problems”* (Michael); *“it helped a little bit but not a great deal”* (Grace). There was also little consensus about the value of repeating the same tasks (concrete objects, labelled concrete objects, and symbolic), *“it’s a good idea, because you could put the blocks in the right places, then you just work out what the answer is, then you get the right answer”* (Darren); *“it was a little bit annoying..., it keeps on copying the question..., [although] it had different ways of doing it, that was good”* (John).

However, almost all the children thought the mathematical tasks were too easy, *“the numbers were too easy, just adding and takeaway..., it needed harder questions but not too difficult..., adding, taking away and dividing, times”* (Evie), *“if the numbers were a bit harder, it would have made it a bit of a challenge”* (Jason). Nevertheless, this may well have been a consequence of the children only playing the prototype game once or twice; they had yet to move on from the lowest numeracy levels. Only John had played sufficient games to notice that the number range went up in the background, *“I like the number growing, because then you can do it with bigger and bigger and bigger, try and do some adding of bigger numbers and taking away”*.

Fulcrum for social interaction and discussion

As noted above, during the two sessions in which Steve was observed using the prototype game with John and Evie, the conversation between them was only occasional. Once Steve had got them started, the children quietly worked through the game, while Steve watched and commented only occasionally, mostly when the child was unable to work out what to do in the gameplay. However, these observations do not appear to match the experiences reported by the children.

Two of the children did say that there was not much talking when they played the game, *"I played it on my own with [Alison]..., we didn't do any talking, I just played the game..., I liked concentrating on playing the game"* (Darren), and *"it was just me, no-one else, I didn't talk with anyone"* (Evie). John and Jason, however, on at least one occasion played the game on adjacent computers, talking as they did so; they disagreed about how useful that was, *"I liked someone to be near to me'..., your friend always helps you..., if the game was easy, you wouldn't need someone next to you..., it's not cheating, talking about it helps me"* (John), *"[John] was sat next to me..., we both helped each other..., I would prefer it on my own, because he was shouting a bit..., we were just having a race, getting a lot of coins"* (Jason). Meanwhile, Michael said that he would have liked the chance to play the game next to a friend, *"it would be good to talk it through with a friend..., they could help me with the problem, and we could work it out together"*. Finally, only Michael and Grace mentioned that they had talked anything through with an adult, and neither of them seemed to place much value on the conversation, *"I had a teacher with me, but that was all..., we did talk about the coins, how much they were worth, how much they add to it"* (Grace), *"we only talked through the problem and [Steve] helped me figure it out"* (Michael).

Outcomes 3: Frieth

The third and final participating school in this research cycle was Frieth, designated here the 'rural' school. At Frieth, the research was facilitated by the school's deputy headteacher, Sara, and the prototype game was used with the children by Diane, a classroom assistant, under the supervision of David, the Year 5 classroom teacher. Five children, all of whom were known to be low-attaining in mathematics, participated: Chloe, Emma, Kieran, Lewis and Matthew (all aged 9 or 10).

The children at Frieth played the prototype game for around fifteen minutes, almost every day, over eight weeks, *"I think fifteen minutes is good, because it's enough to keep it fresh and fun but it's not too much"* (Diane); they stopped using the games only when David decided that *"the time being invested was not necessarily getting the best return"* (David). On arriving in the classroom each morning, rather than waiting for registration the children would 'clock-in', by signing their names on the board, then leave and go straight to the ICT suite. In Frieth, the ICT suite is a crowded space, with around twenty-five computers on workbenches arranged in back-to-back irregular rows and surrounded by bookshelves. It is also usually a busy space, although first thing in the morning the children playing the prototype game mostly had a corner of the room to themselves. There, under Diane's supervision, they would switch on the computers and log onto the prototype game, picking up where they had left off the day before, playing one game level before returning to class, *"we get to the end of one game, and we go back into the classroom..., to be perfectly honest, they probably only miss about five minutes [of class time], because the time that they've done registration and sorted out all the things for their [mental maths warm-up], they get fifteen minutes, but they've probably only missed about five minutes in the class"* (Diane).

The decision for the children to work with the games in a group was a pragmatic one, *"in our school, we don't have that luxury, that facility to have one-on-one..., in our situation I couldn't allow five children to go out one-on-one, that wouldn't be feasible"* (David). In any case, at Frieth the children are familiar with working in pairs or in groups, *"the children are used to doing group work, using that kind of energy, they*

often have a thinking partner or a talking partner..., the topic of conversation usually is work-related, that's how they share their ideas" (David). This was supported by the observations of the children using the prototype game.

As had happened at Lane End, the conversation between the children was animated, as they discussed strategies, asked each other for help, and shared their successes; while Diane watched, offering help when needed and occasionally asking the children to clarify their thinking. Everyone, including Diane, looked as if they were having lots of fun; while the position of the children, in the corner of the room, allowed Diane to see easily what they were all doing. Chloe and Emma sat next to each other, playing different game levels, methodically working their way through the tasks, chatting quietly as they did so, then checking their positions carefully on the leader board. Meanwhile, the three boys sped through the games, competing with one another as they tried to get to the end flags as quickly as possible, and collecting as many coins as they could along the way. Interestingly, on at least one occasion, while the boys were all playing the same game level, the same set of animations, the game served them each a different numeracy level: unnoticed by the boys, they were tackling tasks within different number ranges. For example, on one occasion while Kieran and Matthew were working with numbers up to fifteen, Lewis was working with numbers only up to eight. This was also remarked on by Diane, *"I noticed that when [Lewis] was playing the same game, he actually was working with small numbers, easier maths, that hadn't twigged to them"*.

Three of the children were also observed while they played, with Diane's support, one of the reconfigured *derived facts* games. Although Chloe, Emma and Matthew clearly had some understanding of the *derived facts* principles (commutative, identical, $n+$, $n-$), they all still had considerable difficulty working through the game level, and for several of the tasks Diane had to talk them through step-by-step. Nevertheless, although progress was slow and accompanied by sporadic yelps of anger and frustration, on this occasion they all did manage to work through three or four of the numeracy tasks, identifying the *derived facts* principle before tackling each task itself, *"they don't do this one much, they prefer the other ones, building the bridges and the*

cloud one, they get stuck at the beginning” (Diane). However, observing the children play these derived facts game levels confirmed that the reconfiguration of the derived facts tasks had not been wholly successful. While the rearrangement meant that that the children did have to identify the derived facts principle, which was implemented in response to a specific outcome of the first intervention, the animations illustrating the particular task were still not easily understood by the children: it was often difficult to compare the ‘known’ and ‘unknown’ facts, the animations were too similar and sometimes too fast, and in any case with the higher number ranges part of the task was sometimes off the screen.

Diane

Diane, the classroom assistant, was extremely positive about the prototype game: how much the children had enjoyed playing the game levels, the impact that it had had on them, and what she had learned from working with the children, *“to be honest in the beginning I wasn’t totally keen, I thought ‘oh yes, here’s another computer game thing’, but I’ve been wow’d by it, the way that they help each other..., so there isn’t any downsides”*. For her, a key factor was the children’s engagement, *“they love it..., they tend not to see doing the games on the computer quite as much as a lesson in numeracy, it’s just a game, and so they’re absorbing the number bonds and using all the facts that they’ve at their finger tips mentally..., probably the maths is going in but they’re not aware of it in the same way, it’s probably a good thing because they’re not thinking that they’re doing maths”*. And as they played, Diane clearly picked up on their individual difficulties and was able to give them appropriate strategies. The game’s use of the three sub-tasks (concrete objects, labelled concrete objects, and symbolic), she thought was a particularly helpful feature of the game, *“it takes them a while to realise that..., they’re doing the same thing, it’s just different ways of doing it, but after they start looking at it and think ‘oh, yeah’, I’ve got to fit the shapes and the shapes represent..., and then the second time the shapes have got the numbers on..., it helped Thomas, he noticed straightaway that there are different ways of doing the same thing”*.

By watching as they played the games, and talking with them about how and why they approached the tasks as they did, Diane learned something about each of the children, *“the good thing is I have the opportunity to go and look..., it’s made me understand a bit more about how they learn..., [and] knowing what I know about them will affect how I support them in future”*. For example, for Joe *“it’s all about getting the coins, he would do whatever’s necessary to get as many coins as he could [including some random clicking, but] his numbers weren’t growing, so the support Joe needs is different to the support the others need”*. For Kieran, *“it was more about the time..., he was doing the maths as quickly as he could to beat his time to get faster than the others..., he thought about the maths to achieve the goal..., I think he’s now quicker at those basic operations”*; while Matthew *“worked systematically through but he was in competition with the others, very much competition led”*. In other words, for the boys, the speed, the coins, and the competition – all key components of the platform entertainment game genre – were fundamental to their enjoyment and engagement. Diane believed that, knowing now what particularly interested the boys, she would be better placed to support them in their usual mathematics lessons, *“in the classroom you can, if you’ve got children that are really into games, you can talk to them about their ordinary work in terms of platform games and I think they might understand it more..., in the classroom, with pen and paper..., it would be a case of saying visualise what you saw on the screen, think of it in blocks and do it that way”*.

Meanwhile Emma and Chloe, Diane observed, *“worked quite closely together..., very systematic..., the two girls aren’t necessarily whizzy at platform games and so they’re learning in a different way..., their numbers were increasing, the sums were getting harder..., [now Chloe] is much quicker at mental maths”* and so, accordingly, *“in the classroom, that’s how I need to take them through, step-by-step.”* She also noticed that playing the game had had a specific impact on Chloe. Whereas Chloe would still very often use her fingers for counting and calculating, when playing the game her fingers were otherwise occupied, *“in the classroom [Chloe] was using her fingers, but not here..., her fingers are doing something, so she’s using her brain, so that’s actually*

helping because she's having to think about it..., so I'll try to find things for her to be holding in the class when I'm talking to her".

On a personal level, Diane slightly regretted not having spent time finding out about the games on her own before introducing them to the children, *"my problem is I don't know as much about platform games as the kids do, and it takes me slightly longer to work out what to do"* (Diane). She thought perhaps she should have gone through each game at home, because even if there had been a manual it is unlikely that she would have read it, *"I don't think you need a big manual..., people don't read them, the manual gets shoved somewhere, and then someone else will come in and do it"*. An online help system, however, would have been welcome, so that she could easily have searched for the answer to a particular question about the game, but she would not want the children to have access, *"having a help is sometimes a pain because they'll click on it first for the help 'oh, I don't know how to do this, so I'll get somebody to tell me'..., a bit like going on the Internet to find cheats for their games"*. However, she did think it might be useful if the companion were to provide hints in response to errors made by the children, *"if it's linked to the errors, that would be different"*, so long as it did not speak often, *"I like the fact that there's not too much talking to them [by the game], because you then haven't got to worry about headphones..., there's lots of other games around where there's lots of sound with it which can be quite disruptive to other people"*.

David

David, the teacher, was uncertain about the game-based approach to learning. Following feedback he was getting from Diane, he only observed the children once briefly at the end of the eight weeks, he was somewhat concerned that the children were putting more effort into collecting coins than into the mathematics, *"the children were more interested in clearing the screen of coins before moving on..., so getting those coins was their key element really..., but I just felt that for them it was more about the game rather than the learning"*. On the other hand, he did believe that for some children, hiding the learning behind gameplay could be useful, *"I think there are*

benefits in learning by stealth, especially boys are quite difficult to engage in some activities, some aspects of the curriculum, making it relevant to them and interesting to them, so for that element, the collecting of the coins was important to them and if that helps with the maths then that's good..., it's nice to hide the learning in the game because it doesn't engage the boys".

Although he was less familiar with the numeracy intervention than Diane, as a teacher David still valued the componential approach to numeracy adopted by the games, *"they could be useful because they focus on one particular area, that is useful..., it is another string to the bow"*, but he believed his children actually needed more support in other areas, *"it was other concepts, in shape and space sort of areas, that were causing the problems, and more operations such as division..., so I think for them it might have been some useful reinforcement but it wasn't necessarily a learning curve"*. And while he recognised some value to the limited number ranges, he thought that the children's progression through the numeracy levels was far too slow, *"I'd gone out to see what sort of progress they'd been making and the amount of time that the children had been using it, I thought maybe the levels would have moved on a bit..., so that was my concern, the time being invested was not necessarily getting the best return..., what might have been of more benefit if the games could have geared up quite quickly..., but I just think it was a bit slow progress getting to where they got to in many ways"*.

There were four specific ways in which David believed the use of the prototype game could be made more effective: by selecting more carefully which children would play the game, by building in opportunities for reflection, by controlling the children's gameplay more intelligently, and by giving the teacher easy access to data about the children's progress.

Although the participating children only continued to be served the lower numeracy levels because they had not yet shown themselves to be secure in those levels, and despite the inclusion of the *estimation* and *derived facts* components which involve both conceptual and procedural knowledge, David argued that the prototype game was pitched too low for these five particular children. However, he thought, *"the*

games could be used as a teaching tool for children further down the school, in Year two and Year one, who are learning number bonds..., or in Year three or four where if you've got children who are struggling in maths..., it does tend to be that understanding of number that does get in the way, and maybe that's where these games can come in as a catch-up or reinforcement to help those children..., I think when they get to Year five, it tends to be the application of number, the way things are worded..., and processes with larger numbers..., it's not necessarily those simple bonds, understanding is the new drive, the concepts." Based on David's feedback, the deputy headteacher, in fact decided to continue with the prototype game at Frieth, after the intervention had concluded, but with children in Year three.

Whichever children might use the games, David believed they would benefit from some dedicated time with their teacher immediately after they had finished playing, so that the teacher could get the children to reflect upon the mathematics that they had been exploring. However, in ordinary schools, where the teacher typically has responsibility for another twenty plus children, and there are the ongoing demands of the timetable, this would always be a challenge, *"I would definitely build in some discussion at the end, once they've played the game, hold them all together, so you've got that time built in where you discuss all together that session, whereas with us it was very much time constraints, now next door for the maths lesson"*.

David's final suggestions were both technological. Firstly, he argued that the game should take further control of the children's route through the game and numeracy levels, ensuring that they explore all the components, not just *remembered facts*. In addition, it should monitor and direct their progress, *"I think the game should take the lead in deciding when the child has spent long enough on the games..., if someone wasn't making expected progress on the games, that would need to be flagged up..., or if they are finding it too easy..., now if your [classroom assistant] is able to do that, that's great, but I could see in some circumstances that a child could be working on the class computer over in the corner, with a set of headphones on..., because of time constraints you wouldn't necessarily get to see what that child is doing"*. Secondly, David would like to be able to access easily data about the child's progress, via a simple

online interface, *“it would be useful to be able to see at a glance how the children are doing..., if there was some form of login that was part of the game, then that makes that easier for the teacher to then go and check at a convenient time..., something very simple like a line graph..., that would be helpful because then obviously you could pinpoint things that you could address back in the classroom.”*

The children

The children from Frieth gave very similar feedback to the participating children from Lane End and Spinfield. For example, all of the children from Frieth reported that they had enjoyed playing the prototype game and that they believed the game had helped them with their mathematics, *“they’re pretty cool, they’re interesting..., they helped me with my maths a lot..., in the morning they’re like when you coming in and do it, it warms your brain up, then when we go into class, you’re OK”* (Lewis), *“they’re really good because they teach us loads of maths that we probably don’t know”* (Matthew), *“it’s good because I’m getting faster with bigger numbers, makes me feel happier, better at maths..., [playing a computer game] is not a cheat, it puts fun into it, makes people want to do maths more, and it makes them want to get better at it, sets them a goal to get better”* (Kieran).

Given that the children from Frieth said much the same as the children from Lane End and Spinfield (some of the calculations were too easy, the sub-tasks were helpful, the increasing numeracy levels were rarely noticed...), only a few further distinguishing comments will be mentioned. For one, Emma didn’t like the fact that the coins ‘wasted time’, *“sometimes they put you off your time, so you add on more time if you go for the coins..., more coins or quicker, I prefer to be quicker, so I only get the ones at the bottom”*. Emma, on the other hand, had a reservation about the leader board; she would have liked to have been able to compare her current time with her previous times, *“finding out how long you took was good, [but] it would be good to see all my times”*. Meanwhile, two of the boys thought that some of the leader board times were improbable, *“the times could be a bit more realistic, because you couldn’t do it in twenty-five seconds”* (Kieran), *“I think you shouldn’t be able to cheat, because there’s*

some did it in twenty-five seconds, when you possibly can't do that, unless you cheat or something" (Matthew).

In addition, all of the children agreed they would have liked to play the prototype game at home, although none of them had, *"it would be good to play them at home because if you did them more often you'd get better at everything..., it would be good to play the games with Dad, to talk about it"* (Kieran); and all of the children believed that playing the games had helped them in class, *"it's helped me remember some of the answers in class because you remember when you are playing the game"* (Chloe), *"we did a maths sheet, calculation thing, and the games helped, helped me with the sheet"* (Kieran), *"some of the stuff in the games helped me with [class mathematics] worksheets"* (Lewis). For Matthew, using the game meant that you didn't need to worry about making mistakes, *"it you get it wrong it doesn't matter because you can try again, but it takes you a long way backwards and it wastes a bit of time"*.

Fulcrum for social interaction and discussion

The discussions with the participants at Frieth again suggested that the prototype game might have potential as a fulcrum for social interaction and discussion. However, whereas previously, at Lane End and Spinfield, this had been considered only in terms of conversation between the participating children and between the child and the supporting adult, the discussions at Frieth suggested that it might be extended to include also conversation between the classroom assistant and the teacher, and between the teacher and the child's parents.

At Frieth, the game was certainly used by Diane and the children as a focus for conversation about mathematical ideas. For example, Diane noted that she found it useful to discuss the children's mathematical strategies with them, *"I always ask them if they can work out what they've done wrong, rather than telling them..., if they came up with 'I kept adding five plus two', then you would know they had a problem"*; while, from the observations, it was clear the children valued Diane's occasional comments and the questions that helped them firm up their mathematical thinking. And, as at Lane End and Spinfield, the game was also used for mathematics- and gameplay-

focused conversation between the children, *“the boys are obviously very good at platform games, and sort of said to the girls you do this or you do that and they were away..., then of course the girls are possibly better at the maths so they were able to help the boys when they were not getting it straightaway..., generally, they worked it out between themselves..., and I noticed that by helping each other, they were learning themselves..., actually I found it better because I think they remember things that their, that the other pupils, tell them probably more than me”* (Diane). All the children commented positively on playing in a group, being able to discuss things amongst themselves, but Kieran did have some concerns, *“it’s helpful sometimes but, when you’re trying to concentrate, it can get annoying sometimes, but they’re your friends, so you put up with it..., it’s not better than [talking with] a teacher because they could be wrong, but they’ve done it on their own, so if they’ve done it right on there, you can’t really argue”*.

On the other hand, David suggested that a game might also function as a *“prompt”* or *“conduit”* for informed conversation about the children’s mathematical achievements and difficulties between the teacher and classroom assistant, and between the teacher and the child’s parents. However, for David, the existing prototype did not do enough in this respect, it did not of itself support useful discussion with his classroom assistant, which is why he would have liked easy access to the child’s progress data, *“I think they could work as a useful prompt for a conversation, where they are at the moment..., but the conversations [Diane and I] were having weren’t showing up concerns in terms of so-and-so was finding this particularly difficult, so that’s when I decided I needed to go and have a look at what they were doing”* (David). Nevertheless, he did believe that the game might be useful for parents, both so that they are able to help their own children but also to give a common currency for conversation with the child’s teacher, *“one of the things that we’re constantly asked by parents is for resources and material..., so it can become part of that vocabulary for parents, little Johnny’s got a problem, here’s a programme he can work on at home..., that would be great because there’s less of that available now..., the games might give a conduit for discussion with*

the parent, because obviously you can set it up formally for homework..., then that can be a conversation that you have with the parent” (David).

5.3 ANALYSIS AND REFLECTION

This chapter has discussed the second cycle of design and intervention. Rather than focusing only on the game itself and how that game was played by individual children, this second intervention refined that focus to consider also how the game was used as a fulcrum for social interaction and discussion between the child and supporting adult.

Research sub-question 2.1

What are the responses of a sample of children who are low-attaining in mathematics, and the teaching staff who support them, to the prototype game?

Without exception, the participating children said that they enjoyed using the game; and during the observed sessions, they certainly seemed to be enjoying themselves. This is important because enjoyment is well-known to support learning (Immordino-Yang & Damasio 2011), and enjoyment of GBL has been experimentally linked with academic performance (Giannakos 2013). In particular, they valued the features derived from the platform game genre: an avatar that they could customise, the puzzles that they had to tackle, a timer that they could try to beat, the coins that they could collect, and a leader board on which they could compete. Additionally, and more importantly, almost all of the children believed that playing the game had helped them with their mathematics, even if the tasks were often ‘too easy’, and the teaching staff, with one important exception, mostly agreed. The classroom assistants noted that the children effectively ‘put up with the maths’ in order to play the prototype game, partly because the mathematics seemed to emerge naturally from the gameplay. In effect, the children were ‘learning by stealth’ (Hosie 1985; MacCallum 2011; Prensky 2001a), playing and learning independently of a teacher’s input; forgetting that they were thinking mathematically, a school task, because doing so was in service of playing the game. They were even willing to chat about the mathematics, with the other children

and the supervising adult, because it was relevant to what they were trying to achieve. For similar reasons, the deliberate repetition was mostly ignored or, at the very least, usually accepted. Meanwhile the varied repetition in the three game sub-tasks (concrete objects, labelled concrete objects, and symbolic) was mostly, although not always, seen as being helpful; even if at times the numbers were being used to help calculate the blocks rather than the other way around, as intended by the design.

Furthermore, few of the children noticed that, as they played, the numeracy tasks would become progressively more difficult, as the game adapted to their achievements (Magerko 2008). Although some of the school staff also did not fully understand this feature, it had benefits and disadvantages. For example, it meant that two children could play side-by-side the same game level, while unbeknown to them they tackled quite different levels of numeracy; the friendly competition between them was entirely independent of their mathematical abilities. On the other hand, although they would have seen the 'you moved up a level' screen, they missed out on the positive reinforcement that might have come from making it explicit that they had achieved a specific level of competence.

Inevitably, despite them being lumped together in the single category 'low attaining in mathematics', the fifteen participating children had fifteen quite different sets of individual learning needs: different mathematical competencies, different likes and dislikes, different learning and gaming experiences, and different levels of confidence, all expressed in very different ways, often not explicit (Houssart 2004). In particular, something that this research has virtually ignored are the very different experiences and interests of girls compared with boys, and boys compared with girls (McFarlane *et al.* 2002). Nevertheless, many of the teaching staff did believe that using the game with their children afforded them opportunities to learn about each child's individual needs, and it is perhaps possible to draw some general observations: for example, that the children, when participating in an activity from which the mathematics emerged naturally and in which they had some kind of vested interest, both engaged more effectively with the mathematics and were seen to be learning from so doing.

Research sub-question 2.2

How was the prototype game implemented and used in the sample schools?

Given that an aim of the intervention was to see how the prototype game was implemented and used in the participating schools, when the schools were given access to the game, no restrictions were put on how it could be used or on how much time the children should spend on it. Instead, the teaching staff were only asked to use the game in ways that complemented their usual support, taking into account any factors that were important in their school (such as timetabling and access to computers). The only specific advice given was for the children to be allowed to play only one or two game levels in any one session. Two of the schools used the game with the children in groups, in the ICT suite first thing in the morning for about fifteen minutes on most days, thus missing mostly only 'early work' or registration and class preparation. For them, implementing the game was reasonably straightforward. Meanwhile, the other school used the game, if only a few times before abandoning it, for most of the children's weekly half-hour one-to-one sessions held in the corridor.

In addition, the first school encouraged their children to use the game at home, which two of them did. These children said that they enjoyed playing the game at home with their parents and siblings, and that they believed doing so had helped them with their numeracy. However, although the teaching staff agreed that there were benefits from the children using the game at home, the low take-up meant that home use could not be a focus of this research. Finally, while two of the schools appeared to have little technical difficulty in using the game, the third school found it too unstable and too incomprehensible to be of any real value: if it was not easy to use, it was not going to be used (Cuban 2001; Kirriemuir & McFarlane 2004).

In summary, the first school was the most positive in its reception of the prototype game; the game sessions were dynamic events, involving lots of excited conversation around the game, between the children and between the classroom assistant and children; and the teaching staff were sure that the game had contributed to the children's mathematical development. In the last school, again the sessions were

highly-charged and the children appeared to make steady mathematical progress, there were therefore some benefits, but the teacher believed that the game would need further development before it would be taken up widely. Meanwhile, the staff member at the second school believed that the game simply did not work in its current form, that it would need radical changes before it could be of any use.

The interviews with the teaching staff identified a range of issues, both positive and negative, that any successful game designed to support learning ought to consider. For example, they believed, if carefully designed, a digital game could provide opportunities for guided constructive learning (Leutner 1993). It could provide a variety of authentic mathematical experiences where the mathematics emerges naturally from the virtual environment of the game. It could encourage the child to tackle the mathematical problems, to cross the chasm they calculate how to build a bridge, while preventing them avoiding the mathematics, if they don't build a bridge their avatar dies. And it could provide the teacher with an additional and shortcut opportunity to get to the heart of a child's mathematical problems, to understand exactly where the child's particular difficulties lie.

However, there are a variety of issues that might prevent the game actually being used at all. Implementing the game in the school can be especially challenging. Once a budget to purchase the game has been found, it will still draw heavily on the most expensive of school resources, mainly the availability of school staff and the children's timetabled lessons but also access to ICT facilities. It also requires the teaching staff to have some familiarity with the particular digital game genre, if they are to be able to use those features to best effect, and with the pedagogy underlying the game's approach to learning (in the case of this prototype, the numeracy intervention), if they are going to be able to identify for which children the game might be most suitable (Williamson 2009). This was certainly true of the prototype game, where some misunderstanding about the scope of the numeracy intervention, the level of mathematics for which it has been designed, meant that two of the schools believed the game was too limited. They argued it should cover multiplication and division,

shape and space, concepts and procedures, rather than the three numeracy intervention components that were included in the game.

Research sub-question 2.3

In what ways did the prototype game function as a fulcrum for social interaction and discussion?

As noted above, while the characteristics of the game, how it implements learning theory in the medium of gameplay, are critical, of perhaps equal importance is the way in which the game facilitates educationally meaningful conversation. The intervention identified five potential conversations: between the participating children, between the children and the supporting adults, between the teaching assistant and the teacher, between the parent and their child, and between the parent and the teacher.

Often the children in the group settings would talk about the gameplay, the animations, moving the avatar and collecting coins. At other times it would be a conversation about the mathematics: how particular tasks might be answered, what mathematical strategies they had found to be effective, and how the different tasks related to one another. And while these conversations might not have been always targeted or explicitly productive, the observations and interviews appeared to reveal that those children and supporting adults who engaged in most conversation, found those conversations the most helpful – while those who talked least, thought that doing so was unimportant. Meanwhile the supporting adults also valued the opportunity to encourage the child to think through what they were trying to achieve, to scaffold and take responsibility for their own learning, to engage with the supporting adult when usually they would not do so, and to reflect on what they had achieved, giving the adult a new way into the child's approach to learning.

This intervention also suggested ways in which the prototype game might be used to facilitate a conversation between the supporting adult and the teacher, albeit with further development so that it included for the teacher easy access to data about the children's progress, and between the teacher and the child's parents, perhaps if the

game is 'set' as homework or offered as a supporting resource it might augment the sometimes minimal connection between home and school. And, as suggested by previous research (Holmes, 2011), the game might also provide parents a way in which to engage with their child's learning, a conversation that can otherwise sometimes be difficult to achieve.

Research sub-question 2.4

How might the prototype game be amended to make it a more useful classroom tool?

Despite the different responses to it from the teaching staff, the second iteration of the prototype game appeared to fulfil its intended function; such that, if only because of the 'law of diminishing returns', few further amendments to the prototype would be useful for this research. The children and teachers did suggest some amendments that might have important potential and thus warranted attention. The children suggested giving the learning companion a voice, so that it could give guidance in response to errors or offer motivating comments to congratulate the children on their successes and to reinforce their learning. The teachers suggested the creation of an interface giving them access to the children's progress data, so that the game data could more easily be integrated with the children's classroom progress data. In addition, some technical bugs did need to be fixed, such as the code that caused the game sometimes to freeze just at the point the children were about to pass the final flag and the algorithm that builds the leader board. The *derived facts* game levels also continued to be problematic (supporting the observation reported in earlier research that the *derived facts* component is probably the most difficult to address, Evans 2008). However, it was unclear how to amend them, to make them more successful, without a comprehensive re-design.

Research cycle 3

This chapter discusses the final research cycle of design, intervention, analysis and reflection. This research cycle served two purposes. First, it afforded a last opportunity to reinforce or refute outcomes of the first two interventions, to help achieve a sufficient level of theoretical saturation (Corbin & Strauss 1998) and to provide some validation through the triangulation of data from different sources and an additional method (gameplay data captured automatically by the system) (Denzin 2009; Rhineberger *et al.* 2005). Second, this research cycle investigated the prototype game in a more ‘authentic’ implementation, than those that characterised the first two interventions.

As noted in Chapter 3, a key assumption of the prototype game’s design was that a fully-working final version, if made generally available to schools, would be delivered online. Schools would purchase access to the game to complement their other provision, which might include the numeracy intervention, for children low-attaining in mathematics. Those children would then play the game on a computer with Internet access, whether at school supported by a classroom assistant or at home supported by a parent. From that perspective, the first research cycle (Chapter 4) involved a low-fidelity laboratory study, while the second research cycle (Chapter 5), although grounded in real classrooms, was still some way from the assumed context of a final version of the game.

This third cycle therefore researched the game in a context much closer to the assumed context of a final version of the game, so that the impact of that context on the participants’ attitudes to the game and on its usefulness in the classroom might be considered. It is in this sense that the final intervention aimed to be authentic. As a consequence, control of the game was handed over to the education charity, the

owners of the numeracy intervention, who made it available to teachers and classroom assistants who had completed training for the numeracy intervention. In turn, those teaching staff used online management tools, developed to support the game, to provide children in their care with access to the final prototype, as and when they thought it appropriate to do so. The management tools also enabled the teaching staff to monitor the children's achievements and progress.

Research questions

This third research cycle concludes the process of addressing the two central research questions of this study by considering two sub-questions. The first of these aims to help achieve theoretical saturation and to provide some validation of the previous research cycles, through the triangulation of data from different sources and an additional method. The second sub-question considers the impact on how the prototype game was used when control of the game was given to the charity that owns the numeracy intervention. The charity made the game available to schools as they would have done had it been a finished product.

The two research sub-questions addressed in this final research cycle are:

- 3.1 In what ways do the observations of additional teaching staff and children and gameplay data reinforce or refute relevant outcomes of the previous interventions?
- 3.2 What impact does experiencing the game in a more authentic context have on the participants' use of the game and on their perception of the game's value?

6.1 DESIGN

As noted in Section 5.3, the outcomes of the second research cycle suggested that the second iteration of the prototype mostly fulfilled its role as research instrument and classroom tool. As a consequence, the design of the third iteration of the prototype game involved far fewer variables, and therefore warrants a shorter discussion. The second research cycle did identify the prototype game's approach to *derived facts* as

an ongoing weakness. However, despite extensive discussions, no solutions were identified and so in the design of the final prototype no amendments to the *derived facts* levels were implemented. The successful implementation of *derived facts* in a digital game would require further specific research.

Three outcomes of the second research cycle were addressed in the prototype's final iteration: the software's stability was improved, a voice was given to the companion, and management controls and monitoring functionality were incorporated into the teachers' online interface. In addition, the final iteration of the prototype was integrated into the charity's website from where it could be accessed, via a login requiring usernames and passwords, by the teaching staff and children. Finally, a teachers' user-guide was written.

Software stability

In the second intervention (Chapter 5), it was reported that the prototype game sometimes froze just at the point the children were about to pass the final flag and before their scores were recorded. This type of system failure is unfortunately typical of software as complex as the prototype game, especially when developed within tight time and budget constraints (Adams & Rollings 2006). Nevertheless, given the demoralising effect for the children and the inevitable impact on their willingness to engage and thus on their learning (Boekaerts 2010), considerable effort was made by the developer to identify the cause of the problem and to fix the relevant coding. A second issue identified by the children concerned the scores that appeared on the leader board. Often the 'other' children (the virtual children) were shown to have achieved times that the real children found impossibly fast. Again, the coding, here an algorithm, was adjusted by the developer, in order to make the 'other' children's scores more believable.

Learning companion's voice

As discussed in Chapter 5, a learning companion, a virtual friend to help the children play the game and engage with the mathematics (Chan & Baskin 1988; Johnson *et al.*

2000; Kim 2007), was incorporated into the second prototype. However, the implementation of the companion at that time was minimal. It comprised only a small glowing globe that followed the avatar around the virtual environment. The limitations and potential of this companion were mentioned by several of the participants in the second intervention, by children and adults, and suggestions were made for ways in which it might be better used. For example, *“a little more information about how they’re doing would be quite useful..., ‘well done’, or ‘correct’, so that they know they’ve got the things right”* (Steve, Chapter 5).

Accordingly, in the design of the final prototype, the companion was given a voice and a script that triggered in response to any of four different types of event. The aim was to promote motivation and to give feedback and guidance that supported the learning (Black & Wiliam 1998; Falloon 2010; Kickmeier-Rust *et al.* 2008) (Table 6.1).

Table 6.1

Example learning companion triggers and script.

Trigger	Example script
Successful completion of a task.	<i>“Hooray!”</i> [or] <i>“Excellent!”</i>
First error.	<i>“Try again!”</i> [or] <i>“Have another go!”</i>
Second or subsequent error on <i>remembered facts</i> , game level 1, first sub-task (concrete objects).	<i>“Try to work out how big the hole is. Sometimes you’ll need to add blocks. Sometimes you’ll need to subtract one from another.”</i>
Second or subsequent error on <i>estimation</i> , game level 2, first sub-task (concrete objects).	<i>“Make a good guess about the blocks on the scales.”</i>
Second or subsequent error on <i>derived facts</i> , all game levels, first sub-task (concrete objects).	<i>“Look at the first calculation. Use it to help you work out the answer to the second calculation.”</i>
Second or subsequent error on <i>remembered facts, estimation, and derived facts</i> , all game levels, second sub-task (labelled concrete) and third sub-task (symbolic).	<i>“Think about what you did last time.”</i>

(i) On the successful completion of a task, the companion gives a motivational comment: for example, *“Hooray!”*. (ii) On a first error on any task, given that it may well have been an accidental slip which on reflection the child will be able to correct

without help, the companion encourages the child to try again: for example, *“Have another go!”* (iii) On a second or subsequent error on any first (concrete) sub-task, the child is given a specific prompt to help them determine a correct response, the assumption being that two errors mean the child is unable to respond correctly to the task without such a prompt: for example, *“Make a good guess about the blocks on the scales.”* And (iv) on two or more subsequent errors on any second (labelled concrete) or third (symbolic) sub-task, the child is reminded to think about and apply what they learned in the previous sub-task: for example, *“Think about what you did last time.”*

Management tools

While there has been extensive research into GBL, far less attention has been paid to the integration of game-based learning into classroom practice and its management (Pivec & Pivec 2008). Nevertheless the importance of management to the successful implementation of interventions and digital technology in the classroom has long been established (Gross 2007; Forman *et al.* 2009; Lewin & Luckin 2010). Accordingly, and also in response to teachers’ feedback in the second intervention, the third iteration of the prototype game included an online ‘teacher interface’. This provided access to a range of management and monitoring tools for the supervising adult (teacher or classroom assistant). In fact, the numeracy game interface and tools were built upon a pre-existing system already used by the charity for online games that it offers to support its literacy intervention. The management tools enable the charity to allocate user credits to the school, and school staff to allocate game credits to individual children (Figure 6.1, p.173) and to manage the children in groups or classes (Figure 6.2, p.173).

In another part of the teacher interface, in response to another outcome of the second intervention, achievement and progress monitoring tools were added: *“it would be useful to be able to see at a glance how the children are doing* (David, Chapter 5). Data tracked automatically by the system for each child (when they played, for how long, the times they achieved, and their specific mathematical errors) were made available for easy interrogation, to enable the supervising adult to monitor progress and to identify individual successes and any weaknesses requiring further attention.

Manage your games

Organisations: St Peters

Back to main screen

Edit user: Jake S

First name: Jake

Last name: S

Email address: (optional, but helpful for password retrieval)

Group / class: Year 6

Software	Credits	Allow access
Catch Up Numeracy	6 available	☒

Cancel Save

Figure 6.1
Allocating game credits to a child.

Manage your games

Organisations: St Peters

Back to main screen

No access allocated

Access allocated but game not started

Game started (can no longer be modified)

show organisation statistics

show credit info

create group / class

Year 6	Numeracy	add new user	edit	delete	print login details
Jake S Username:jakes Password:catchup63			edit	statistics	
Ethan L Username:ethanl Password:catchup30			edit	statistics	
Morgan T Username:morgant Password:catchup53			edit	statistics	
Ruby C Username:rubbyc Password:catchup27			edit	statistics	
Mia L Username:mial Password:catchup75			edit	statistics	
Shannon S Username:shannons Password:catchup84			edit	statistics	
Zak T Username:zakt Password:catchup98			edit	statistics	

Users not assigned to a group

Numeracy

add new user

print login details

There are currently no users in this group

Figure 6.2
Managing children in groups or classes.

⁹ Figures 6.1 to 6.5 all contain dummy or anonymised data.

The data is provided at three levels of detail. The first level shows which games were played, when they were played and for how long they were played, and gives a summary record of errors made for the most recent gameplay (Figure 6.3). The second level of detail gives summary statistics for each individual gameplay (Figure 6.4), while the third level gives statistics for each individual task (Figure 6.5, p.175).

Manage your games

Organisation:

St Peters

Back to main screen

- User Statistics: Jake S

Game no.	Component	Level	Game	No of times played	Total time spent playing this game	First play date	First play time	Last play date	Last play time	Last play 1st attempt errors	Last play 2nd attempt errors	Last play 3rd attempt errors	
1.1	Remembered Facts	Level 1	Bridges	2	6m 42s	15//20 at 11:35	3m 42s	21//20 at 11:58	2m 59s	4	1	1	details
1.3	Remembered Facts	Level 2	Ladders	8	22m 27s	15//20 at 11:26	3m 8s	29//20 at 11:43	3m 40s	4	0	0	details
2.1	Estimation	Level 2	Sky fans	3	17m 4s	21//20 at 11:50	3m 31s	29//20 at 11:38	5m 51s	2	2	2	details
2.2	Estimation	Level 2	Scales	4	18m 31s	25//20 at 11:07	2m 1s	3//20 at 11:48	2m 43s	2	2	2	details

Figure 6.3

Which games were played when.

Manage your games								
Organisation: St Peters								Back to main screen
- User Statistics: Jake S								
-- Individual game play Statistics: Remembered Facts (Bridges)								
Game no.	Component	Level	Game	Time taken	1st attempt	2nd attempt	3rd attempt	
1.1	Remembered Facts	Numeracy level 1	Bridges	3m 42s	3 errors	1 error	1 error	error details
1.1	Remembered Facts	Numeracy level 1	Bridges	2m 59s	4 errors	1 error	1 error	error details

Figure 6.4

Statistics for individual gameplays.

In the example shown in Figure 6.5, p.175, Jake S made one error on the task '5 – 4', indicated by the single black exclamation mark in a yellow circle. For the same component and gameplay, Jake then made three errors on the task '5 – 1', indicated by

the three rows of increasing numbers of exclamation marks. This display thus provides the supervising adult with a quick snapshot of the child's achievement and progress.

Manage your games

Organisation:

St Peters

Back to main screen

- User Statistics: Jake S

-- Individual game play Statistics: Remembered Facts (Bridges)

--- Individual game play detailed Statistics: 15/ /20 11:35:37

Game no.	Component	Level	Game	Date and time	Task	Error level
1.1	Remembered Facts	Numeracy level 1	Bridges	15/ /20 at 11:32	5 - 4	!
1.1	Remembered Facts	Numeracy level 1	Bridges	15/ /20 at 11:33	2 + 3	!
1.1	Remembered Facts	Numeracy level 1	Bridges	15/ /20 at 11:33	5 - 1	!
1.1	Remembered Facts	Numeracy level 1	Bridges	15/ /20 at 11:34	5 - 1	! !
1.1	Remembered Facts	Numeracy level 1	Bridges	15/ /20 at 11:34	5 - 1	! ! !

Figure 6.5

Statistics for individual tasks.

Finally, a 2,000-word user-guide was written for the supervising adults, especially for those unfamiliar with the platform game approach, explaining how the game works, how it might be played and how it might be used as part of an overall intervention.

6.2 INTERVENTION

Context, sampling and methods

The intervention took place online between May and July 2012. The sampling and methods used in this intervention built on those used in the previous research cycles, hence only the differences will be discussed here.

In order to match as closely as possible the assumed context of the final game, in other words to maximise the authenticity of this cycle of the research, explicit control of the game was first handed over to the charity (the researcher retained background control and access). Participants were then recruited by charity staff, who emailed teachers and classroom assistants on their database who (i) had recently participated in training

for the numeracy intervention and were therefore assumed to have some familiarity with the numeracy concepts (numeracy components and numeracy levels) implemented in the game, and (ii) had indicated a willingness to be involved in trialling digital games that complement the intervention. The sampling was therefore purposeful (participant numbers are given in Table 6.3, p.178, and discussed in the Outcomes section below), and provided some triangulation of data from different sources. The teaching staff were offered free access for up to five children per school to play the prototype game as part of a development and research project. All teaching staff who replied saying that they would like to be involved were given details.

Initially, staff from five schools, those who had trained earliest and were therefore assumed to be most familiar with the intervention, were invited to participate (Cohort 1). Although the aim was to make the intervention as authentic as possible, as it was part of a research project, compromises were still necessary: (i) the staff were asked for their informed consent to be involved in the research and, before starting, were required to obtain informed consent from any participating children and their parents; (ii) they were asked to complete online questionnaires (Appendix J) at the start and end of the intervention and to participate in telephone interviews; and (iii) they were asked to arrange for the participating children to complete online questionnaires (Appendix J) at the start and end of the intervention.

Using the online system already familiar to them (the numeracy game was integrated into the system as just another product, alongside the charity's literacy games that they had been selling for some time), charity staff allocated each participating school five user credits. This automatically triggered an email to the teaching staff giving the numeracy game's web address, their individual log-in details, and the user guide. The staff were then free to allocate user credits to individual children and to use the game in any way that they chose. For the purposes of the research, the participating teaching staff were also given a web link to the online questionnaires.

After approximately one month, to allow time for the developer to address any problems that arose for the first cohort (although no such problems did arise), staff from

a further 45 schools were invited to participate (Cohort 2). Again in order to improve the match between the context of the intervention and the assumed context of the final game, the workload imposed on this cohort for the purposes of the research was reduced. While informed consent was obtained for all of the participants and the staff agreed to complete the online survey, they were not asked to participate in interviews nor were they asked to arrange for the children to complete any questionnaire.

Three types of data were collected (Table 6.2): interview (telephone interviews with teaching staff from Cohort 1), survey (pre- and post-intervention online anonymous questionnaires⁴ for adults from both cohorts and for children from Cohort 1, Appendix J), and numerical (data collected automatically by the system, to provide some further data triangulation, from which broad inferences might be drawn).

Table 6.2

Data collection methods used in the third research cycle.

Data collection methods	Notes	Cohort 1		Cohort 2	
		Adults	Children	Adults	Children
Interviews	Semi-structured Telephone Audio-recorded Pre- and post-intervention	✓	-	-	-
Questionnaires	Online Lickert scale responses Pre- and post-intervention	✓	✓	✓	-
Questionnaires	Online Free text answers Pre- and post-intervention	✓	-	✓	-
Gameplay data	Numeracy component, time to play, errors made etc.	-	✓	-	✓

Outcomes

The intervention involved 72 children and 29 adults, from 24 schools across England and Wales (Table 6.3, p.178). Participant numbers are reported here, in this outcomes section, for two reasons: because the implementation of the game in schools was one

focus of the intervention, but also because of the large difference between the number of schools who responded to the initial invitation and were offered free access to the game (50) and the number of schools that actually did take up that offer (24).

Table 6.3

Research cycle 3: intervention participants.

Participants	Cohort 1	Cohort 2	Total
Schools	5	19 (45 invited)	24
Adults	8	21	29
Children	20	52	72

Brief conversations, facilitated by the charity with three of the schools who were invited but did not participate, revealed some possible reasons for the low take-up: lack of staff availability, busy timetables, and changed school circumstances. The low take-up might also have been due to the fact that the offer was part of a research project and therefore had additional requirements and different implications (this was mentioned by one of the schools), or because of difficulties teaching staff might have experienced getting started with the game, logging onto the charity's website or allocating user credits to the children. However, in conversations with the three schools, none of them mentioned any technical difficulties. Given that the relationship was between the charity and the schools, it was neither appropriate nor possible to contact all the schools that had decided not to participate in the study. Those school staff who did choose to participate and commented on their decision gave as their main reason for doing so the lack of effective resources for children who are low-attaining in mathematics in general and to complement the numeracy intervention in particular.

All of the staff, both cohorts, from the 24 schools that did choose to participate, reported that getting started was mostly straightforward. The staff confirmed that they had no difficulties logging on to the charity's web-site, accessing or using the teacher interface or assigning user credits to the children. However, counterintuitively, despite the fact that the progress statistics could be accessed from the main online management screen (Figure 6.2, p.173) and that comprehensive instructions were in

the user guide provided to the teachers, only one of the teachers reported looking at the statistical information about their children's performance in the game. In fact, only that one person was even aware that the statistics were available to view.

The only difficulties when getting started reported by the staff were around identifying which children to involve. This was despite the fact that the game was offered to the schools as a complement to the numeracy intervention which they already delivered, and for which they had already identified suitable children. Almost as many different selection criteria were mentioned as children who played the game: because the child needed practice to reinforce what they had learned in class; because the child was SEN, that is they had special education needs, although for some because they were not SEN but "*needed a booster*" (Caryn)¹⁰; to support mental maths, which was identified as a 'problem for most children' (Lyn); because the child had concentration problems and made lots of 'silly mistakes' (Angela), or because they had processing problems or struggled to articulate their thoughts; because the child was dyscalculic, although what this meant in practice was never elaborated; because the child did not work well in a group, or because they were not confident enough to work on their own; because the child had poor attendance, although for some teaching staff a child's poor attendance was a reason for not including them; or because it was not clear what the child's difficulties were, and the game was seen as an opportunity to gain greater insight into their mathematical understanding and their particular needs.

Consequently, although all of the children selected to play the game were in Year 2 or Year 3, that is they were between the ages of six and nine years old, as a group they were very heterogeneous. Many of them were new to the intervention, but almost a quarter had, contrary to the recommendations of the charity (Catch Up 2009b), been on the intervention for around a year. Their previous achievements, before the start of the intervention, were also widely distributed across the numeracy levels (Table 6.4, p.180).

¹⁰ In this chapter, all quotations in double inverted commas are taken from the interviews with teaching staff in Cohort 1, while all quotations in single inverted commas are drawn from the online questionnaires completed by teaching staff from both cohorts.

While almost all of the children were working within Levels 1 to 6 across the three components addressed by the game, in two of the components they were mostly working at the lower levels: in *remembered facts* almost three quarters of the children, and in *estimation* around two thirds of the children, were working at or below Level 3. In *derived facts*, the children were distributed across the range of the first six levels.

Table 6.4

Numeracy Level of participating children at the start of the intervention (approximate percentages).

Numeracy Level:	1	2	3	4	5	6	7	8
<i>Remembered facts</i>	40%	5%	25%	15%		15%		
<i>Estimation</i>	30%	15%	20%	5%	5%	25%	5%	
<i>Derived facts</i>	30%		30%	5%	5%	30%		

NB As there are fewer than 100 participants, the figures have been rounded to the nearest 5%. Rounding errors mean that the figures given for *estimation* do not add up to 100%.

The first cohort of children were also dissimilar in terms of their self-reported levels of mathematical competence and confidence¹¹. While around half of them noted that they found mathematics difficult, and worried when they were not able to complete calculations, the remainder noted that they were confident in mathematics and were happy to do calculations in class. However, for this latter group, there is clearly a disconnect between the teachers' perception of the children's abilities, as evidenced by the fact that the children had been selected both for the numeracy intervention and the prototype game, and their own perception of their abilities.

Nevertheless, whatever their self-confidence and attitudes to mathematics, all twenty children who completed the questionnaire noted that they would be happy to play a computer game designed to help them with their numeracy, because all but one enjoyed playing entertainment computer games and most noted they believed that computer games could help them with their learning. The fact that one of the children

¹¹ The children's feedback is drawn from the online questionnaires completed at the start and end of the intervention by the children in Cohort 1.

confirmed that they did not enjoy playing computer games bears repeating, as it is something rarely acknowledged either by developers of GBL or in the GBL literature (a notable exception being Whitton 2011).

There were also wide variations in how all teaching staff, in both cohorts, used the prototype game (as corroborated by the gameplay data logged automatically by the system). They reported that they arranged for the children to play the game three to four times each week of the intervention, although in one school it was played by one child as many as ten times in a single week, and in two other schools the game was rarely used at all. On average, across all 24 schools, the children spent around twelve minutes in any one gameplay session (times ranged between two and fifty minutes), with a single game level taking around eight minutes on average to complete (times ranged between two and twenty-one minutes).

In some cases, playing a game level or two became part of the children's regular numeracy session, either as a warm-up at the start of the session, or as an incentive or reward for effort at the end of the session, *"the digital games are a treat, an added bonus"* (Louise), or as a complete alternative to the session: *"with that one boy, I didn't do the normal [numeracy intervention] session, as I did with everyone else..., I only worked with him on the games because, working with him one-to-one, his concentration still wasn't good"* (Sandra). This is again contrary to the advice of the charity, who recommend that the child should receive two complete numeracy intervention sessions twice a week and, as noted in the user guide, that the game should be used only as a supplement. This extensive use of the game, to replace all or part of the sessions, might have been because the participating school staff were unsure of the status of the game *vis-à-vis* the numeracy intervention, or because they were aware that they were participating in a research study and were therefore keen to use the game as much as possible. Other schools used the game whenever the child's timetable permitted, sometimes before the numeracy intervention session, sometimes afterwards, and sometimes at random times in the school week to avoid the child missing the same lessons. For other children, the game was specifically timetabled. The most popular time, outside of the sessions, was the start of the school day, with the children being

withdrawn from assembly: ‘that was the only time I could fit it in’ (Jocelyn). In one school, the participating children were pulled out of the end of their usual mathematics lesson so that they might play the game and consolidate their mathematical thinking, even though it is unlikely that there was ever a direct match between the mathematics covered in class and the mathematics played in the game.

Most of the staff arranged for the children to play the game on their own, so that they might concentrate ‘without distractions from other children’ (Christine) while giving the adult the opportunity to support and observe at the same time: *“I like to be with the children when they play the games because I want to understand also where they’re going wrong”* (Sandra). Other staff arranged for two or more children to play the games together, and allowed them to discuss their play as they did so (which will be discussed in more detail below); while several of the teaching staff used the game for what was described more than once as ‘park and play’: giving the children something constructive to do while the adult was otherwise engaged. For example, one classroom assistant described how she would take three children at a time out of their class. Two of the children would sit at one end of the room, quietly playing the game, while she delivered the numeracy intervention to the third. At the end of each fifteen minutes allocated to the numeracy intervention, the children would swap activities.

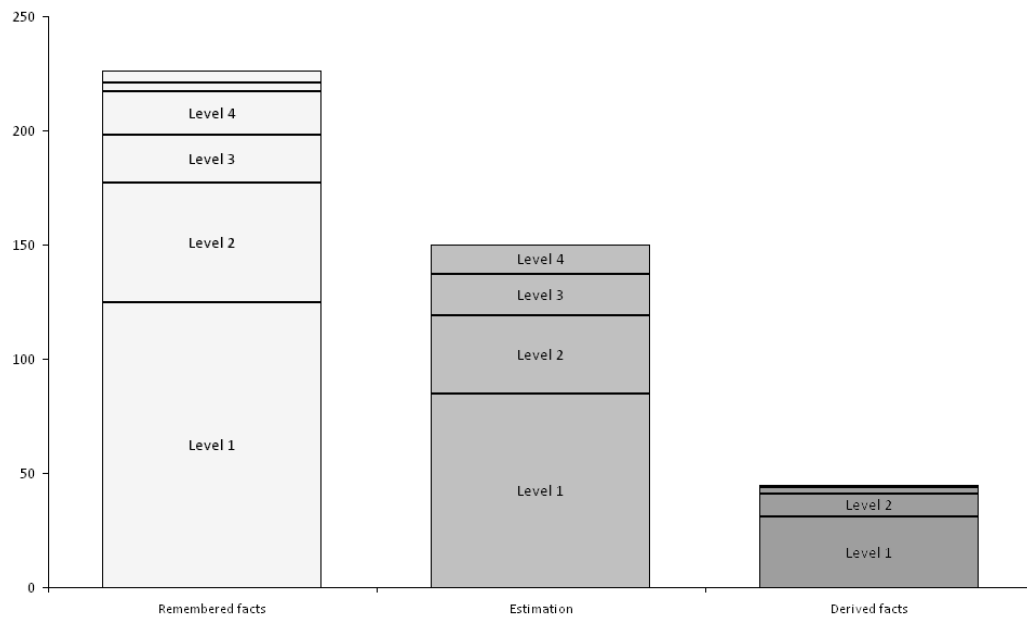
In total, as reported in the gameplay data logged automatically by the system, the children played 421 games across the three components (Table 6.5 and Figure 6.6, p183). For example, the *remembered facts* component was played one and a half times as often as the *estimation* component, and around five times as often as the *derived facts* component.

Table 6.5

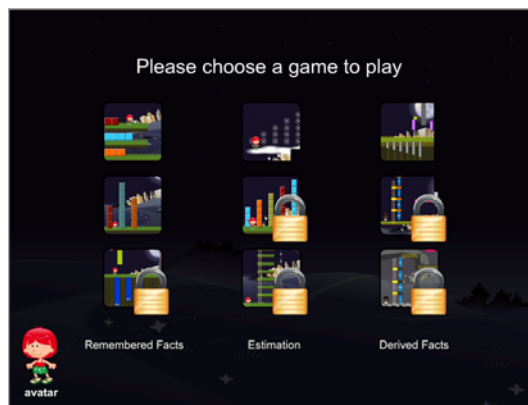
Number of times each numeracy level (number range) in each component was played.

Numeracy Level:	1	2	3	4	5	6	All
<i>Remembered facts</i>	125 100%	52 42%*	21 17%	19 15%	4 3%	5 4%	226
<i>Estimation</i>	85 100%	34 40%	18 21%	13 15%	0	0	150
<i>Derived facts</i>	31 100%	10 32%	3 10%	1 3%	0	0	45

* The percentage figures are calculated with respect to the number of times Level 1 was completed.

**Figure 6.6**

Number of times each numeracy level (number range) in each component was played.

**Figure 6.7**

Menu screen.

Inevitably, as frequently encountered in the emerging field of learning analytics (Bienkowski *et al.* 2012; Ferguson 2012; Siemens 2012), such an observation raises more questions than answers. Did the children mostly play *remembered facts* because the teaching staff believed they needed more practice in this particular component? Was it that the staff were less comfortable with or less interested in tackling the other components? Was it because the game's implementation of *derived facts* continued to have problems? Or was the reason more prosaic? Were the games played in this

pattern simply because that is how the components appear in the menu, and because of player inertia? In other words, was *remembered facts* played more often simply because it is, reading left to right, the first column in the menu, and once they'd started with that component, the children and adults simply stuck with what they knew? The interviewees were unable to clarify, although two did comment that few children played the *derived facts* component because of its poor implementation.

Table 6.5 (p.182) and Figure 6.6 (p.183) also clearly illustrate the drop-off in game plays from level to level, with the drop-off between levels played in the *remembered facts* and *estimation* components being broadly similar: around 40% of those who completed Level 1 in the *remembered facts* and *estimation* components also completed Level 2, around 20% also completed Level 3 and around 15% also completed Level 4. The drop-off between levels for the *derived facts* component is far more pronounced: 32%, 10%, 3%.

The data logged automatically by the system also includes the amount of time taken to complete each numeracy level for each component. However, this data comes with two 'health warnings'. First, the data for the numeracy level (number range) does not account for the impact of the game level (animation and gameplay) on the amount of time taken. This is important because the numeracy level and game level were dissociated from one other in the second iteration of the prototype game, such that it is possible to play any game level at any numeracy level, and some animations simply take longer to play. Second, 'time taken' refers to the time between the game start and the game end. But clearly there is no record of whether the child was actually playing the game all that time, or whether between tasks their attention was elsewhere, possibly because they were engaged in meaningful conversation about the mathematics, alternatively for other less productive reasons. In addition, unfinished games are not recorded: a child may well have played a game for some minutes before abandoning it but that time in play would not be recorded. Nonetheless, taking these important caveats into account, some broad inferences might still be drawn from the data.

The median time and range of times taken to complete each numeracy level for each component is illustrated in Figure 6.8, p.185, (the median time is used rather than the

mean to reduce the impact of outliers at the top end of the data). Immediately apparent are the differences between the components, with the *derived facts* numeracy levels taking around twice as long to complete as the other two components – another possible reason why the *derived facts* levels were played less often. For the other two components, *remembered facts* and *estimation*, it is possible to discern in the graph a slight reduction in the time taken across the numeracy levels¹², despite the fact that the number range and the nominal level of difficulty increases from level to level. However, this interpretation of the data while possibly seductive requires another ‘health warning’.

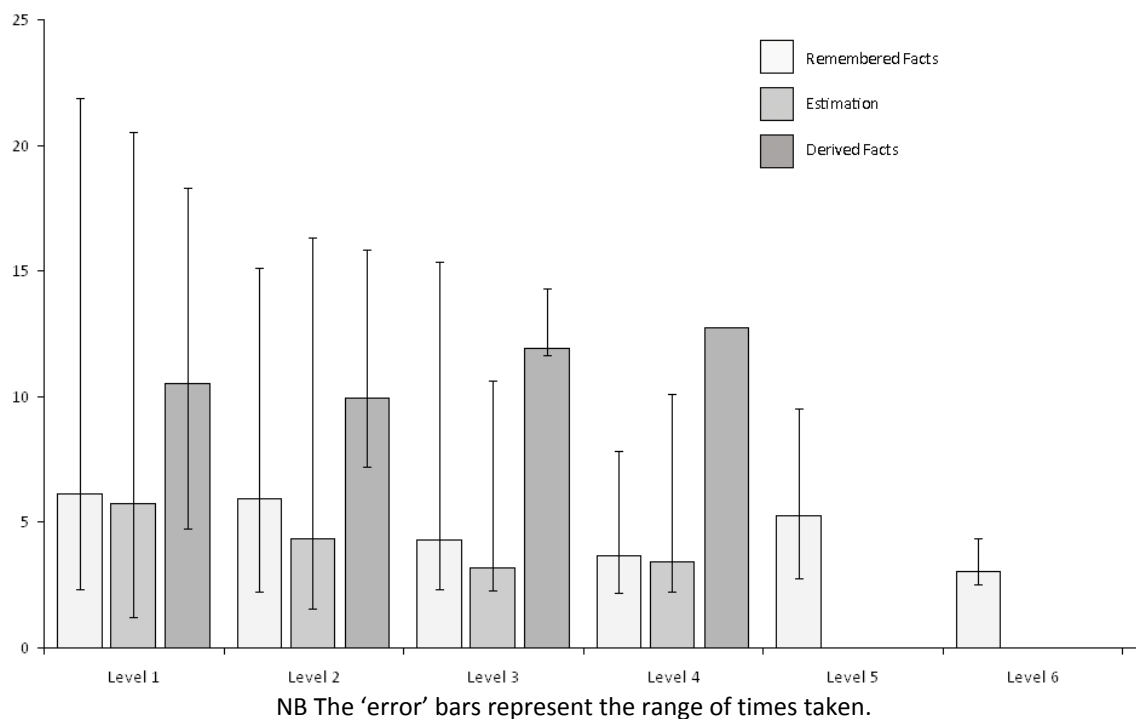


Figure 6.8

Median time (minutes) taken to play each numeracy level in each component.

¹² *t*-test analyses comparing the time taken to complete the first and fourth levels for the *remembered facts* component and for the *estimation* component confirmed that there were statistically significant differences between them. However, for the reasons given in the main text, any inferred impact of the game cannot be relied upon and so is not considered further.

Rather than showing that the children got faster with the number ranges as they moved up through the levels, it might simply suggest that the children are faster at playing the game elements (animation and gameplay): any experimental study would need to distinguish between these two entangled features of the game. The children's acceleration through the levels might also be attributable to the other teaching that they had received during the same period, or indeed by their general maturation.

Nevertheless, whatever the numerical data or its interpretation, most of the teaching staff said they believed the game to be broadly effective and worthwhile, *"some students had been very reluctant during sessions but were much more involved with the games"* (Suzi). As a consequence, depending on the needs of the individual children and the availability of sufficient time and space, they would choose to use the game again in the future: *"I think at least two of the boys have learned by playing the games, I think that has come out in their maths"* (Denise). The game was seen as being particularly effective in encouraging the children to engage with the mathematics repeatedly, until they achieved some success: *"working in the game, it did slow him down, it did actually focus his mind, he did try to rush through most of the calculation but of course the system wouldn't let him go across the hole until he had completed the calculation, that was really good"* (Sandra). Many of the staff also commented that playing the game had helped the children to reinforce their classroom learning and, particularly for those working at National Curriculum Level 2, to consolidate their numeracy; while others argued the games gave the children more confidence, a willingness to try things with little fear of failure or embarrassment, and provided an 'extra way to learn' (Lynne).

While some staff expressed concern that the game elements might overshadow the mathematics, for most situating the mathematics in the virtual world of the computer game was key. Because the children enjoyed playing entertainment computer games, they were prepared to 'put up with' the mathematics in the context of playing the game, 'the game format encourages those who find learning maths a chore to participate' (Jeremy). However, for one staff member, it was the fact that the game involved using a computer, rather than anything intrinsic to the game itself, that was thought to be most important:

“from his point of view it looked great because he enjoys using the computer..., it didn’t actually matter that he was doing some maths at the same time” (Sandra).

In any case, most of the children enjoyed playing the game, ‘they wanted to talk about it every time they used it’ (Alun), and thought it had helped them with their mathematics, *“the one who made the most progress loved them..., he really enjoyed going to the sessions, really enjoyed playing the games and played them at home”* (Amy). However, not all of the children found the game easy to play. Whether this was because of the mathematics or the gameplay was not clear from the questionnaire responses, although the children did differ widely in how easy they found the mathematics. Nevertheless, the follow-up questionnaire completed by the first cohort of children revealed some improvements in their self-confidence, in their learning tenacity (their refusal to give up in the face of difficulties), and in their growth mindset (their belief that they could do better if they tried again, Dweck 2000).

The children enjoyed the look and feel of the game (even if at least one adult thought the game looked dated), and particularly liked being able to choose which game level (animations) to play. They also liked the gamification elements (Deterding *et al.* 2011; Groh 2012): being able to individualise their avatar, unlocking game levels, collecting the coins, and the leader board, *“they enjoyed seeing where they were, whether they’d moved up..., and that sometimes they were quite high up the leader board..., that made them feel good about it all”* (Sandra). In addition, around two-thirds of the children liked the now-talking companion and found what it said ‘very useful’. Most also liked being able to work out how to answer the tasks, rather than just being tested on what they already knew, being able to try as often as they wanted, and the immediate feedback. And, according to the adults, they particularly liked being able to explore the mathematical possibilities without leaving behind telltale marks, as they would if they were making corrections on paper.

As noted earlier, most of the children played the game on their own, while the adult watched and supported them. The teaching staff valued being able to observe the children, in order to learn more about their mathematical understandings and skills: ‘it

was interesting to see how they worked out sums they struggled on without any other support' (Christine), *"the [classroom assistants] learned more about the children's different styles of approach"* (Louise), 'watching them on the computer has been really useful for screening, to help decide whether or not they are SEN' (Lynne). But for others it was as important, if not more so, to use the game to engage the children in discussion about their learning.

From my perspective, they needed the adult interaction, it's not a park-and-play activity, there needs to be that engagement with the adult, I think the games give an opportunity to talk and explore..., the numeracy is challenging to deliver and you all get far more out of it if there is the conversation and the digital games can support that process..., I was able to have sensible discussions with the children about their progress, in terms of the strategies they were using and what they needed to do to work it out. (Denise, interview)

The conversation provided an opportunity for the adult to focus on the child's approach to mathematics: *"it's about ensuring they understand the process rather than just clicking on the right button, that's the idea why they do them before the one-on-one, so there can be a couple of minutes discussion"* (Caryn).

Only around a quarter of the teaching staff used the game with groups of children, but those who did so found the conversations that it generated valuable. Playing the game with their classmates encouraged children who rarely elsewhere engaged with mathematics to vocalise and discuss the strategies that they were using, raising levels of mathematical understanding for everyone taking part in the discussion: 'they were talking about maths whereas before they kept quiet' (Dafydd), 'by talking it through they were making sense of the decisions that they had to make' (Janice), *"there were times when they were talking through the method, you need to do this, or need to think that..., that helped him because he was explaining it and it helped the others because sometimes it's different having something explained by your peers rather than by an adult..., the peer interaction means that they are engaged at all times"* (Denise). For some of the children, these conversations with their peers provided a rare opportunity to shine, mathematically, in public: 'in some cases the students helped each other, and showed off their skills which made them feel empowered' (Janet).

To encourage discussion around the mathematics and learning was one reason the teaching staff gave for asking parents to play the game with their children (to enable parental access, the child's individual login details could be printed from the system). Another reason was simply to provide homework which the teaching staff could easily monitor (even though this facility was only used in one school): *"We gave the children their passwords so they could play them at home, and I could monitor how many hours they spent on them"* (Linda).

Almost all the schools passed on the children's login details, but giving the parents access in this way had varying degrees of success. At one school, all the gameplay took place at home; at another, fewer than half the invited parents got involved. In any case, although the children's survey indicated that the children liked being able to discuss the game as they played it with their parents, the teachers' survey only referred to parents a few times: 'the parents said the children were enjoying and learning with enthusiasm' (Bethan), 'the parents were very keen on it and encouraged the children to play it' (Ceri), and 'it helped us to feel more of a team and see where their child need help' (Jeremy). The low emphasis placed by teachers on using the game to involve parents, despite suggestions in the user guide and the well-known contribution parents can make to their low-attaining children's progress (Baker 2003; Davies & Spencer 2010; Peters *et al.* 2008), is unfortunate; particularly as earlier research has shown that similar games designed for literacy (Holmes 2011) and an interactive mathematics education system designed for primary school children (Lewin & Luckin 2010) have been used to provide parents, who otherwise might have limited contact with their child's school, a conduit and catalyst for discussion about the child's needs and progress.

Several teachers did, however, comment on a cumulative disadvantage or Matthew Effect¹³ (Merton 1968; Stanovich 1986; Walberg & Tsai 1983) attributable to the parental home: *"It was very obvious which children had access to a computer on a*

¹³ "For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath" (Gospel according to Matthew, XXV, 29.)

regular basis and which didn't; those who had access previously were very quick to pick up how to use the games; those who hadn't, struggled a bit" (Lesley). The teachers were concerned that children who do not have access to a computer at home, as is the case for children in a third of low-income UK families (Office for National Statistics 2013), are further disadvantaged (Jackson *et al.* 2006), especially in the context of computer-based resources such as digital games for which they might therefore require additional support: *"For the children who weren't familiar with computers, I spent as much time explaining what they had to do in the first instance..., others were very savvy about what they had to do or they were able to work out what they had to do without any input from me"* (Amy).

The theory-based approach to learning adopted by the game (emphasising both knowledge construction and retrieval practice, while incorporating Bruner's 'spiral' of learning moments and 'modes of representation') attracted positive comments from almost all the teaching staff. For example, always beginning the game at the lowest numeracy levels (the lowest number range), whatever the child's current numeracy level, before building up to the larger numbers, was considered generally effective. Starting low was thought to give the children a chance to familiarise themselves with the game by using numbers in which they were already very confident, helping to build their self-esteem. However, three problems were mentioned: (i) some of the children, according to the staff, thought that starting with the lowest numbers was boring and 'a waste of time' (Michael); (ii) starting low meant that sometimes the *estimation* tasks were inauthentic, as the children often knew the correct answer and so had no need to estimate, *"it's strange with estimation because the children don't really want to get things wrong"* (Sandra); and (iii) building the number ranges up in the background, rather than explicitly, took away useful scaffolding and opportunities for the children to notice and hence reflect upon their own progress. In fact, the game does explicitly flag up the child's progress in the numeracy: once a child has completed a numeracy level they are presented with a screen and spoken message that celebrate the fact that they have 'moved up a level' (Figure 5.2, p115). Nevertheless, at least one staff thought that this was not sufficiently explicit: 'When they went up a level, I just

wondered if more could be made of the fact that next time they log on they're going to be working with higher numbers' (Dafydd).

The way in which the game provided opportunities both for knowledge construction and retrieval practice was approved by almost all the respondents. The constructivist approach operationalised in the first of each set of three sub-tasks, in which the player constructs their own mathematical knowledge by manipulating concrete objects, was again mostly thought to be useful. The staff commented, both in the interviews and questionnaire, that the children liked being able to make several attempts and enjoyed learning from their mistakes, without the negative feelings of failure that they sometimes experienced elsewhere when doing mathematics. It helped them realise that getting the answer wrong was nothing to worry about, and that they could work out the correct answer if they kept trying. This 'trial and error' approach also allowed them to take ownership of the concept, which was then consolidated by means of the repeated practice.

For one teacher, however, the game was entirely unsuitable for introducing mathematical components. She preferred to teach the concept of the specific component one-to-one, teacher directly to child, using where appropriate physical rather than virtual objects, and used the game just for reinforcement. Another teacher, however, thought the knowledge construction was effective so long as it was mediated by an adult: *"I think it's useful that the children can discover the answer by playing with the objects but I think there has to be adult involvement to help them vocalise the thought processes, to tease out what they need to do..., they don't easily arrive at the right answer on their own"* (Lesley). With that caveat, this teacher liked the way in which the game implemented Bruner's modes of representations: *"Once I'd sussed it out, I liked the way you get the same task three times..., that made sense to me, it worked for me because it's how you would deliver it if you were delivering it hands on..., you could see the children making the connections stronger over time"* (Lesley).

Other teaching staff also commented positively: the approach provided a step-by-step process which 'helped fix things in the concrete before the abstract' (Lynne), as the

children used the objects to help them work out the number task, *“it gives the children an awareness of what numbers look like in real terms”* (Suzi). This was particularly useful for one child who began with little understanding of numerals. However, two members of staff described how some of the children found the constructivist approach difficult and confusing. Whether it was because of the numeracy task, the way in which the task had been implemented, the gameplay or the process of knowledge construction itself, the staff were unsure; but the children’s frustration meant they soon lost interest. Nevertheless, by the time that most of the children had used the game once or twice, they understood the progression, had noticed patterns in the mathematics and had begun to build their level of understanding.

Most of the teaching staff thought the practice based around the repetition was also useful, to help the children increase their speed in mathematical thinking, to help improve their short-term memory, and to provide multiple opportunities for the teaching staff to appraise what the children knew and understood. But mostly, the repetition was thought useful because the numeracy in the game both complemented and reinforced what had been learned in the individual numeracy session: *“the repetition did help them secure their remembered facts”* (Sandra). And it was because the repetition was wrapped up in the gameplay that the children were more willing to put in the necessary effort: *“it’s an attractive medium for them to practise their skills again and again... and get more confidence in the components”* (Linda). Inevitably, there was however some disagreement, with one member of staff commenting that the game levels were too repetitive, although it was unclear from the phrasing of the responses whether they were too repetitive for the child or the adult; and another pointing out that, that when the mathematics was ‘too easy’ (Janet), the children thought the repetition was boring.

The teaching staff, almost all of whom were familiar with the numeracy intervention, also questioned the way in which the numeracy components had been implemented in the game. It is a core principle of the numeracy intervention that activities undertaken in any individual session should always focus on just one component: in other words, an activity chosen to give the child practice with *remembered facts* should not involve

counting or estimation (Catch Up 2009b). However, one of the teaching staff pointed out that the components in the game sometimes “*run into each other*” (Sandra): the first *remembered facts* sub-tasks, for example, which require the children to complete problems using blocks or ladders, cannot be answered by recalling already known mathematical facts but only by counting or estimating.

Most of the teachers were less familiar with the platform approach adopted by the game, which also caused them some concerns. The disassociation of numeracy level and game level, for example, caused particular confusion. Comments included: ‘extremely hard to understand how to play’ (Michael), ‘took a long time to work out objective’ (Alun), and ‘the children found it easier than me’ (Steph). The assumption that teaching staff would be more likely than the typical digital-game player to read written instructions (Gee 2004b) proved to be incorrect. Despite the two thousand words of the user guide, which set out to explain exactly how the game functioned and could be played, the belief was that instructions weren’t given. An alternative approach, suggested by one respondent, was for the learning companion to be more pro-active. Instead of just reacting to the user’s actions, at the start of each task it could explain briefly how that task might best be tackled (for example, how to use the spacebar to select the blocks to fill the gap so that it might be crossed) and how the following section of virtual environment might most effectively be negotiated (for example, the need to press the arrow keys repeatedly to make the avatar jump higher).

The final outcome from this intervention that warrants mentioning concerns the level of control, real and perceived, that the teaching staff could exercise over the game. As previously described, each component in the game always begins at the lowest numeracy level (number range). In other words, at the start of a component, the level of difficulty presented in the game is unrelated to the child’s current numeracy level as assessed in the numeracy intervention sessions. The game then progresses up through the numeracy levels, independently of the game levels (animations), according to the success of the children in each task. If the children are mostly successful in a gameplay, the next time they will be given tasks from the next highest numeracy level. If they are mostly unsuccessful, they will continue working with numbers from the same

numeracy level. It is in this sense that the game is adaptive. However, some teaching staff gave reasons why they thought this approach should be amended: to avoid the tasks being 'too easy' and hence 'boring', so that the tasks presented in the game matched the child's current numeracy level as assessed in the intervention session, and so that the level of difficulty could be adjusted to deal with if the child received help at home from a parent or sibling: *"I'm just thinking of a child..., who might play on a game with an older brother or sister or mum or dad..., they then obviously go through to a higher level..., however, when they're back in school, because they don't have the mum, dad, brother, sister next to them, they then can't access that game"* (Caryn).

6.3 ANALYSIS AND REFLECTION

This chapter has discussed the third cycle of design and intervention, which involved teaching staff who were invited to participate by the charity. The aim was to determine whether the observations of those staff, and of children who played the game under their supervision, provided some validation of the previous interventions and helped the research to achieve a sufficient level of theoretical saturation.

Research sub-question 3.1

In what ways do the observations of additional teaching staff and children and gameplay data reinforce or refute relevant outcomes of the previous interventions?

A key outcome of the previous intervention was the recognition that implementing in a school a game designed to support children who are low attaining in mathematics can be especially challenging. Games consume a variety of resources: budget to make the original purchase, the availability of school staff, the children's time, and access to ICT facilities. It also requires that the staff tasked with its implementation believe that the game has some value for the children and is thus worth their efforts. The fact that, in the final intervention, fewer than half of the schools who asked for and were given free access to the game were able to make use of it, together with the wide variation in the ways in which the participating schools did use the game, only serves to

underline the previous finding: the complex nature of the classroom setting that a game designed to support learning must accommodate (Berliner 2002; Brown 1992). This final intervention also reinforced the previous observation that the single category 'child low attaining in mathematics' covers a complex variety of individual learning needs: different mathematical competencies, different likes and dislikes, different learning experiences, and different levels of confidence, differences which made it difficult for some staff in the most recent intervention to decide which children to include.

Nevertheless, like most of the teaching staff in the previous interventions, most in this intervention were generally positive about the impact of the game on the children who played it. The staff in all the studies have identified improvements in children's engagement with mathematics, their mathematical abilities, their self-confidence, and their willingness to try things with little fear of failure, as outcomes of the children playing the game; and many of the staff have commented that playing the game helped the children to reinforce their classroom learning. In addition, the questionnaires confirmed that almost all of the children in the most recent intervention, like those in the previous studies, enjoyed playing the game and believed that it had helped them with their mathematics; and as before, almost all of the children enjoyed being able to choose which game level (animations) to play, the look and feel of the platform-styled game, and the gamification elements (being able to personalise their avatar, the collecting of coins, and the leader board).

Similarly, almost all of the teaching staff in the final intervention agreed with the earlier participants that integrating the mathematics in a digital game was effective. In particular, doing so increased the children's motivation to engage. Situating the mathematics in something with which they were familiar and was meaningful to them gave these children who are low-attaining in mathematics a way into the subject that elsewhere they found especially difficult. In addition, they were prepared to 'put up with' the mathematics in the context of playing the game because the mathematics seemed to emerge naturally from the gameplay. However, for some teaching staff in each of the studies, this 'chocolate-covered broccoli approach' (Bruckman 1999) is not

without problems. Staff in each of the last two studies raised a similar concern, that the game features, despite the constructivist approach used in the first sub-task, might overshadow the mathematics and therefore delay or reduce the children's engagement with the mathematics that they encounter in the classroom. In other words, rather than using a medium that allows the children to 'put up with' the mathematics, these teaching staff would have preferred something that would help the children discover mathematics' intrinsic value.

The majority of teaching staff in the final intervention agreed with those in the previous interventions that the theory-based approach to learning adopted by the game was effective. The way in which the game implemented Bruner's three modes of representation was again approved: *"it worked for me because it's how you would deliver it if you were delivering it hands on"* (Denise). In particular, the way in which the first of each set of three sub-tasks encourages the child to construct their own knowledge by manipulating concrete objects, while the subsequent sub-tasks moved from the concrete to the symbolic and provided opportunities for practice which helped consolidate the learning, was again mostly thought to be useful – even if sometimes, as before, the children used the numbers to help them work out the objects rather than the other way around as had first been intended. And the fact that the children were able to use a 'trial and error' approach, to make as many attempts as they needed, learning from their mistakes without fear of embarrassment or the 'negative feelings of failure' that they sometimes experienced elsewhere when doing mathematics, was again commented upon very positively.

The teaching staff in all the studies agreed that the practice based around repetition brought multiple benefits, for the children to consolidate their mathematics and for the teaching staff to observe what the children knew and understood – although for some the game levels were too repetitive. But for the staff in the final intervention, who were very familiar with the numeracy intervention, the key benefit was that the practice both complemented and reinforced what had been introduced and learned in the individual numeracy session.

While some of the school staff in the two most recent interventions were confused by it, the spiral adaptive approach adopted by the game, which involved the disassociation of the numeracy levels (number ranges) and game levels (animations) and the automatic increase in difficulty beginning at the lowest numeracy level, was also again received mostly positively. However, whereas one teacher in the second intervention had suggested that the game needed to provide more of an automated structure, staff in the most recent intervention said they would have liked the opportunity to intervene: to be able to decide where to start the child in the numeracy levels, perhaps according to their numeracy level in the intervention sessions, because if the tasks were too easy the child quickly became bored, and to be able to adjust the child's numeracy level as appropriate at any time in the game. Meanwhile, teaching staff from both recent studies also thought that the children's progress through the numeracy levels in the game should be made more explicit.

Despite the importance to this research of the theory-based approach to learning adopted by the game, the key outcome of the earlier two studies was the game's potential as a fulcrum for social interaction and discussion. Five potential conversations were identified: between the participating children, between the children and the supporting adults, between the teaching assistant and the teacher, between the parent and their child, and between the parent and the teacher. This potential was also highlighted by the final intervention, albeit in a more limited way. While almost all the teaching staff in the final intervention very much valued observing the children play the game, and others thought that conversation with the child centred on the game was particularly useful, only a few arranged for it to be played in groups, and only two commented on their conversations with parents. However, as in the earlier studies, teaching staff in this intervention argued that the child would benefit most from the game if it was used with adult discussion *"to help them vocalise the thought processes, to tease out what they need to do"* (Denise). And as before, many of the children got most out of playing the game with their classmates. This encouraged children who elsewhere rarely engage with mathematics to discuss the

mathematical strategies that they were using, thus raising levels of mathematical understanding for all the children taking part in the discussion.

There was however an outcome of the final intervention that had not been mentioned in the previous studies, the possible contribution of the game to a cumulative disadvantage or Matthew Effect for those children who don't have access to a computer at home. The concern expressed by two of the teaching staff involved in the final intervention was that, for those children who have not had much exposure to computers or computer games, the prototype game represented more of an obstacle to their mathematical progress, as they first had to learn how to use a computer game, rather than an aid. A sandbox approach, in which the game itself shows you how to play, might begin to address but would not solve such a problem.

Research sub-question 3.2

What impact does experiencing the game in a more authentic context have on the participants' use of the game and on their perception of the game's value?

In the final intervention most of the participating teaching staff were easily able to get started with the game, logging onto the charity's website and allocating user credits to the children – all without any help or guidance from the researcher. However, like two of the teaching staff in the previous intervention, many of the adults in this intervention were unfamiliar with digital games, their characteristics and how they are played. It might be tempting to explain the difficulties they therefore experienced, such as understanding how to play and working out the gameplay objectives, in terms of a 'digital immigrants' versus 'digital natives' contrast (Prensky 2001b), but for many reasons this is a highly contested area and an unhelpful characterisation (Bayne & Ross 2007; Bennett *et al.* 2008; Helsper & Eynon 2010). For example, not all the children were familiar with playing computer games, particularly those who did not have access to a computer at home, nor did they all find the game easy to play. Meanwhile, on the other hand, almost all the teaching staff appeared to adopt an approach more often ascribed to 'digital natives': rather than reading the available instructions, they assumed the gameplay would be intuitive and were critical when they found it not to

be as they expected. Given this context, if digital games are to be used effectively in schools to support children who are low-attaining in mathematics, or indeed to support any children, there is likely to be a need for some form of professional development centred on games-based learning (Becker 2007; Jones 2004; Ketelhut & Schifter 2011).

The low take-up of the game by those schools that had expressed an interest, the consequences for the implementation of the game of the complex nature of the school environment (Berliner 2002), and the heterogeneity of the participating children have all been mentioned earlier. However, what has yet to be considered is the fact that these particular school staff were invited to participate in the final intervention because they were very familiar with the numeracy intervention, the logic being that teachers and classroom assistants who have been trained to deliver the intervention are the most likely users of a finished version of the game. The observations of these likely future users about the way in which the numeracy intervention had been interpreted in the game are therefore especially useful.

For the most part, the teaching staff thought that the implementation of the numeracy intervention in the game was effective. In particular, the separation of the components into separate game levels matched the way in which they had been trained to deliver the individual sessions. However, as mentioned previously, one teacher pointed out that the components in the game appeared sometimes to ‘run into each other’: the first *remembered facts* sub-tasks, which require the children to complete problems using blocks or ladders, cannot be answered by recalling already known mathematical facts but only by counting or estimating, both of which are themselves separate numeracy components. There is therefore, on reflection, a flaw in the approach taken in the game’s design. The design seeks to leverage the positive aspects of both the numeracy intervention, which dictates rightly or wrongly that the components should be kept strictly separated, as well as Bruner’s modes of representation, which as they have been interpreted mean that more than one component might be addressed in any one gameplay. Any future design of the game might therefore have either to relax the intervention’s strict separation, or abandon the implementation of Bruner’s mode

of representation. Or at least, as the teacher's observation points out, the game probably cannot implement both at the same time.

Various other issues were raised by the more authentic approach adopted in this final intervention. To accommodate the disparate approaches of the teaching staff, a digital game for children low-attaining in mathematics needs to provide a structure which is both didactic and flexible. While it should encourage children to play what they need to play, rather than what they find easy to play, it should also allow the adult to intervene easily, to decide what they believe the children should be practising, to fit in with the child's specific needs or their classroom learning. Rather than being limited to being a 'park and play' activity, it should also encourage and facilitate conversation: discussion between the child and the adult, and collaborative learning between the children, which some of the teaching staff argued was particularly valuable. Finally, the teaching guide and possibly professional development, ought to highlight the potential of the game as a catalyst or conduit for conversation with otherwise hard-to-reach parents, as well as the potential benefits of parents using the game to involve themselves in their children's learning.

Discussion

This study was grounded in a sequence of premises (Chapter 2), beginning with the recognition that there are some children who are low-attaining in mathematics for whom conventional intervention is insufficient, and ending with two contentions: that digital GBL might be especially suitable for those children, and that few examples of GBL are grounded in learning theory. These premises provided a starting theoretical framework and suggested a design-based investigation (Chapter 3) into both the design and use of a prototype digital game for children who are low-attaining in mathematics that implements principles of an effective mathematics intervention and insights from learning theory and the cognitive sciences.

The study aimed, therefore, to develop theory about both the process of learning and the medium designed to support that learning, learning theory and learning design theory (Figure 3.6, p.54). It addressed two interdependent central research questions: How might a prototype digital game be designed to support children who are low-attaining in mathematics? What happens when such a game is used in schools?

Before continuing the discussion, it is important to consider first the impact of the interests mentioned in Section 3.2, specifically that the numeracy intervention was co-authored by this DPhil candidate, that until December 2011 the research was partly funded by the Esmée Fairbairn Foundation via the Catch Up organisation, and that the Catch Up organisation have indicated that they intend selling a modified version of the prototype game.

As discussed in Section 2.2, the numeracy intervention was selected for this research because it is a lighter touch intervention that does not require the involvement of specialist teachers, it has some synergy with digital games (such as the levels of difficulty) and it has been shown to be effective (Holmes & Dowker, in press). However, the fact that, as a co-author, this DPhil candidate was more than familiar with the numeracy intervention and valued its principles also naturally played a part in the decision (Anderson 1998). Nevertheless, a critical approach was adopted towards the numeracy intervention, despite this candidate's involvement in its authorship. This is evidenced by questions raised in the following discussion about some of the numeracy intervention's core principles.

Throughout the research, an arm's-length relationship was maintained with the funding charities. The charities had no other involvement in the research (apart from in the third research cycle when, as discussed in Section 6.2, the Catch Up organisation facilitated access to the game for teaching staff). In particular, neither charity had any involvement in the specification or design of the prototype game, nor did they contribute to any data gathering or data analysis for the research, nor did they have any opportunity to exert any influence on the outcomes, discussion or conclusion.

Nevertheless, it must be acknowledged that an aim at the outset of this design-based investigation was to work towards an 'effective' game and to identify useful principles for its implementation in schools. This is because devising effective support for children who are low-attaining, thus making education fairer (Selwyn 2012), is important both for the individual children and for society in general. However, as evidenced in this thesis by the discussion of both positive and negative feedback and the recognition of the various ways in which the prototype game falls short of being effective, every effort was taken to represent accurately and rigorously the outcomes of this research (Ross et al. 2010).

As discussed in Chapter 3, there were three cycles of design, intervention, analysis and reflection. The first research cycle (Chapter 4) involved the initial design of a prototype game, grounded in the review of the literature, which was researched in one school in what was in effect a low-fidelity laboratory study. The second research cycle (Chapter 5)

involved the design of a second iteration of the game based on the outcomes of the previous research cycle, including the input of teaching staff and children, which was researched in more depth, in three more authentic school contexts. The third research cycle (Chapter 6) involved the design of a third iteration of the game based on the outcomes of the second research cycle, which to help achieve theoretical saturation and to situate the research in as authentic a context as possible was researched online with 24 schools.

Each of the three research cycles addressed a separate set of research sub-questions. All of these aimed to contribute to the study's central research questions but each was developed according to the context of the particular intervention as well as, when appropriate, in response to the outcomes of the previous research cycle. As a consequence, the chapters reporting the three research cycles have discussed a wide range of outcomes. In this chapter, the intention is to re-focus on the central research questions by discussing three key outcomes. For the first research question, this chapter will consider the learning theory core of the prototype game: including the numeracy intervention and Bruner's modes of representation. For the second research question, this chapter will explore the potential of a well-designed digital game as a fulcrum for social interaction and discussion. First, to provide context, the prototype game's design and some general outcomes are briefly reviewed.

7.1 DESIGN REVIEW

The design began with the decision to synthesise behaviourist and guided constructivist approaches to learning in the format of a digital game: to foreground learning through gameplay while providing multiple opportunities for practice. Some examples of recent GBL adopt wholesale a constructivist approach (for example *Quest Atlantis*, Barab *et al.* 2005), while most GBL adopts an entirely behaviourist approach (for example *Neurogames*, Reed 2010). In contrast, the prototype game draws on both (Burkhardt 2006). In addition to providing opportunities for the child to construct an answer meaningful to them, the game also delivers multiple repetitions and deliberate

practice, in order to help them encode what they have learned into their long-term memory, to achieve the numeracy automaticity that they need to progress in their mathematics (Howard-Jones 2009; Meyler *et al.* 2008; Shaywitz & Shaywitz 2008).

The game's design also implements principles from the numeracy intervention and incorporated an interpretation of Bruner's modes of representation. Four principles of the numeracy intervention were translated into the prototype game: the componential approach to numeracy, the levels of attainment, the focus on only one numeracy component at one level of attainment in any one session, and the learning objectives. The modes of representation were incorporated into the game to support the child's transition from the concrete to the symbolic, and to give additional opportunities for deliberate practice. In the prototype game each task is presented three times: first, only the concrete objects are shown, then the objects labelled with numbers, and finally only the numbers (Figure 4.5, p.81).

Having considered a variety of digital game genres, the prototype game was designed as a non-violent platform game (a genre exemplified in the *Super Mario Bros.* franchise from Nintendo). A character or avatar representing the player moves left to right through a 2.5D environment, encountering various obstacles that have to be negotiated (such as holes in the path, gaps in the clouds, or spewing volcanoes). The form taken by each obstacle is determined by the numeracy component being addressed in that particular game level. The players' aim is to travel through the environment to an end flag as quickly as possible, *en route* negotiating all of the obstacles, using the objects provided, and collecting as many coins hanging in the virtual sky as possible. The final iteration of the game, developed in response to feedback given in the earlier research cycles, also incorporates a variety of other gamification elements (Deterding *et al.* 2011): a customisable avatar, an on-screen timer, a leader board, and a talking companion.

7.2 GENERAL OUTCOMES

Designing a prototype game that implemented principles of the numeracy intervention and insights from learning theory proved to be challenging. It was difficult to design a variety of activities that addressed each of the three components across the full range of the three levels of attainment (numbers up to twenty), using the mechanism of Bruner's modes of representation, and involving both constructivist and behaviourist opportunities to create and automatise mathematical knowledge. Giving just one example, separating the components from one another to minimise cognitive overload was not always successful: the *remembered facts* games involved both counting and estimation. Nevertheless, despite the various difficulties, the prototype game did mostly achieve its aims. It operationalised principles of the numeracy intervention and some insights from learning theory and the cognitive sciences in the format of a popular digital game genre, making it reasonably attractive and accessible for children. And, if only for this reason, even if it was not quite as good as the computer games that they played at home, it did motivate almost all the children to engage over extended periods with the numeracy that they otherwise found especially difficult and often avoided.

The prototype game was used by teaching staff, and sometimes by parents, in a wide variety of ways: partly because of available resources and the demands of the school, partly because of the widely varying needs of the individual children, and partly because of the preferences and expectations of the individual staff. It was used with individual children and with groups of children; in ICT suites, classrooms and corridors; as part of or in lieu of the children's individual numeracy session; before, during or after the individual session; as an integral part of the numeracy intervention or as a reward for hard work in a session; as a collaborative activity or, while the teaching staff attended to other children, as a 'park and play' activity; and for any length of time between ten and twenty-five minutes. In short, there is little point attempting to dictate how a game should be used in schools, even if training is provided (which, as noted above, is likely to be necessary for most teaching staff, Becker 2007; Jones 2004; Ketelhut & Schifter 2011). Instead, the developers of games-based interventions need

to accommodate or at least acknowledge the fact that, as noted above, classrooms are often 'messy' and always in flux (Berliner 2002; Gherardi & Turner 2002).

When the prototype game appeared to be working well, the sessions were dynamic and highly-charged events, involving lots of excited conversation between all of the participants, children and classroom assistants alike, and the children appeared to be making steady progress. However, the feedback identified a variety of reasons why such a game might not be used at all. It requires the allocation of expensive school resources: including teaching staff, the children's availability, and ICT facilities. It also requires the teaching staff tasked with its implementation to have some familiarity with digital games, particularly as not all children do, if they are to be able to use those features to best effect. They also need to have some understanding of the pedagogy underlying the game's approach to learning, if they are going to be able to identify for which children the game might be most suitable (Bourgonjon *et al.* 2013; Dickey 2013; Williamson 2009). They also need to believe that the game has some value for the children and is thus worth their efforts (Kenny & McDaniel 2011).

The teaching staff in this research also varied greatly in their expectations of the game. Some thought it should be a fully self-determining and comprehensive solution to each child's individual mathematical needs, and were disappointed that it was not. For those staff, the game should assess the child's individual needs and skill levels, should provide appropriately targeted activities, and report progress in an easily-accessible format, all without much adult intervention. They also argued that the game should build on the addition and subtraction, to include multiplication, division, shape and space.

For other teaching staff, the game was already too prescriptive. They would have preferred to be able to decide which activities the children played, the level of the numeracy and the type of tasks, according to their professional judgements of the child's needs: they wanted full control rather than to have to rely upon the game's algorithms. However, the majority of the teaching staff were inevitably somewhere in between. They liked the way in which the game complemented components from the

numeracy intervention and was automatically adaptive to the needs of the individual child, and they thought that the constructivist, behaviourist and gamification elements were effective; but they too wanted to be able to intervene when they thought appropriate, to overrule the algorithms and, if only temporarily, to take back control from the computer (Kenny & McDaniel 2011).

For most of the interviewed children, the game mechanics were both familiar and sometimes confusing. Almost all of them, including most of those who said that they did not play entertainment games at home, appeared to immediately understand the gameplay conventions; they knew exactly how to begin (whereas several of the teaching staff who were unfamiliar with computer games found that more difficult). The need to make the avatar travel through the environment, overcoming obstacles and to achieve the end goal, was understood quickly by the children without any explicit instruction, and they were all also familiar with having to jump their avatar in order to collect the gold coins. But, many of the children, and more of the adults, found the particular way in which the game had been implemented difficult at first to understand. For example, the idea that blocks might be used to fill gaps by moving the avatar alongside and pressing the spacebar they found less obvious. This observation confirms that games designed for use by teachers and children ought not assume that their gameplay mechanisms are either transparent or intuitive (Dickey 2013).

In fact, for many of the children, the coins, represented by no more than little yellow discs floating in the virtual space, were the most important part of the gameplay, the immediate and highly valued but uncertain reward for a successful negotiation of an obstacle, and a key reason to press on (how many coins can they collect by the end of the session?). The variety of other gamification elements, implemented in the second and third iterations, were suggested by the children and were clearly inspired by their experience of entertainment games: the ability to personalise the avatar, a timer and a leader board. Being able to personalise the avatar was very popular. In particular, it helped give some of the children a sense of ownership of the game and thus contributed to a sense of ownership of the learning, which is frequently identified as being critical for deep learning (Eales *et al.* 2002; Enghag & Niedderer 2008). It was

their avatar, it allowed them to project themselves more effectively into the game, making success all the more important and sweeter when achieved. Meanwhile, the timer that ticks away throughout the gameplay, and is noted in the leader board but has no impact on the child's position in the leader board, received mixed reviews. Most of the children liked the mild urgency imposed by the timer, again it was a familiar characteristic of entertainment games which helped make the numeracy game seem less like a school task; whereas for some teaching staff the timer added an unnecessary and unhelpful extra pressure.

Feedback about the leader board, however, was almost all positive. The leader board gives a situated measure of the child's progress in the informal visual language of entertainment games familiar from home. As the child progresses through the levels of numeracy attainment, so their name moves up the leader board. It also introduces a competitive edge to their engagement and provides an authentic goal for them to pursue, to get their name to the top of the board, all of which the children valued. However, the apparent competition, created by the system placing the child on the leader board according to their current numeracy level rather than, despite appearances, according to their time performance in relation to the other children's time performance, is a deception. The other names are fictitious and their times are generated by the system to ensure that the child's position on the leader board is related to their numeracy level. It thus raises ethical concerns. However, the teaching staff interviewed about this approach could not see any problems. They thought the ends (encouraging the child to continue engaging with the numeracy) justified the means (the deception). Nevertheless, although the leader board did appear to help increase the children's motivation to continue, and the deception also removed the need to make public the scores of real children, whether this approach should be used in future games designed for children needs further thought (Bowman 2011; Kimmel *et al.* 2011; Witzel & Mercer 2003).

Before completing this discussion of the prototype game's general outcomes, and despite the study's emphasis on understanding the learning design and learning processes, the overall effectiveness of the game will briefly be considered. However,

this will be grounded in the various perspectives of the participants, rather than being a formal evaluation which as established at the outset was neither the focus nor the spirit of this research.

The responses from the participating teaching staff and children were broadly positive, although with some key exceptions. For example, almost all of the teachers believed that the game made the mathematics more accessible and meaningful to the children, more authentic, because it was grounded in and affected the world in which they were playing. The fact that the mathematics was situated in a familiar digital world in which the mathematical thinking had direct consequences (the only way to make progress was to calculate how to bridge an obstacle) gave them both an understanding of the implications of their mathematical decisions and a reason to engage. In addition, although measuring progress was not part of the research, it is worth considering the educational impact of the game on the children, as perceived by the children and teaching staff. What was clear from the interviews was that all the children believed they had learned something by playing the game (thus supporting the outcomes of earlier research, Holmes 2011). They now found it easier to recall automatically mathematical facts and to apply automatically mathematical processes in their mainstream classes, and they were more confident with the concepts of numeracy. The teaching staff mostly agreed, with improvements in the children's mathematical skills and self-confidence being the outcomes mentioned most often.

Many of the teaching staff also mentioned that in the game, unlike in the mathematics classroom, the children were often willing to tackle tasks repeatedly until they were successful. Without any external encouragement, the children usually refused to give up in the face of difficulty: getting their avatar past the obstruction and collecting coins was all that mattered. They would try every strategy to 'beat' the numeracy that they could think of, without fear of failure or embarrassment (Martin & Marsh 2003), sometimes deliberating out loud or discussing with the other children, but also sometimes clicking randomly, in order to succeed in the game.

However, some children would have liked the gameplay to be more varied and the numeracy to be more challenging; and, it needs to be reiterated, not all the teaching staff thought that the game was effective. A few staff reported that the games were full of bugs, dated in design, a waste of time for children who need help with their mathematics, and too incomprehensible to be of any real value. These responses, at least, serve as a reminder for designers of games or other interventions that, despite national teaching standards, curricula and assessments, children and teachers are all very different. They all have individual experiences, contexts, needs and demands. Moreover, exactly the same intervention, be it a teaching strategy or a digital game, might be both perceived and implemented in completely different ways by different teachers (Jackson 2012). The negative responses also remind us that if a teaching resource is not easy to use, or is not thought to be useful, no matter how effective it might be, it simply is not going to be used (Cuban 2001; Kirriemuir & McFarlane 2004).

There have been multiple attempts to establish frameworks that facilitate the objective evaluation of GBL software (including Ak 2012; Amory & Seagram 2003; Becker 2011; de Freitas & Oliver 2006; Liu & Lin 2009). Becker (2011), for example, suggests educational games are evaluated in terms of things that might be learned in the game that the designer has deliberately included, things that have to be learned in the game in order to win, things that players learn that were never intended by the designer, and what was actually learned. De Freitas and Oliver (2006), on the other hand, outlines a comprehensive framework for the selection, use and evaluation of games in formal learning. Their framework comprised four dimensions: the intended educational context, the target learners, the gameplay, and the pedagogy; although, as Dunwell and colleagues point out (2011), developers are typically only able to modify the last two of these dimensions.

Nevertheless, whatever the value of these evaluative frameworks, whether or not they are 'accurate', the present study suggests that they are inevitably inadequate. The prototype game was clearly perceived by the majority of the participants in this study to have achieved some kind of GBL 'quality threshold', and is likely to have been viewed positively by one of these evaluative frameworks, yet it completely failed in

one school. Any evaluative framework has to go beyond the game's intended context, recognise the enormous variety of possible contexts, and consider the importance of flexible GBL approaches. Moreover, these evaluative frameworks tend to concentrate on the internalities of the educational game, 'is it a good game', and do not consider their potential as fulcrums for social interaction and discussion. The teaching staff who believed the game did provide the children with useful numeracy support, saw it being most effective as a collaborative tool: as a talking point for when they were working with individual children or for when parents played the game together with their own children, or as a focus for conversation for groups of children playing the game on computers next to one other. This is a key outcome which will later be discussed in more detail.

7.3 NUMERACY INTERVENTION

The recognition that GBL might be suitable for children who are low-attaining (Holmes 2011; Sanger *et al.* 1997; Sedighian & Sedighian 1996), and that widely-used numeracy interventions, although usually effective, are not always sufficient for all children low-attaining in mathematics (Dowker 2009), suggested the research of a digital game that builds upon one such intervention. The Catch Up Numeracy intervention (referred to throughout this thesis as the numeracy intervention) was selected because both its componential approach to numeracy and other games implementing principles of a parallel literacy intervention have previously been shown to be effective or useful (Holmes 2011; Holmes & Dowker, in press).

As noted earlier, four principles of the numeracy intervention were translated into the prototype game: (i) the componential approach to numeracy and (ii) the levels of attainment, which together comprise the two dimensions of the intervention, (iii) the focus on only one numeracy component at one level of attainment in any one session, to minimise cognitive overload, and (iv) the numeracy intervention's learning objectives. Three components of numeracy were represented in the game, *remembered facts*, *estimation*, and *derived facts*, at the first six levels of attainment. The game was

configured so that any one gameplay session incorporated only one of the numeracy components at only one level of attainment, while the overarching learning objective was for the children to become secure in all three components with numbers up to twenty. The ways in which each of these principles were implemented in the game were broadly approved by all of the teaching staff familiar with the intervention, and by most of the staff who were not. Nevertheless, the implementation was not without issues.

The prototype game includes nine separate game levels, three for each of the three components selected for the research. The three game levels designed for the *remembered facts* component involves obstacles that have to be bridged, gaps of specific sizes in horizontal and vertical paths, and doors that have to be opened, by recovering keys from holes of specific sizes. In the final research cycle, these game levels were played by far the most frequently, one and a half times as often as the *estimation* game levels, and around five times as often as the *derived facts* game levels. However, it was not possible to ascertain from the interview responses whether this was because the teaching staff believed the children needed more practice in this particular component (which earlier research suggests is unlikely, Holmes & Dowker, in press), because they were less comfortable tackling the other components (which the earlier research suggests is possible), or because the *remembered facts* gameplay, not the numeracy, is the least cognitively demanding gameplay in the prototype game (it reflects the learning of number bonds, in which children often have extensive experience, and requires straightforward and accurate answers). Alternatively, perhaps the *remembered facts* game levels were played most often simply because they are, reading left to right, the first column in the menu, and once they'd started with that component, the children and adults simply stuck with what they knew, working towards the higher numeracy levels (Johnson 2010; Sík Lányi & Brown 2010). The various components may well be fundamental to the learning of numeracy, but this observation suggests a need for research into the teachers' and children's perception of their importance (Borthwick 2011; Briand-Newman *et al.* 2012; Tchoshanov 2010).

The *estimation* game levels involved clouds, balances and nets; and, although they were clearly enjoyed by and appeared to benefit all of the children observed, they too did not work quite as intended. However, this was mainly because the numeracy levels played in the game levels involved number sentences or tasks with which the students were already familiar. As the children were easily able to calculate an accurate answer, estimating the answer became an inauthentic task, undertaken only because the game demanded it – not a useful outcome for a game aiming to make the mathematics more authentic for the children (Galarneau 2005; Herrington *et al.* 2003). Nevertheless, once the children understood that they could proceed through the game by estimating the answers, rather than having to calculate them accurately, they all appeared to enjoy moving rapidly through the tasks and, although there was some use of counting, the children's procedural knowledge of estimation did appear to have been reinforced by their engagement with the game.

Translating the *derived facts* principles into a digital game proved to be as difficult as earlier research had suggested it might be (Evans 2008). In the prototype, the known and unknown facts are presented as two animations, the second of which has to be solved; but in the latter two research cycles, before being able to attempt the task, the child first had to determine which type of *derived fact* was being illustrated (whether it was identical, commutative, $n+$ or $n-$, all terms familiar to children who are participating in the numeracy intervention). This additional requirement, identifying the type of *derived fact*, was suggested by one of the teaching staff, so that the game replicated more faithfully how *derived facts* are taught in the numeracy intervention. Nevertheless, the *derived facts* game levels still caused considerable confusion, understandably for children and adults who were unfamiliar with the numeracy intervention, but even for the teaching staff who had undertaken training in the numeracy intervention and the children they were supporting. For example, the observed children mostly calculated the answer to the unknown fact without any reference to the known fact, while many of them found it especially difficult to identify the type of *derived fact*. It is likely at least partly for these reasons that the *derived facts* game levels were played infrequently in the final research cycle. These

observations also raise questions of relevance to the numeracy intervention as a whole, outside of the prototype game: whether the teaching staff, who had been trained to deliver the numeracy intervention, were actually sufficiently comfortable with this particular aspect; and whether better guidance or further training around the numeracy components is necessary or would be useful (Rubie-Davies *et al.* 2010).

When the child first plays the prototype game, the second and third game levels for each component are locked. However, once a game level for a component has been completed, irrespective of the number of numeracy tasks completed correctly, the next game level for that component is unlocked, until all three are available to play. In other words, the additional game levels become available as soon as the player completes an earlier game level, whatever their success with the numeracy tasks. Although the game levels are not the hierarchy that the name suggests (the name *game levels* was retained to maintain the association with entertainment games), this approach allows the children a choice over which animations to play in each session, giving them some ownership over how they interact with the numeracy, which was commented upon positively by the children who were interviewed. This disconnect between the increasing difficulty of mathematics and the various animated games is an unusual feature which, once understood, was valued by all the participants who commented.

Irrespective of their skills or their current numeracy level in the numeracy intervention, when the child first plays any particular component in the final iteration of the prototype game they are presented with twelve tasks involving numbers within the number range of the first level of attainment (from one to five). If they answer at least ten of those tasks correctly at first attempt, they are deemed to have completed that numeracy level and the tasks presented the next time that they play any game level for the same component will involve numbers from the next numeracy level (in the range of one to eight). Otherwise, the tasks presented in the next gameplay will again be in the first number range. This process continues, moving the child quickly through the numeracy levels, almost without them noticing (they are 'learning by stealth', Hosie 1985; MacCallum 2011; Prensky 2001a), until they reach a level commensurate with

their current abilities, and then more slowly through the remaining levels until they are finally secure with tasks in the sixth number range (numbers up to twenty).

Always beginning with the first numeracy level, that is to say using numbers in which they were already likely to be very confident, aimed to give the child some easy wins, to boost their self-confidence and to provide some fun while they learned how to negotiate the game's gameplay. However, although all the children appeared to enjoy those easy wins, the way in which the game operationalised progress through the numeracy levels inevitably had some disadvantages. First, some of the children said the number ranges that they encountered were too easy, which was boring and demotivating as they felt they were being patronised. Second, if they found the numeracy tasks or the gameplay difficult, it might take them many sessions to find their 'natural level' (their zone of proximal development, the point of equilibrium between tasks that they find easy and tasks they find challenging, that they can only achieve with the support of more capable others, Vygotsky 1978). Third, once they have found their natural level, it means the child might then play the same level of numeracy tasks over many sessions, because this is the level that they currently find difficult (and even if they are making progress within the level, it might appear that they are now standing still). Fourth, building the number ranges up in the background, rather than explicitly, although it might have taken away some of the fear, also took away some useful scaffolding and opportunities for the children to notice and hence reflect upon their own progress.

In fact, once a child has completed a numeracy level, they are presented with a screen and spoken message that celebrate the fact that they have 'moved up a level'. The aim is to orientate the child, in the language of the numeracy intervention, to reward their achievement, and to motivate them to want to play again. However, more than one adult thought that these messages were insufficient. They believed that the numeracy levels provide the children with useful scaffolding and targets, which the game fails to leverage properly. Rather than allowing the children's progress through the levels to happen in the background, without the child's realisation, they argued it should make that progress far more explicit.

Another problem here, though, is a disconnect between the child's actual ability, as evidenced by their progress through the numeracy levels, and their teacher's perception of their ability. In at least one case, the children were stopped from using the game because after several sessions they were still working with tasks at a relatively low numeracy level. Although these particular children clearly still had serious difficulties with these functional level tasks, and their gameplay suggested they were unlikely to be able to cope with higher level mathematics, the teacher decided for a variety of reasons that they now needed to move on. Unfortunately, this teacher did not take advantage of information from the games to identify where the children still had difficulties so that those difficulties could be addressed.

The game also implemented a third distinguishing principle of the numeracy intervention, that activities undertaken in any one individual session should include a limited number range within just one component of numeracy. This approach, which is unlike most mainstream mathematics teaching, aims to minimise cognitive overload for learners who are low-attaining in mathematics (Sweller 1994). However, as a few teaching staff pointed out, the numeracy components in the game sometimes overlapped, which muddled the clarity and caused the children some difficulties. For example, the *remembered facts* gameplay implemented in the prototype (for which the children are supposed to draw upon previously learned and now *remembered facts*) also involved the numeracy components of *counting* and *estimation*. In the first iteration, the gaps and blocks in the *estimation* game levels were divided into units and so, understandably, the children counted the units in order to complete the tasks. In the second iteration, the unit divisions were removed, to prevent counting, but this only meant the children now had to estimate. For the final iteration the unit divisions were reinstated (*estimation* was implemented elsewhere in the game, and overlapping with *counting* was considered less of a problem). Nevertheless, the necessary conclusion is that implementing *remembered facts* in the image format used in the prototype game, inevitably involves either *counting* or *estimation*, prevents the child working with only one component at a time, and thus, although providing useful and

enjoyable practice with number bonds, falls short of the numeracy intervention's stated requirements.

In addition, although perhaps intuitive, separating the mathematics into the separate components and working with only a small number range at a time, in other words making things 'simple' for the children because they are low-attaining, is not without criticism (Houssart 2002, 2004; Mason 2005). Perhaps it was the fact that the numeracy components are separated and the numeracy is broken into such small chunks that prevented the children from making faster progress in both the game and their numeracy, but the feedback from the teaching staff and children suggests otherwise. Although, a common view was that the numeracy started too low, whether or not it was too low depended on the skills of the individual child, and this might in any case be addressed by giving the teacher more control over the system so that they can set the child's starting level in the game to their current numeracy level, or perhaps one below their current level, in the numeracy intervention. Meanwhile, breaking the numeracy into bite-sized chunks, because of its in-built progression did appear to help these children who were low-attaining to understand the mathematics that they were working with, to make steady progress, and to become more confident in their own mathematical skills.

Overall, the way in which the numeracy intervention was implemented in the prototype game was broadly approved both by teachers familiar with the numeracy intervention and by the organisation that disseminates the numeracy intervention, who note 'very strong evidence that the games do contribute to an improvement in a learner's numeracy skills and knowledge' (Catch Up 2012, p.4). However, whereas the numeracy intervention specifies that the components should be kept strictly separated, in the game there was clearly some overlap; and whereas the numeracy intervention specifies that the numeracy learning for children who are low-attaining in mathematics should proceed in small number range chunks, doing so in the game led to the children finding some sessions too easy and the teachers wanting more control.

The question here, therefore, is whether the attempt to interpret the numeracy intervention strictly is inevitably flawed. While the separation of numeracy into the various components is conceptually sound, and breaking up the progress into bite-sized chunks is intuitively appealing, perhaps insisting on these two-dimensions of simplification is too stringent for implementing in a computer game, and possibly counter-productive. Perhaps the game should aim instead only to interpret the numeracy intervention's approach, rather than to apply it strictly. On the other hand, perhaps the problems raised by the implementation of the numeracy intervention in the prototype game has implications beyond the game. Perhaps it says something more general about the face-to-face delivery of the numeracy intervention itself. The separation of the components and the chunking into bite-size number ranges do appear to provide teaching staff with useful scaffolding (Holmes & Dowker, in press). However, as other research indicates, teaching staff delivering the numeracy intervention liberally interpret many aspects of it (Jackson 2012). Perhaps, because of the difficulties, they already do the same with the numeracy intervention's two dimensions. In short, the game's design and feedback suggests that the advice around the rigid separation of the components and the chunking into bite-size number ranges that teaching staff are supposed to apply during the numeracy intervention's individual session needs to be moderated; or, at least, further research around that aspect of the numeracy intervention's face-to-face delivery is needed.

7.4 LEARNING THEORY

As noted above, the design of the prototype drew on both guided constructivist and behaviourist approaches to learning (Burkhardt 2006; Greeno *et al.* 1996; Mayer 2004): to foreground learning through gameplay while providing multiple opportunities for practice. The mechanism used was Bruner's modes of representation.

Foregrounding learning *through* gameplay was identified as a method employed to good effect in many entertainment games (Gee 2004b) but not often seen in GBL. There are many examples of GBL in which the gameplay happens *after* the learning, as

a reward for the successful practice of educational content (for example *Neurogames*, Reed 2010). There are other examples where the learning takes place *during* the gameplay but is unrelated to it (for example *Zombie Division*, Habgood 2005). Meanwhile, learning *through* gameplay, when it is used, is mostly used to focus on soft skills such as problem solving or communication (Ju & Wagner 1997), or to give students opportunities to experience educational content (for example *Quest Atlantis*, Barab *et al.* 2005) rather than to facilitate the active learning and remembering of that educational content.

Immersing the numeracy in the gameplay aims to give children an opportunity to *discover* the numeracy facts, procedures and concepts for themselves (Devlin 2011). Rather than expecting them to solve abstract number problems, the game involves authentic problems situated in the digital environment, such as obstacles that have to be negotiated in order to proceed through the virtual environment (Galarneau 2005; Herrington *et al.* 2003). The game includes problems that can only be solved by thinking mathematically, by manipulating objects rather than numbers, trying a variety of strategies; the aim being to enable the children to alter their existing knowledge of number, moving from Piaget's assimilation to accommodation, to construct personal understandings.

Although learning *through* digital gameplay was identified as having most potential, the literature also suggested that repetition and practice had important benefits for learning, especially for children who are low-attaining in mathematics (Baroody *et al.* 2009; Delazer *et al.* 2005; Domahs & Delazer 2005). Repetition and practice might be particularly helpful if it builds upon the child's current developmental level and involves them systematically revisiting the same broad conceptual/procedural processes at increasing levels of detail and sophistication in a spiral of learning moments (Bruner 1960). The literature suggests that deliberate practice can help ensure that a child's numeracy skills become automatic and without error, thus freeing their working memory for other cognitive demands such as more complex and multi-step mathematics (Crawford 2003; Goynne *et al.* 2000; Shaywitz & Shaywitz 2008).

The mechanism of Bruner's modes of representation, implemented in the format of a 'platform game', was used to effect a synthesis between these two approaches: to provide opportunities both for guided constructivist learning and deliberate practice. To interpret Bruner's enactive mode, learning by doing, the game enabled the children to select and move, to act upon, objects within the virtual environment (inevitably, interpreting this in a digital game, making the actions virtual, misses out potential benefits of physically moving objects around, losing the possibility of useful muscle memories). To interpret the iconic mode, the numeracy tasks were first presented and tackled as concrete objects. This gives the child an opportunity to construct an answer, an understanding of the mathematics, if necessary through trial and error, and without any reference to numerals (the task involves only a physical obstacle, such as a gap that needs to be bridged, a weight that needs to be estimated, a waterfall that needs to be stopped...). Finally, the transition to the symbolic mode, which children who are low-attaining in mathematics sometimes find especially difficult, was supported by re-presenting exactly the same tasks twice more, to constitute a series of repeated but increasingly abstract levels of repetition, once with the same concrete objects labelled with numerals, once only with the numerals. The aim was to provide a first level of repetition which spirals up from the lower iconic cognitive level to the higher symbolic cognitive level.

Almost all of the interviewed teaching staff believed that the game made the mathematics more accessible and meaningful to the children, more authentic, because it was grounded in and affected the platform world in which they were playing. The game did provide the children with an opportunity to explore the environment and construct knowledge for themselves, to alter their existing knowledge of number, to move from assimilation to accommodation, by manipulating the concrete objects in order to negotiate the obstacle. In the prototype game, the mathematics had a certain iconic physicality that could be understood by the children; and, perhaps unlike worksheet mathematics, it somehow mattered. Successfully working through the mathematical tasks (constructing bridges and ladders) allowed the children to progress quickly through the world and collect coins, not as a simple or unconnected reward for

answering questions correctly but rather because their use of mathematical thinking, engaging with the mathematical task in front of them, had directly affected the world of the game. They got to see the physical consequences of their calculations and actions. When they first encountered the game the children mostly recognised straightaway what they had to do (journey their avatar through the digital environment and collect coins) but were surprised when they were unable to jump the gaps (as they might have been able to do in an entertainment game). However, most of the children quickly realised that they needed to use the given objects to bridge the gaps, and it did not take long before they were trying possible solutions, discovering the right answer, and being rewarded with the opportunity to grab more gold coins. The children clearly enjoyed this process, which motivated their engagement with the mathematics.

Many of the adult participants also commented that, in contrast to their approach to mathematics elsewhere, in the game the children were willing to try each task as often as necessary. They were able to use a trial and error approach, to make as many attempts as they needed, either by eye or by counting but with reference to their prior experience, learning from their mistakes without fear of embarrassment or the negative feelings of failure that they sometimes experienced elsewhere when doing mathematics. At no time did failure appear to be taken to heart, instead the children just redoubled their efforts, sometimes with support either from other children or from the supervising adult (Mayer 2004; Kirschner *et al.* 2006). Nevertheless, although the possibilities for action were restricted, the avatar could only move so far and there were few other things in view, some children found the instruction-free virtual world confusing, as did some of the teaching staff. So they clicked randomly, until they received active support to guide them back towards more successful strategies and outcomes. In fact it might be argued that the knowledge construction was effective only, or at least often, if it was mediated by an adult.

However, although this guided-constructivist/modes of representation approach was enjoyed by most of the children, who clearly learned something from it, and was therefore welcomed by the teaching staff, in fact it turned out that for the game it was

extremely limiting. It was extraordinarily difficult to devise iconic-based scenarios to support exploration and constructivist learning for numbers greater than about ten. The objects either become too large to display in a single screen, or the unit divisions too small to count. How such an approach might then support multiplications, as requested by some teaching staff, or additions beyond twenty is very unclear. As discussed, there certainly were some benefits – it helped engage the children in this study, it helped them construct their own understanding of the mathematics, and it was meaningful for them – but it seems likely that this approach is suitable only for children who are having difficulties with numbers below twenty. Another possibility is that, rather than for children who are low-attaining having already experienced mathematics at school over several years, perhaps this approach is more suitable for children who are beginning school mathematics.

As noted, the literature since Thorndike (1922) suggests that repetition and practice can also have important benefits for learning, especially for children who are low-attaining in mathematics, helping them achieve a level of automaticity necessary for their learning of higher-level mathematics (Baroody *et al.* 2009; Delazer *et al.* 2005; Domahs & Delazer 2005). Interviews with the children confirmed that they were mostly happy to engage in the repeated practice, that they enjoyed the ‘easy wins’ that allowed them to progress through the game quickly so that they might collect greater quantities of gold coins. However, for other children the game was far too repetitive which, especially if the tasks were too easy, quickly became boring.

The prototype involved three levels of repetition, the modes of representation (in which the same task is repeated at increasingly abstract levels), the repetition of the numeracy tasks and the repetition of the gameplay. While other research suggests that representing the task in concrete terms might actually impede rather than facilitate the progress to the symbolic (McNeil *et al.* 2009), for the lower-achieving children in this study the repetition involving the modes of representation does appear to have helped reinforce the connection between authentic concrete problems and numerical symbols and vice-versa. These children soon learned to remember the answer to the concrete problem which they could then apply easily to the labelled concrete and

symbolic versions, thus strengthening the relevant mathematical non-declarative skills, and recognising the similarities between the different approaches. In short, the increasingly abstract repetition helped the children construct and consolidate their own mathematical understandings. It was also very noticeable, in the observations, that most of the children actively enjoyed the rhythm of the repetitions centred on the modes, even if for some the numbers were used to help determine the objects rather than as intended, while for others the game ceases to be a game when only numbers are presented and becomes instead a school mathematics task. In addition, although at first this approach was found confusing by some teaching staff, once they had had time to experience it in practice they were positive because they saw the process, moving from the concrete to the symbolic, as being similar to the way in which they taught or deliver the numeracy intervention.

Arranging the repetition of numeracy tasks as a spiral of learning, that is starting with low numbers then, once those numbers are firmly embedded, repeating the same tasks but with higher numbers, was also received mostly positively: the children progressed up through the levels without really noticing or being frightened by the increasing difficulty. In other words, while it reinforced what the children had learned, the spiral of gameplay mostly hid from them that they were repeatedly engaging with the same mathematics at increasing levels of difficulty. Having constructed their own numeracy knowledge, by interacting with the onscreen objects, repetition of the same task in slightly different formats helped the children consolidate that knowledge by stealth (Hosie 1985; MacCallum 2011; Prensky 2001a) without them worrying about or avoiding the mathematics.

However, the fact that this spiral adaptive approach was achieved by disassociating the numeracy levels (number ranges) from the game levels (animations) was confusing for many of the teaching staff, who expected the changes in number range to match the changes in game level. Perhaps another approach would have been more successful, perhaps the automatic spiral of repetition of numeracy tasks needed to be addressed more intelligently. Instead of using an adaptive approach *between* each game session, perhaps the game needs to evaluate the child's skills continuously, adjusting the

difficulty of the numeracy task according to their successes and failures *within* each game session (Kickmeier-Rust & Albert 2010; Peirce *et al.* 2008; Vandewaetere *et al.* 2013). This would inevitably mean abandoning the numeracy levels adopted from the numeracy intervention. Alternatively, making the functioning more easily understood might have meant abandoning the name 'game levels' adopted from entertainment games.

The impact of the repetitive gameplay was moderated by giving the child a choice, over time, over which gameplay to play. Naturally, even more choice would have been welcomed, but the choice of game did appear to increase the child's motivation to continue engaging with the mathematics. In any case, clearly the challenge for any game designed to support children who are low-attaining in mathematics is to effect a balance between sufficient repetition (to help the child encode the facts, concepts and procedures into long-term memory) and sufficient variation (to maximise motivation to engage with the repetition). This challenge is further complicated by two additional factors: time and control. First, there is an overarching need to minimise the time that the child plays the game to consolidate their numeracy, their school timetables are already otherwise pressured. In other words, the sufficient and acceptable repetition needs to be achieved sufficiently quickly. Second, whereas one teacher suggested the game needed to be even more automatic, others said they would have liked the opportunity to intervene, to be able to decide where to start the child in the numeracy levels, perhaps according to their numeracy level in the numeracy intervention sessions, and to be able to adjust the child's numeracy level as appropriate at any time in the game.

Nevertheless, the teaching staff mostly agreed that the retrieval practice and task repetition in the game had contributed to the improvements the children made in their numeracy; with some teaching staff arguing that it is all about the repeated practice, it was the only reason for using the game, to help 'fix' the calculations in the child's head. It also helped increase their speed, enabling them to recall quickly relevant facts, concepts or procedures, allowing them to answer over time increasing numbers of questions correctly, more quickly and with growing confidence. Some

teaching staff also noted that the retrieval practice was also especially helpful for those children who found it difficult to concentrate on learning tasks for any length of time. In fact, for the teaching staff participants most familiar with the numeracy intervention, the key benefit was that the practice both complemented the approach taken by the numeracy intervention and reinforced what had been learned in the individual numeracy sessions. For these staff, the numeracy levels are therefore fundamental to the game and should not be abandoned.

The repetition presented in the game (via the modes of representation, within the gameplay and as a spiral of increasing difficulty) had one final important benefit, it provided the teaching staff with more opportunities and time for them to observe easily exactly what the children knew and understood, and to engage the children in productive conversation around the mathematics. This potential role of the game as stimulus and fulcrum for mathematical dialogue, unanticipated at the beginning of the research, affording moments for social-constructivism, is explored next.

7.5 DIALOGUE

As noted previously, much research into GBL focuses on ways in which the games themselves might be made most effective (what Barab, a leading GBL researcher, refers to as the 'g' of games-based learning, 2013). Indeed, as discussed in Section 7.2, this design-based study has generated some principles which might inform the development of future games that support children who are low-attaining in mathematics. Other research looks at how games are used in classrooms and in particular at their effectiveness for learning (what Barab refers to as the 'G' of Games-based learning, *ibid.*). Again, in the second and third research cycles (Chapters 5 and 6), this study has considered the various ways in which teaching staff chose to use the game, and the children's and adult's perceptions of the impact of so doing.

The present study supports previous research in showing that a games-based approach does have multiple potential benefits for learning, if the game is *designed* effectively (which for this research means if it is grounded in learning theory), achieves what

might be thought of as a quality threshold, and is believed by teaching staff to be worth their investment. But the study also supports other research in showing that any potential benefits will only be realised if the game is also *used* effectively.

It can be observed at a surface level that effective use involves considerations such as whether or not children play the game individually or in groups. It also involves the teacher's familiarity with games-based approaches to learning, their belief in the specific game's efficacy, and their willingness to devote the necessary time and other resources. Meanwhile, maximising effective use might also require some form of professional development for the teaching staff involved (Becker 2007; Jones 2004; Ketelhut & Schifter 2011), or at least appropriate support somehow incorporated within the game itself. But the present study suggests that these considerations do not go far enough: the function of digital games designed for children who are low-attaining in mathematics also requires theorising.

Ever since Skinner (1958) first proposed self-instruction by machine (based on earlier research into the machine-testing of intelligence, Pressey 1926), learning technologies have been conceived as standalone solutions for teaching and learning. The teaching-machine to all intents replaces the teacher:

The machine itself, of course, does not teach ... but the effect upon each student is surprisingly like that of a private tutor.... (i) There is a constant interchange between program and student.... (ii) Like a good tutor, the machine insists that a given point be thoroughly understood ... before the student moves on.... (iii) Like a good tutor, the machine presents just that material for which the student is ready.... (iv) Like a skilful tutor, the machine helps the student to come up with the right answer.... (v) Lastly, of course, the machine, like the private tutor, reinforces the student for every correct response, using this immediate feedback ... to shape his behavior most efficiently. (Skinner 1958)

This understanding has more recently been extended to 'computer-aided instruction' (Arnold 2008) and 'intelligent tutoring systems' (for example, Graesser 1999). It also pervades games designed for learning (for example, Gee 2004a; Reed 2010; West 2010). Even Papert's constructivist alternative, keeps the technology at the centre of the learning process. In 'Mindstorms. Children, Computers and Powerful Ideas', Papert

(1980) describes the development of a 'computer-controlled cybernetic animal', the Turtle, which is programmable by children using the LOGO language. For Papert, the potential of the Turtle for learning stems from the fact that it 'serves no other purpose than of being good to program and good to think with' (*ibid.*, p.11), in short that it is what he calls an 'object to think with', an object 'that enables children to think concretely about thinking itself' (Resnick *et al.* 1988, p.15). In other words, a programmable machine can be a tool which both mediates and facilitates a child to think through and actively construct their own understandings.

This compelling description, of programmable computers as objects-to-think-with, has surprisingly only appeared occasionally in the literature (*cf.* Abrahamson & Howison 2010; Knight & Knight 1995; Stahl 2000); and, when it has appeared, it has mostly been used uncritically. For example, Turkle writes little more than 'the computer, quite literally, became Deborah's object to think with for thinking about herself' (1984, 2005, p.6), while Keeble simply acknowledges that 'objects to think with [are] rooted in two pedagogical constructs: a constructivist philosophy and an emphasis on concrete thinking for all ages' (2008, p.7). But as students become active constructors of knowledge through using an object to think with, rather than passive recipients of teaching machine or computer-aided instruction, there again remains little space for teachers: 'teachers shift ... to guiding students as they experience their own learning process' (Blunt 2006, p.41).

However, the outcomes of the present study suggest that neither of these approaches, computer as behaviourist 'teaching machine' or as constructivist 'object to think with', are sufficient (Rieber 1992). Neither recognises that students both need opportunities to discover and construct their own knowledge, with guidance about how they might go about doing so, and opportunities for retrieval practice (Karpicke & Roediger 2008; Kirschner *et al.* 2006; Mayer 2004). Furthermore, neither approach takes proper account of classroom realities, of learning dynamics, of a digital game's affordances, or of the role of the teacher as teacher.

In particular, neither of these approaches fully considers what part the technology might play, as did the prototype game, in educationally productive conversation: 'the

teacher is no longer merely the one-who-knows, but one who is himself taught in dialogue with the students, who in turn while being taught also teach' (Freire 1996, p.61). Dialogue also plays a key role in the social constructivist model of learning associated with Vygotsky, for whom meaning making or learning is seen as a fundamentally dialogic process through which Piagetian accommodation is negotiated. Learning is understood to occur within the learner's zone of proximal development, 'the distance between the actual developmental level [what a learner is able to do by themselves today] ... and the level of potential development [what they will be able to do with assistance tomorrow] as determined through problem solving under adult guidance, or in collaboration with more capable peers' (Vygotsky 1930).

Social constructivism, however, goes beyond individual learning to consider ways in which individuals working collaboratively, through dialogue, develop understanding: 'it explains not only how individuals learn from interaction with others, but also how collective understanding is created from interactions' (Mercer & Howe 2012, p.13), among individuals 'meaning always assumes at least two perspectives at once' (Wegerif 2011, p.180), 'knowledge is not merely stored in our minds, it circulates between us when we communicate with each other in concrete activities' (Säljö 2009, p.150). In social situations, including the classrooms observed in this study, ideas are explored, rehearsed, challenged mainly through talk; with words and other artefacts functioning as the tools by which individual and shared understandings are co-created in a process of encounter and response (Gadamer 1960).

The present study suggests that dialogue itself and the artefacts used sometimes to facilitate that dialogue both have special relevance to the use of digital games in classrooms. Dialogue is defined as discussion between two or more people directed towards the exploration of a particular subject or the resolution of a problem (ODE 2005). It is an active process of constructing shared knowledge which involves participants responding to the moment, giving their view, justifying their view and negotiating the views of others, plus a willingness to reflect upon and to change one's own ideas. This is exactly the type of conversation that was observed taking place while children engaged with the prototype game. Dialogue creates a space within

which those elements of discussion exist and are situated, in which participants recognise and respond to the perspectives of others (Wegerif 2011).

Although engaging learners in thought-provoking dialogue has been shown to enhance learning outcomes (Rojas-Drummond & Mercer 2003), dialogic teaching and learning is still not common in classrooms: 'most teachers do not have a high level of understanding of how talk 'works' as the main tool of their trade, and very few have been taught specific strategies for using it to the best effect' (Mercer *et al.* 2009, p.363). Nevertheless, dialogue as an evolving pedagogical approach has received much attention (*cf.* Alexander 2008a; Fisher 2007; Lyle 2008; Mortimer & Scott 2003), with others considering dialogue in the context of the mathematics classroom (*cf.* Houssart 2004; 2009; Kyriacou & Issitt 2008; Sfard *et al.* 1998) or of learning technologies (*cf.* Hennessy 2011; Lewin *et al.* 2008; Mercer *et al.* 2010; Ravenscroft 2007).

Mortimer and Scott (2003), for example, describe how classroom talk lies along a continuum between traditional 'authoritative' talk, in which the teacher uses didactic approaches in order to inculcate 'correct' understandings, and sociocultural 'dialogic' talk, which involves both the teacher and students as co-creators of meaning and understanding. Mercer and Howe (2012) build on this and argue that teachers need to re-balance talk in their classroom to prioritise dialogic talk. They identify a number of strategies as being 'particularly valuable', including: using open questions, to explore students' understanding; encouraging students to express what they know in their own language, to explain their ideas and to justify their views; allowing students time and space to construct thoughtful answers and to put those thoughts into words; sometimes allowing student contributions to redirect the direction of the discussion; and designing learning tasks that actively require collective and consensus thinking. Interestingly, many of these strategies were observed being employed in the sessions involving the prototype game.

Alexander (2008b, 2010) focuses on 'dialogic teaching', which again is more than just classroom talk. Instead, it is a professional outlook rather than a specific method which involves using talk to engage students, to extend their thinking, and to enhance their

learning: questions are designed to elicit more than simple recall, answers are built upon rather than just received, feedback aims to promote thinking and to encourage further reflection. Simultaneously, dialogic teaching enables the teacher to assess learning needs, guide learning and monitor progress. Alexander (2008b) identifies five principles: dialogic teaching is collective, which is to say participants address learning tasks together; it is reciprocal, it involves participants listening to one other, sharing ideas and considering alternative viewpoints; it is supportive, allowing children to share their ideas without fear of failure and to help each other achieve common understandings; it is cumulative, enabling the children to build on what they have learned previously towards higher levels of understanding; and it is purposeful, although it is open, it is planned and structured towards specific learning goals. It also involves raising children's awareness of the potential educational power of talk so that they develop a meta-awareness of the use of talk for learning. Again, many of these principles were observed as happening both within and around the prototype game.

The 'self-evident' value of a dialogic approach for the *mathematics* classroom was, however, unpacked by Sfard and colleagues (1998), who conclude that while conversation does seem to have potential for the teaching and learning of mathematics, only certain types of conversation are likely to realise this potential.

Classroom discussion provokes a lot of reflection and gives an opportunity to compare, criticise, refute, complete, reject, and so on.... If the discourse is to be effective, participants have to be constructive and creative, communicate mathematically in a productive manner, [and] allow for meta-cognitive shifts'. (*ibid.*, p.45)

Moreover, while conversations between a teacher and students provide opportunities to identify student misconceptions, conversations among students are only beneficial if mathematical rules are already properly understood. Mason also argues (*ibid.*) that effective discourse in the mathematics classroom requires what he calls a 'conjecturing atmosphere', which permits everything said to be provisional – rather than pre-formulated, correct and justifiable – so that ideas might be critically examined and possibly modified in response to other people's comments, all without fear or ridicule.

Houssart has conducted extensive ethnographic research into primary school mathematics classrooms, in which she notes discourse is often limited and predictable, and dominated by instructions and explanation from the teacher (*cf.* 2001; 2009). Pupils are often only allowed to speak after putting up their hands and waiting for the teacher's permission, and then are expected to respond directly to a teacher's question. This is quite unlike the dynamic sessions in which the prototype game was played by a group of children, while they chatted through the numeracy with each other and with the supervising adult. However, Houssart also observed that, although pupils were generally familiar with the unwritten rules controlling classroom discourse, 'alongside this official teacher-directed talk there was unofficial talk in all the classrooms, not sanctioned by the teacher, but nevertheless about mathematics' (2009, p.60). The approach of one particular group, whom she has called the 'whisperers', is especially instructive:

Whether the boys were making comments for themselves or others, the comments provided evidence of unofficial mathematical activity in which the boys were engaging. It showed that they were taking opportunities to do some mathematics which matched their own view of the subject. Whispering may have aided their thought processes. It also meant they were able to register their understanding and sometimes their dissent. (Houssart 2001, p.6)

Houssart argues (2009) that this unofficial talk has important potential benefits for children's learning of mathematics. Accordingly, teachers should be listening out for and encouraging the whisperers' sometimes idiosyncratic comments, without causing them to feel they are breaking any rules: when they have discovered something for themselves or have made their own connections, when they want to build upon or add to the ideas presented by the teacher, or when the teacher has explained something that is still causing some confusion, much as several of the children did as they played the prototype game. Perhaps most importantly, the whisperers might be encouraged to contribute their thoughts to the class, translating the classroom mathematical language into their own idioms for everyone else's benefit. Inevitably, the group of children for whom the prototype game was designed include many who are whisperers in their mainstream classrooms. Playing together and discussing the game gave these children opportunities

to share their understandings out loud, while giving the supervising adult opportunities to encourage reflection and identity and address confusion and misconceptions.

Kyriacou & Issitt (2008) undertook a systematic review of studies investigating teacher-initiated teacher-pupil dialogue to promote conceptual understanding of mathematics in KS2 and KS3 classrooms. All fifteen of the studies that they included confirmed that (as noted by Mercer *et al.* 2009) limited initiation-response-feedback approaches (the routine of teacher posing a closed question, students offering an answer, and teacher providing a short evaluation) remains dominant in mathematics classrooms: 'for each individual pupil the interaction is short, usually requires an answer to a closed question, and is terminated by evaluative feedback (for example, "Yes", "No", "Well done")' (Kyriacou & Issitt 2008, p.8). They all also argued that the quality of classroom dialogue needs to improve if it is to promote pupils' conceptual understanding of mathematics, although there was little evidence in the research that purposeful dialogue actually led to the desired outcomes. Nevertheless, Kyriacou & Issitt, suggest some key characteristics of effective teacher-initiated dialogue in mathematics classrooms: going beyond initiation-response-feedback, to include open-ended questions and the discussion of misconceptions; focusing on mathematical thinking rather than just getting correct answers; teachers working collaboratively with pupils to explore mathematical problems; teachers listening to pupils and being willing to change their minds and re-direct the discussion in the light of what is said; providing scaffolding and opportunities for pupils to reflect on the task in which they are engaged; enhancing pupils' knowledge about the usefulness of dialogue as a learning experience; and inclusive teaching, conveying to all pupils regardless of their ability that their contribution is equally valued and will be taken seriously. Yet again, many of these characteristics were observed in classrooms when children were playing the prototype game. For example, more than once, children were heard to be discussing a mathematical principle, giving voice to misconceptions, which allowed the teaching assistant an opportunity to guide and remediate using open-ended questions.

Although purposeful dialogue in the mathematics classroom is broadly accepted as valuable, and strategies for promoting effective dialogue in mathematical classrooms

have been extensively researched and described, rather less attention has been paid to tools that might be used to enhance or facilitate that dialogue. Exceptions are work centred on 'dialogue games' (Ravenscroft 2007; Ravenscroft & Pilkington 2000), and on the role of interactive whiteboards as mediating artefacts (Hennessy 2011; Lewin *et al.* 2008; Mercer *et al.* 2010).

Ravenscroft and his colleagues have devised and researched a series of what they call educational dialogue games, which are distinguished from video games, such as *CoLLeGE*, *AcademicTalk* and *InterLoc* (summarised in Ravenscroft 2007). These computer-based tools model features of effective dialogic interaction (such as the roles of the participants, the rules of turn-taking and types of speech acts) in the format of a computer text interface simultaneously visible to and editable by users on multiple computers. The windows contain suggested dialogue turns from which participants might pick to generate a conversation, and a running log of that conversation. Although to the casual observer these various systems might look rigid or prescriptive, their aim is to provide suggestions and scaffolding to promote and train users in the skills of purposeful and reflective conversation. In fact, Ravenscroft concludes that his dialogue games 'can mediate, catalyse and amplify fundamental human communicative processes in the pursuit of deep learning' but he also recognises that 'it is essential that we do not "replace" dialogue-rich learning practices with ones that are communicatively impoverished, such as an over-reliance on "interactive content"' (*ibid.*, p.463).

In contrast to these 'dialogue games', in which pre-specified dialogue rules and samples are used to scaffold the learning of classroom dialogue skills, others have considered the use of the ubiquitous interactive whiteboard (IWB) as an open and content-neutral 'mediating artefact' that can be used to facilitate but not structure classroom dialogue (Hennessy 2011; Lewin *et al.* 2008; Mercer *et al.* 2010): 'the potential is for new dialogues to revolve and evolve around digital artefacts jointly created by teachers and learners on the IWB' (Hennessy 2011, p.464). Interactive whiteboards offer a variety of opportunities for teachers and children to interact with a multitude of digital resources (such as text, images, videos and web pages), for

example by dragging objects into novel juxtapositions or by drawing or annotating directly on the screen, thus extended dialogue to include the nonverbal and redefining it as multimodal. The notion that the interactive whiteboard is thus a 'mediating artefact' builds on the work of Wertsch and Säljö: 'tool-mediated action [is] a precursor to subsequent forms of mental functioning' (Wertsch 1991, p.21), 'the mastery of mediational means is thus an essential aspect of the process of learning (Säljö 2002, p.152). In the classroom, the IWB can open up a physical and cognitive dialogic space in which the variety of personal and shared perspectives are negotiated (Hennessy 2011); it is a mediating artefact, privileged by virtue of its dominating position at the front of the class, that enables teachers to scaffold learning and involve students in the co-construction of knowledge, support students' evolving ideas and maintain continuity over time, and develop pupil-to-pupil dialogue and pupil questioning (Lewin *et al.* 2008; Mercer *et al.* 2010).

The possibility raised by the current study, however, is that a digital game grounded in learning theory, that is perceived by the teaching staff to surpass a quality threshold, and that is used by groups of students who are supported by an adult, might similarly function as a mediating artefact, facilitating productive mathematical dialogue and thus enhancing learning (Houssart & Sams 2008; Laurillard & Baajour 2009).

As noted in each of the three research cycles, the prototype game was received most positively when it involved the children and teaching staff working collaboratively, exploring the game's virtual environment and the mathematics together, building a conversation that promoted thinking and reflection, enabling the children to learn through action and interaction. The children were observed chatting about the game among themselves, about the gameplay, drawing on their experience of entertainment games, but often about the mathematics, giving each other support while expressing and exchanging ideas. They were involved in giving and justifying their views, about how tasks might be tackled, and in negotiating the views of the other children; and showed themselves willing to reflect upon and change their starting positions. In fact, it might be argued that playing the prototype game encouraged children who elsewhere rarely succeed in mathematics, or who usually avoid getting involved (the

whisperers), to engage actively and willingly in discussions around mathematical strategies, thus raising levels of mathematical understanding for all the children taking part (Houssart & Sams 2008). It might also be argued that the game initiates a safe conjectural dialogic space in which the children may discuss and explore the mathematical concepts, may try their hand, without fear of failure (Mason in Sfard *et al.* 1998). Rather than worrying about having to deliver the 'correct answer', the only cost of error is a brief on-screen virtual death, the children can instead focus on exploring possibilities, thinking mathematically and constructing their own knowledge.

The game appeared to have most positive effect when the dialogue also involved the adult, helping the children vocalise their thought processes, teasing out what they needed to do, and providing support for both the gameplay and mathematics. Using the game required the teacher to adopt a new way of supporting the children. Rather than being the deliverer of specific knowledge, using an initiation-response-feedback approach typical of classrooms, they instead began helping the children draw on their experiences of playing the prototype game to construct their own mathematical understandings. Observing the children working through the structured activities incorporated in the game, while engaging them in open dialogue or listening to their 'unofficial' whispered talk, also provided the adult with opportunities to infer something about the children's learning needs. It gave them unprecedented access to the child's mathematical thinking processes and approach to arithmetic, helping them to identify and address misconceptions and understand exactly where the child's specific difficulties lay. For example, encouraging the children to articulate what they were doing revealed disconnects between what the individual child's records suggested they knew and what they actually did know and were capable of putting into practice. In addition, more than one discussion around mathematical tasks suggested, for apparently the first time, the possibility for one child of noticeable working memory deficits.

Dialogue centred on the prototype game also afforded opportunities for the adult to provide guidance and to intervene proactively, both of which was highly valued by the children: the adult's intervention was not seen as judgemental but rather as helpful,

allowing them to proceed quickly through the gameplay, so that they might collect yet more coins, and reinforcing their success. In fact, the adult's involvement was critical. As Sfard and colleagues note (1998), mathematical knowledge construction is only effective if the children's dialogue does not disseminate misconceptions. Either the children have to be proficient in the particular mathematical rules, or the adult has to guide and mediate, or, where a digital game is functioning as the mediating artefact, the rules have to be made manifest within the prototype game itself. If the game is functioning effectively (if it has surpassed the quality threshold), when the children exchange misconceptions, the game should prevent them moving through the gameplay thus encouraging them to reflect again. When the child has misunderstood particular mathematical concepts or procedures, or if they have misremembered mathematical facts, the game should prevent them reinforcing the error, by not permitting the error (something that pen and paper worksheets are not able to do).

However, the notion that the prototype game functions and thus might be understood as a 'mediating artefact' needs to be considered further. Does this compelling neologism explain what is actually going on when the prototype game is being used as described? As noted above, Hennessey (2011) and Lewin (2008) and colleagues introduce mediating artefact in the rather different context of interactive whiteboards, where it is especially useful for the very reason that interactive whiteboards are content-neutral. They facilitate the presentation of and interaction with any digital or other content that the teacher and class wish to explore; they function as a medium which disseminates and impacts upon that content but is neither synonymous with it nor defined by it. The prototype game is also clearly an artefact and it does function necessarily as a medium, in the sense described by Wertsch (1991) and Säljö (2002). But it also involves specific and pre-defined educational content, the three components of numeracy as conceived within the numeracy intervention, delivered in a logical pedagogically-grounded sequence, and has specific internal aims, for children to become proficient in each of those components with numbers up to twenty (similar could be said of many other games designed to support learning). Thus, although the prototype game might be said to be a mediating artefact, such a description is

ultimately inadequate. Any comprehensive understanding also needs to account for the fact that the game is not content-neutral, that it brings with it specific mathematical content and related learning aims.

During the course of this study, a range of alternative candidate descriptors have come to mind or have been suggested: fulcrum ('a thing that plays a central or essential role in an activity, event, or situation', ODE 2005), conduit ('a channel or medium by which anything – e.g. knowledge, influence, wealth, etc. – is conveyed', ODE 2005), hub ('the effective centre of an activity, region, or network', ODE 2005), 'learning machine' (in contrast to Skinner's 'teaching machines', 1958), and 'Babel fish' ('if you stick a Babel fish in your ear you can instantly understand anything said to you in any form of language', Adams 1979, p.48). For example, it might be argued that the prototype game functions as a fulcrum for the reason that it was shown to play a central role in facilitating dialogue, knowledge construction and deliberate practice. Alternatively, the game might be conceived as a conduit for the exchange of knowledge and information, informed conversation, between the participating children and adults. The game might also be thought of as some kind of 'learning machine' in the sense that it contains and aims to facilitate the learning of specific education content. On the other hand, the idea that the prototype game functions like a computer hub suggests a networked dialogue, with the game as hub facilitating communication between disparate and distributed nodes. Finally, the game might be conceived as a 'Babel fish' universal translator, making possible communication between participants (children, teaching staff and parents) who come from different worlds, or perspectives, and sometimes speak very different languages.

All of these descriptors point in useful directions, and all the functions that they imply are necessary for any comprehensive understanding of a digital game grounded in learning theory, that is perceived to surpass a quality threshold and is used by groups of students who are supported by an adult. However, none of these descriptors are sufficient. For example, none accounts for the role of the adult in guiding the learning (perhaps it is the adult who is in a sense the mediator). Nor do they accommodate the extended role of the prototype game outside of the classroom, as a learning

opportunity for the children to use at home with their parents. This reflection suggests that the game might facilitate multiple educationally productive conversations (Mercer 2010; Schleppegrell 2007; Sfard *et al.* 1998), here involving both mathematics and learning between a variety of stake-holders, as shown schematically in Figure 7.1: (i) between the students, (ii) between the classroom assistant and students, and (iii) between the teacher and classroom assistant. In addition, although there was limited evidence in this study, reference to a previous study (Holmes 2011) and to other research looking at the use of technology for learning in the home (Davies 2011), suggested that the game might also facilitate conversations (iv) between the parents and student, and (v) between the parents and teaching staff.

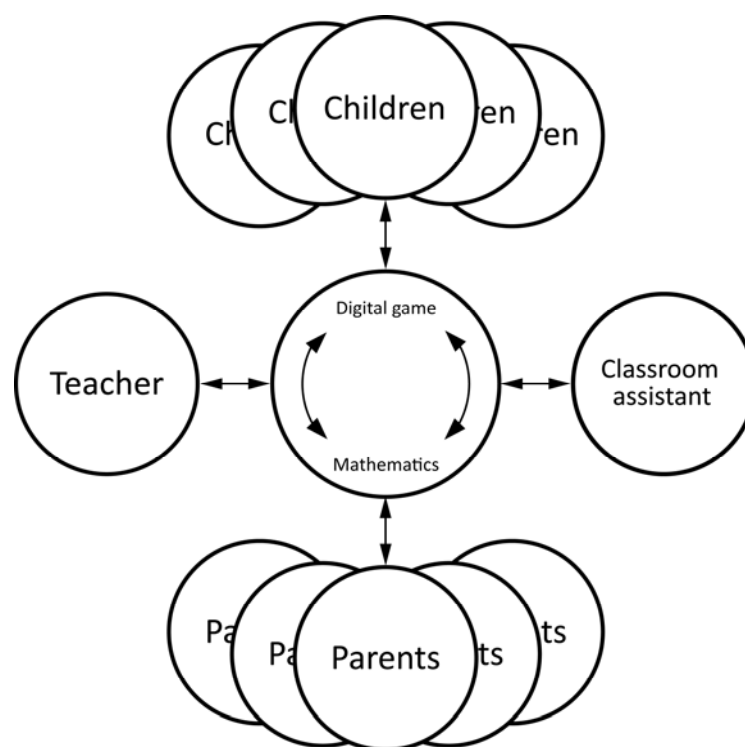


Figure 7.1

Multiple possible conversations potentially afforded by a digital game.

These multiple stakeholders and conversations suggest that it might be worth returning to and building upon Papert's description of the programmable computer as an 'object to think with', to conceptualise the prototype game instead as an 'object to think,

learn and teach with'. A digital game that is grounded in learning theory and that surpasses a quality threshold, that is believed by teaching staff to be worth their investment, might provide constructivist and dialogic opportunities to facilitate the children's mathematical thinking, guided activities and dialogic opportunities to facilitate their learning of specific mathematical constructs, and practical exemplars and dialogic opportunities to facilitate the teaching staff's engagement in active teaching.

Shown schematically in Figure 7.2, the game functions for each child as an object to think with, that provides them with a guiding medium through which to discover and construct their own mathematical knowledge. The game also situates the mathematics, only permits progress if the task is answered correctly, is fun and engaging, provides appropriate rehearsal practice, and allows the child to fail without embarrassing consequences. It also facilitates dialogic and conceptual exchange between the children, it is social, allowing them to share their mathematical ideas and to contribute to each others' knowledge construction and learning.

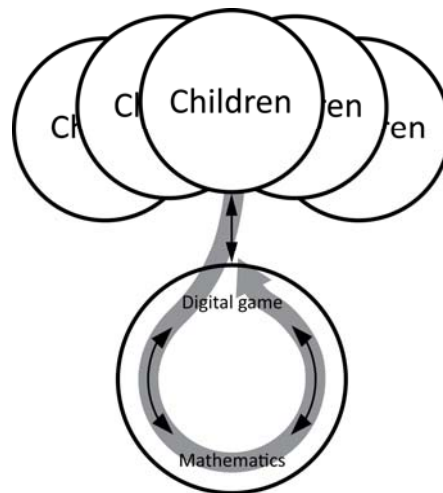


Figure 7.2

The game as an object to think with about mathematics.

A similar path can be traced from the classroom assistant, through the mediating game, to the children (Figure 7.3, p.240), to the teacher, or to the parents. For them,

the game functions as an object which both gives access to and provides a structure for supporting the children's mathematical understanding. It functions as a hook on which to hang conversations about the mathematics, or, with the teacher and parents, about the child's achievements and needs. Another path might also be traced for the teacher. For them, in addition to supporting the children's mathematical needs, a suitable game might provide information about the children's progress which can inform their learning profiles and facilitate conversations with the other adults. And for some parents, a path can again be traced through the game, which uses a possibly familiar language of computer games, to each of the other stakeholders. It might both provide a way for them to engage with their children as they work mathematically, and something tangible on which to initiate conversations with the school staff about their child's mathematical progress.

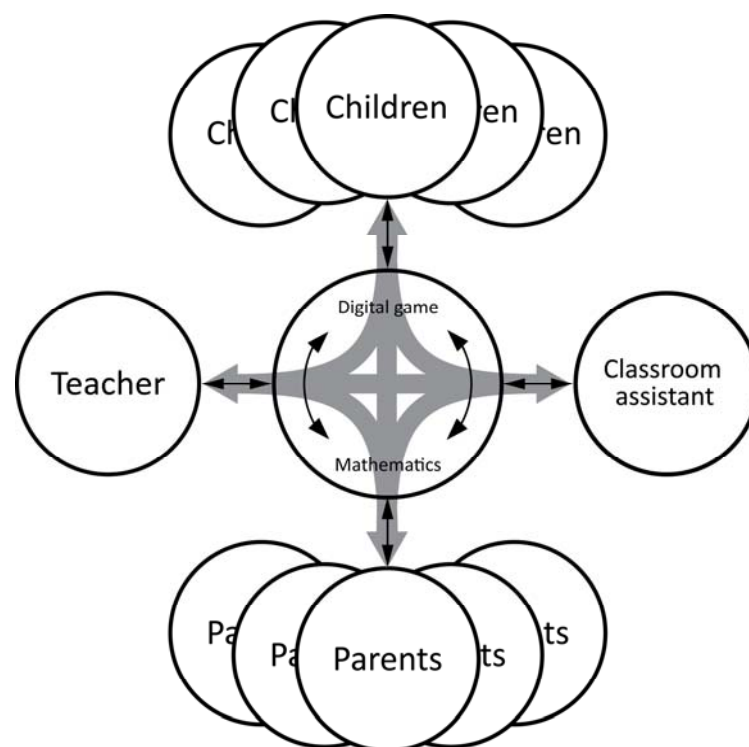


Figure 7.3

The game mediating conversations between all the stakeholders.

For children who are low-attaining in mathematics, a 'well-designed' game might provide an authentic medium through which they are able to make sense of their

encounters with mathematical objects, engage with and strengthen their mathematical thinking and learning, both individually and collaboratively, and thus develop a level of mathematical competence more commensurate with their age (Eisenberg 2002; Gray & Tall 2001; Kotsopoulos 2007); for the teaching staff, it might provide a medium through which to understand individual thinking and needs, so that they might identify and provide the most appropriate and timely guidance (Drijvers *et al.* 2010; Miranda 2003); and for the parents, it might provide both a medium through which they can experience and contribute to their own child's learning (Anderson *et al.* 2005; Holmes 2011; Lewin & Luckin 2010) and a potential conduit for dialogue with school staff, a conversation that can be otherwise sometimes difficult to achieve (Grant 2009; Harris & Goodall 2008; Hollingworth *et al.* 2009). The study showed that each of these conversations were 'caused' or facilitated by the prototype game, and that the conversations were productive and hence worth promoting. Further research will need to establish how these complex roles might be enhanced.

7.6 SUMMARY

Discussions around the potential of 'good' digital games for learning (Gee 1999) are almost always limited to its motivational and constructivist affordances (*cf.* Boyle *et al.* 2013; Connolly *et al.* 2012; Perrotta *et al.* 2013). However, this research has made clear that the potential of GBL needs to be more carefully considered. Firstly, notions of what actually constitutes 'good' GBL needs to go beyond ludology, the formal properties unique to digital games (Frasca 1999), to consider how the game implements insights from learning theory, which aligns with de Freitas and Oliver's pedagogy dimension (2006).

'Good' GBL (Table 7.1, p.242) might for example be purposeful, with specific learning objectives; it might be smart, with the level of difficulty responding dynamically to the growing capabilities of the child; and it might be authentic, with the learning content grounded in a context that is somehow meaningful to the child. It will also use gamification techniques or simply be fun to play, to motivate the child to engage with

the learning content. However, the contention here is that, from an internal perspective, ‘good’ GBL also needs to implement grounded insights from learning theory, such as the constructivist and behaviourist approaches to learning, the numeracy intervention, and the modes of representation implemented in the prototype game.

Table 7.1

Internal features of a digital game grounded in learning theory, for children low-attaining in mathematics.

Feature	Implemented in a game designed for children low-attaining in mathematics
Purposeful	Has specific learning objectives (derived from the numeracy intervention)
Implements learning theory	Constructivist: provides guided opportunities for the child to discover and construct their own mathematical knowledge. Behaviourist: provides retrieval practice opportunities for the child to consolidate (automatise) their mathematical knowledge. Modes of representation: supports the child’s progress from concrete to symbolic mathematical understandings.
Smart	Adapts to and builds upon the mathematical skills of the child.
Fun and gamified	Motivates the child to engage repeatedly with the mathematics.
Minimises fear of failure	Enables the child to engage with mathematical thinking which elsewhere they might avoid because of fear of failure.
Authentic	Grounds the mathematics in games-based contexts familiar to the child (rather than in textbooks or worksheets).

Moreover, while some games might tacitly or un-reflectively implement learning theory, that learning theory instead needs to be made explicit. This is partly so that teachers can evaluate the usefulness of the game for their own classrooms, because as this research has also shown, no matter how ‘effective’ a particular game, if it is not perceived to be of value, it will not be used. But foregrounding the learning theory in the medium of the game also allows others to re-consider the learning theory’s usefulness beyond the game for whatever learning objectives the game purports to support. For example, the present research has raised the possibility that the rigid separation of numeracy components as advocated by the numeracy intervention is unworkable in practice, which is perhaps why it often does not happen (Jackson 2012).

It has also noted both the large potential and the important limitations of Bruner's modes of representation for the teaching of addition or multiplication involving numbers larger than twenty.

From an external perspective, the present research has also raised the potential of a digital game as a fulcrum for important social interaction and educationally productive discussion, around both the mathematics and the child's understandings, capabilities and progress (Figure 7.3, p.240); a potential more or less ignored by all of the GBL evaluative schema identified in Section 7.2 (Ak 2012; Amory & Seagram 2003; Becker 2011; de Freitas & Oliver 2006; Liu & Lin 2009). As noted in the previous section, the observed and potential social-constructivist role of a digital game designed to support learning might be summarised as an artefact that stimulates, scaffolds and mediates dialogue. A properly-configured digital game used collaboratively might encourage children to talk through and discuss the mathematics, both with their peers and with supporting adults, teaching staff or parents, helping them to construct and better understand their personal mathematical knowledge. It might also provide teaching staff with opportunities to understand individual needs so that they might give appropriate and timely guidance. And it might provide parents with a way to connect both with their child's learning of mathematics and with the school staff.

In terms of the schematic in Figure 7.3 (p.240), a digital game as designed and researched in this study might be considered in two dimensions. First, the internal features of the game (represented by the central circle), what it is: how it implements learning theory and pedagogy through gameplay, how it motivates and engages its players, how it guides discovery, how it facilitates learning and the consolidation of learning, how it is purposeful, and whether it is perceived (by children, teaching staff and parents) to have surpassed a quality threshold. Secondly, the external features of the game (the outer circles and their network links), what the game makes possible: in particular the educational conversations that it stimulates, scaffolds and mediates between the multiple stakeholders in and around the 'messy' context of the classroom for which it is designed.

Conclusion

This investigation began with the observations that there are many children who are low-attaining in mathematics for whom conventional intervention can be effective but not always sufficient, and that digital games might prove useful. It set out to address two interdependent central research questions: How might a prototype digital game be designed to support children who are low-attaining in mathematics? What happens when such a game is used in schools?

At the outset, it was broadly anticipated that the first question informed by the second question would reveal potential design principles for a generic game, or rather principles for what have now been identified as the game's internal features. These design principles would synthesise features of entertainment digital games, aspects of the numeracy intervention and insights from learning theory and the cognitive sciences. Indeed, as discussed in Chapter 7, the three cycles of design, intervention, analysis and reflection have suggested such a catalogue of internal design principles.

A useful digital game for children low-attaining in mathematics will leverage the rule-based playful characteristics of entertainment games, the attractive animations and gamification features such as the leader board, which motivate these children to persevere with the mathematics that they sometimes elsewhere prefer to avoid. It will also situate the mathematics in contexts more meaningful, or authentic, for the child, and will provide multiple opportunities for them to think mathematically, without fear of failure. However, although important, these principles are so far conventional.

Other outcomes have been more striking. This investigation has suggested that, unlike most current GBL, any game designed for supporting learning should also consider synthesising, rather than keeping separate, guided constructivist opportunities, which enable the child to discover and construct their own mathematical knowledge, and behaviourist opportunities, retrieval practice that helps the child encode their constructed mathematical knowledge into long-term memory. There should also be purposeful learning objectives, grounded in an effective research-based numeracy intervention rather than based on common-sense intuition, and smart adaptivity, which pitches the mathematics at the child's current mathematical capabilities and builds up through the levels of difficulty in response to their growing confidence. In addition, a game for children who are low-attaining in mathematics might also consider Bruner's modes of representation, as a way of helping the child to make connections between concrete and symbolic mathematics, facilitating their transition from iconic to symbolic representations and thus enabling them to progress securely to more cognitively demanding mathematics. While none of this has been shown to be always essential, all of it has been shown to have important potential.

It was also anticipated that the second research question would reveal how the game was integrated into schools, when and how it was used to support children identified as low-attaining in mathematics, and what was achieved. Indeed, these were helpful outcomes of this investigation. For example, as discussed in Section 7.2, because of available resources, individual needs and expectations, the game was used in as many different ways as there were teaching staff involved: the children, staff rationale, locations, times, and durations all varied markedly, which the design of any useful GBL would somehow have to accommodate or at least acknowledge. In addition, the investigation suggested that a strict separation of numeracy components, as advocated by the numeracy intervention, might be unrealisable in practice and thus should be reconsidered. However, there were also other, unanticipated but notable, outcomes, which centred on teacher perceptions, collaborative learning, and the game's potential for stimulating, scaffolding and mediating dialogue.

While it is acknowledged that developers of GBL should strive to make their games achieve a quality threshold, for which the evaluative frameworks mentioned in Chapter 7 might be useful, if the games are going to be used in real classrooms what is equally as important is for teachers to perceive the game as relevant and effective, as flexible and easy to implement, and as a complement to rather than a distraction from their established teaching practices. In short, if it is not thought by the teacher to meet these criteria, no matter how ‘good’ the game might be, as measured within evaluative frameworks or by experimental studies, it simply is not going to be used. Any potential would thus be squandered. This is not a unique observation, indeed it supports earlier research (Cuban 2001; Kirriemuir & McFarlane 2004), but it does not yet appear to have been taken seriously by the GBL community.

Meanwhile, a digital game’s potential for collaborative and dialogue-based learning go hand in hand. Digital games designed to support learning, such as the prototype in this investigation, might be played by an individual child without supervision (what is sometimes pejoratively called ‘park and play’). This is how game-based learning is most often conceived in the literature: an individual child playing a game on an individual computer or tablet. When the prototype game was used like this, with the game’s internal features working in concert, ‘dialogue’ was limited to the one-way feedback provided by the learning companion. Nevertheless, teaching staff reported that many children did make some useful progress. The possibility of standalone digital GBL engaging players in ‘intelligent’ two-way dialogue, perhaps involving conversational learning companions, is an intriguing prospect but is still some way off (Eynon & Davies 2010; McNamara *et al.* 2009).

However, the game was also often played by individual children supervised by an adult, with the adult and the child sat next to one another in front of the computer. In this context, the child again benefits from the internal features of the game, but much else also might happen. As the child plays the game and chats about their gameplay and mathematics strategies, the supervising adult gains insight into the child’s current mathematical understanding, how they think about the mathematics and approach mathematical calculations, which in turn allows any misconceptions to be addressed. At the same time, the conversation allows a teacher or classroom assistant to scaffold and

help progress the child's mathematical development. When the supervising adult is instead a parent, which happened only occasionally in this study, the game might have helped parent and child to explore the mathematics together, to share the learning, which other forms of homework do not so readily allow or at least rarely encourage. Moreover, for some parents, those who found mathematics difficult at school or who for whatever reasons now find it difficult to engage with teachers, the game might also provide a conversational hook or simply a starting or reference point to facilitate their communication about their child's mathematical learning needs with the school.

The prototype game was also often played by several children simultaneously, using individual computers but sat near to one another, supervised by a teacher or teaching assistant. It was this scenario which led to the most dynamic sessions observed for this research, with the children excitedly sharing their ideas both about the gameplay and the mathematics, discussing strategies, scaffolding each other's thinking, helping each other to learn. Meanwhile, the supervising adult listened in, gaining novel insights into the children's mathematical understandings, and wherever helpful provided guidance, further promoting the children's learning and progress in mathematics. Throughout, the numeracy content, levels of difficulty, and gameplay, all encapsulated in the prototype game, provided an effective structure and a vocabulary, a mediating scaffold, around which the conversations could develop.

These collaborative contexts thus revealed the prototype game's external potential, as an artefact that stimulates, scaffolds and mediates dialogue. While the internal features of digital games designed for children low-attaining in mathematics have to be carefully configured, so that any such game achieves the quality threshold that much GBL has elsewhere been shown to achieve and so provides useful support to those children who need it, the contention here is that attention should also be given to the game's external potential. The prototype game designed and researched in this investigation synthesised constructivist and behaviourist approaches to the learning of numeracy in the format of an engaging digital game, enabling learning through the digital gameplay, and in so doing clearly provided useful support for some children low-attaining in mathematics. However, it is the social-constructivist potential of

suitably designed GBL, when most GBL is played individually (Clark *et al.* 2013), which is of interest but unexplored in the literature. It is thus the potential of a digital game designed to support children who are low-attaining in mathematics as an artefact that both supports individual learning and stimulates, scaffolds and mediates dialogue that constitutes this investigation's key novel insight.

In summary, this design-based investigation has shown that a prototype digital game that implements principles of an effective numeracy intervention and that draws on insights from learning theory and the cognitive sciences can be designed and can be useful in schools for children who are low attaining in mathematics. Such a game benefits from features of puzzle and platform entertainment games, including the use of configurable avatars, speaking digital companions, leader boards, and levels, all of which contributes to the children's engagement and ultimately their mathematical progress. Situating the mathematics in a digital game's virtual environment also helped make the mathematics more meaningful, or authentic, for the children; while the multiple opportunities to construct and practice their mathematical knowledge also helped address the children's fear of mathematics failure.

The prototype game was also thought to be useful by many of the teaching staff. However, for such a game to be taken up widely by schools, it has to be perceived by teachers to have achieved a quality threshold, to complement their teaching practice, and to be worthwhile for these vulnerable but busy children. Nevertheless, despite its benefits, the prototype's internal features were ultimately limited. Where the prototype game has been shown to be most useful is when it serves as a fulcrum for social interaction and educationally productive discussion between the children and adults: when it thus becomes an artefact that both supports individual learning and stimulates, scaffolds and mediates dialogue-based collaborative learning. This exciting potential might inform both current games-based learning practice and future research.

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Expert interviewees

Interviewee	Role	Expertise
Steve Chinn	Researcher/author	Children with literacy and numeracy difficulties.
Ann Dowker	University Research Lecturer, Department of Experimental Psychology, University of Oxford.	Individual differences in arithmetic: implications for psychology, neuroscience and education
Di Hatchett	Director, Every Child a Chance Trust.	Pedagogy and government policy for struggling learners. Every Child a Chance Trust is the organisation tasked by the previous government to tackle the needs of children with literacy and numeracy difficulties.
Paul Howard-Jones	Reader in Neuroeducation, Graduate School of Education, University of Bristol	Application of the cognitive sciences to education, including games-based learning.
Kath John	Local authority consultant (Vale of Glamorgan).	Responsible for managing Catch Up Numeracy in all schools across her local authority.
Jonathan Reed	Neuropsychologist and developer of Neurogames	Neurogames: drill and practice games for children learning to read and beginning mathematics.
Mike Ross	Educational consultant	Responsible for implementing 'Assessment for Learning' and 'Let's Think' in the Vale of Glamorgan and across Wales.
Tim Rylands	Educational consultant	Known for being an 'inspirational' teacher. Has made extensive use of the game 'Myst' in classrooms studying English literature.
David Squire	Game-based learning developer and researcher	Has been involved in the research and development of numerous game-based learning projects.
Ben Williamson	Researcher (formerly with Futurelab) and University Lecturer (Exeter)	Has undertaken various research reports into game-based learning.

Games and game platforms

Title	Developer	Link
<i>Angry Birds</i>	Rovio	http://www.angrybirds.com
<i>Call of Duty</i>	Activision Publishing	http://www.callofduty.com
<i>Dance Central</i>	Harmonix Music Systems	http://www.dancecentral.com
<i>Doom</i>	id Software	http://www.idsoftware.com/games/doom
<i>Dr Kawashima</i>	Nintendo	http://www.braintraining.com.au
<i>Flight Control</i>	Firemint	https://itunes.apple.com/gb/app/flight-control/id306220440?mt=8&affid=1930871
<i>Grand Theft Auto</i>	Rockstar Games	http://www.rockstargames.com/grandtheftauto
<i>Mario Brothers</i>	Nintendo	http://mario.nintendo.com
<i>Miniclip</i>	Miniclip	http://www.miniclip.com
<i>Myst</i>	Cyan Worlds	http://www.cyanworlds.com/products/myst.php
<i>Neurogames</i>	Neurogames	http://www.neurogames.co.uk/
<i>Nintendo Wii</i>	Nintendo	http://www.nintendo.co.uk/Wii/Wii-94559.html
<i>Pac-Man</i>	NAMCO BANDAI Games	http://pacman.com/en
<i>Pong</i>	(Atari)*	(http://www.ponggame.org)
<i>Quest Atlantis</i>	Atlantis Remixed Project	http://atlantisremixed.org
<i>Space Invaders</i>	(Taito)	(http://www.spaceinvaders.de)
<i>Spacewar!</i>	(MIT)	(http://museum.mit.edu/150/25)
<i>Super Mario Bros.</i>	Nintendo	http://www.nintendo.co.uk/Games/Nintendo-Characters-Hub/Super-Mario-Hub/Super-Mario-Bros-Hub-Mario-Games-627604.html
<i>Temple Run</i>	Imangi Studios	http://www.imangistudios.com/
<i>Time to Eat</i>	Pollak, J., Gay, G., Byrne, S., Wagner, E., Retelny, D. & Humphreys, L., 2010. It's Time to Eat! Using Mobile Games to Promote Healthy Eating. <i>Pervasive Computing, IEEE</i> , 9(3), pp.21–27.	
<i>Timez Attack</i>	Big Brainz	http://www.bigbrainz.com/
<i>Tetris</i>	Tetris Holdings	http://www.tetris.com/
<i>The Sims</i>	EA Games	http://thesims.com
<i>Wii Sports</i>	Nintendo	http://www.nintendo.co.uk/Games/Wii/Wii-Sports-283971.html
<i>World of Warcraft</i>	Blizzard Entertainment	http://us.blizzard.com/en-us/games/wow
<i>X-Box Kinect</i>	Microsoft	http://www.microsoft.com

* Information in parentheses refer to historical games that are not now generally available.

Interview schedules

In the interviews, the following questions were used to initiate the dialogue. The participants' responses led to many follow-up questions.

Research Cycle 1

Teaching staff initial interview:

- I'd like to talk a bit about the children who you have selected to be involved. How old are they?
- Why have they been selected for participation in this project?
- Without giving me any personal details, can you describe what kind of child they are?
- How do they fit into class?
- Do they enjoy being at school?
- What is it like for them when the class topic is maths?
- Do they enjoy maths?
- In what ways do they find maths difficult?
- Are they receiving any additional support?
- How does that affect them?
- What impact does that have on them (their learning, their participation in other classes, their behaviour)?
- When you mentioned they would be participating in this project, using computer games, what was their reaction?
- What do you think they might get out of this project?
- Do you think computer games might be used to help children learn?

Participating children initial interview:

- What's your name?
- [Explanation of project, confirmation of consent, confirmation of their right to withdraw.]
- Can you tell me a bit about school? What's your favourite subject? And what's your worst subject?
- Do you enjoy learning about numeracy/maths?
- Do you think it is important to be able to do numeracy/maths?
- Do you ever do numeracy/maths at home?
- Does anyone else do numeracy/maths at home?
- How good do you think you are at doing numeracy/maths in your head?
- How much do you like doing calculations?
- Do you like doing calculations on paper (writing things down)?
- How do you feel if your teacher asks you to do numeracy/maths?
- If you had a friend who could not do numeracy/maths, what would you tell them they needed to do?
- How easy do you find numeracy/maths (out of 10)?
- Do you play computer games?
- What do you like about playing computer games?
- What do you find easy, what do you find difficult?
- Do you think computer games can help you learn?

Teaching staff follow-up interview:

- Do you think these games made any difference to the children?
- How, if at all, do you think the game helped the children with their mathematics?
- What were the children's reactions to playing the game?

- Do you think these games are a good way of getting the children to talk about the mathematics?
- Were you able to learn anything about the children and their mathematics by watching them play?
- Were you able to learn anything about the children and their mathematics by listening to what they said as they played the game?
- How do you think you might use the game?
- What do you think the games could do to facilitate transfer?
- How could the game be improved to make it more useful for the children?
- How could the game be improved to make it more useful for you?

Participating children follow-up interview:

- How did you find the games?
- Do you think if you played that game again, would it help more?
- Do you think it is a good way to learn?
- What makes it a good way to learn?
- What is it about the game that is helping you with the mathematics?
- If you were asked to play it at home, for your homework, what would you think?
- If you were to do this at home, do you think it would be useful to you or not?
- What do you think about the animations and the characters?
- Do you see the game as fun or as work?
- How could we make the game better?
- Anything else?

Research Cycle 2

Teaching staff and participating children initial interviews as per Research Cycle 1.

Teaching staff follow up interview:

- How has it been going?
- How often have you been using the game?
- How has it fitted into school life?
- Have you learned anything about the children or their skills/knowledge by watching them playing the game?
- Do you think these games made any difference to the children?
- How, if at all, do you think the game helped the children with their mathematics?
- What were the children's reactions to playing the game?
- Do you think these games help to get the children talking about maths?
- Were you able to learn anything about the children and their mathematics by watching them?
- What are you getting out of it?
- Has there been any impact in class?
- Have the children played with their parents/carers?
- What problems have there been?
- How do you see it being used, if at all?
- What improvements need to be made to the game?
- What other improvements would you like to see?
- Any other advice or thoughts?

Participating children follow-up interview:

- Have you enjoyed playing the games?
- Do you think you've been learning anything?
- In class, have you ever thought of answers that playing the game helped you to remember?
- Do you prefer playing quietly on your own, or talking with friends or your teachers?
- If your teacher didn't ask you to play the game, would you still want to? And would you?
- Have you played with your parents/carers?
- What have you enjoyed most/least?
- Do you think of it as playing or learning?
- How can we make it better?

Research Cycle 3*Teaching staff initial interview:*

- How are you currently using Catch Up Numeracy (how many children are involved, how are they timetabled...)?
- How do you intend using the Catch Up Numeracy digital games (how many children will be involved, when and how do you intend the children to play the games, what do you hope to get out of using the games...)?
- Without giving full names, please would you tell me about each individual child who will be participating in the games (their strengths and weaknesses, their attitudes to learning and to mathematics, why you have selected them to participate, what you hope the individual children will get out of playing the games...)?
- Do you intend the children to play the games individually or in pairs/groups (with each child using an individual computer)?
- Do you intend encouraging parents to encourage their children to play the games at home?
- Do you expect to learn anything from watching/supporting the children as they play the games?

Teaching staff follow-up interview:

- How have you been using the Catch Up Numeracy digital games (how many children are involved, when and how often have they been playing the games, in general how has it been going...)?
- What problems have there been?
- How have you fitted the games into school life (timetabling, withdrawal from class...)?
- What are the children getting out of playing the games (in particular, are they learning anything...)?
- Have you noticed any changes in the children's attitudes to learning or to mathematics?
- Have the children been playing the games individually or in pairs/groups?
- If they have been playing in groups, has that had any impact?
- Have the children played the games at home, supported by their parents/carers? If so, has that had any impact?
- If the children have played the game in groups, have they gained anything from talking with each other?
- Have you learned anything from watching/supporting the children as they play the games (if so, what...)?
- Have you gained anything from watching/supporting the children as they play the games?
- Has there been any impact in class?
- How do you see it being used, if at all, by other schools?
- What improvements are needed?
- Other advice or thoughts?

Paper-based questionnaires

The following questions have been reformatted to reduce space.

Teaching staff:

Between 1 (least) and 5 (most):

- How confident are you that you know how best to support children who have difficulties with numeracy?
- How confident are you that you have sufficient strategies to fully support children who have difficulties with numeracy?
- How confident are you that you have sufficient resources to fully support children who have difficulties with numeracy?
- How confident are you that the school keeps parents properly informed of their child's difficulties with numeracy?
- How familiar are you with the principles of the Catch up Numeracy intervention?
- How much do you enjoy playing computer games?
- How much do you enjoy playing computer game with children in your school?
- How useful to you think it would be for children who have difficulties with numeracy to play computer games designed to help them with their numeracy?
- How useful do you think it would be for children who have difficulties with numeracy to play computer games designed to complement Catch Up Numeracy?
- How happy would you be to use computer games as part of the support you give to children who have difficulties with numeracy?

Participating children:

Between 1 (least) and 5 (most) (or spoken answer):

- How much do you enjoy school?
- How much do you enjoy arithmetic/numeracy/maths?
- How easy do you find arithmetic/numeracy/maths?
- Do you have any difficulties with arithmetic/numeracy/maths?
- How does it make you feel when you have difficulties with arithmetic/numeracy/maths?
- How easy do you find doing calculations in your head?
- How easy do you find doing calculations on paper?
- How worried do you get when doing arithmetic/numeracy/maths?
- How happy are you when doing arithmetic/numeracy/maths?
- How worried are you, when you find arithmetic/numeracy/maths too difficult?
- How much do you agree with the statement: you have a certain amount of intelligence (cleverness) and you really can't do much to change it.
- How much do you agree with the statement: your intelligence (cleverness) is something about you that you can't change very much.
- How much do you agree with the statement: you can learn new things but you can't really change your intelligence (cleverness)
- How much do you enjoy playing computer games?
- How much do you enjoy playing computer games with your parents/carers?
- How much would you like to play computer games that helped you with your arithmetic/numeracy/maths?
- How much do you think playing computer games might help you with your arithmetic/numeracy/maths?
- Can you mix together playing games and learning, or should they always be separate?

Pictorial Lickert scale

The two versions of the 'smiley face' Lickert scale were used alternately.



Example of data coding

Example raw interview data

The following text is an extract from a Research Cycle 2 follow-up interview (with the SENCO from Lane End school known as 'Ben').

<Internals\Research cycle 2\b. Follow up\Lane End\Ben> Paragraph 7

:: I can't model, same as if it were a normal calculation we were doing in a classroom, I would go over and discuss it and I would model, OK maybe this is how you can solve it. Cos that's not there, because it's on the screen, it's different. It usually starts, well what did you do? What was the previous calculation, how did you solve that? And then they think, OK I did this, this and this. And they try to repeat that process. So it's getting them to think what they initially did and how that helped them solve this. It changes that dynamic, that relationship between us. Because it also takes away that... with children where, you know you do it for me, and I'm not you know. The object is to solve the problem, but you or the TA will usually write the answer for me. And I don't have to completely take on board what you're saying.

Example coded interview data (by interviewee: Ben)

The following text illustrates how the above example of Ben's interview data was coded (using the qualitative analysis computer software NVivo 8). Within the software, any section of an interview may be encoded with a variety of codes.

<Internals\Research cycle 2\b. Follow up\Lane End\Ben> - Disadvantage of games

:: I can't model, same as if it were a normal calculation we were doing in a classroom, I would go over and discuss it and I would model, OK maybe this is how you can solve it. Cos that's not there, because it's on the screen, it's different.

<Internals\Research cycle 2\b. Follow up\Lane End\Ben> - Using the games

:: I can't model, same as if it were a normal calculation we were doing in a classroom, I would go over and discuss it and I would model, OK maybe this is how you can solve it. Cos that's not there, because it's on the screen, it's different. It usually starts, well what did you do? What was the previous calculation, how did you solve that? And then they think, OK I did this, this and this. And they try to repeat that process. So it's getting them to think what they initially did and how that helped them solve this. It changes that dynamic, that relationship between us. Because it also takes away that... with children where, you know you do it for me, and I'm not you know. The object is to solve the problem, but you or the TA will usually write the answer for me. And I don't have to completely take on board what you're saying.

<Internals\Research cycle 2\b. Follow up\Lane End\Ben> - Talking

:: It usually starts, well what did you do? What was the previous calculation, how did you solve that? And then they think, OK I did this, this and this. And they try to repeat that process. So it's getting them to think what they initially did and how that helped them solve this.

<Internals\Research cycle 2\b. Follow up\Lane End\Ben> - Adult / child relationship

:: It changes that dynamic, that relationship between us. Because it also takes away that... with children where, you know you do it for me, and I'm not you know. The object is to solve the problem, but you or the TA will usually write the answer for me. And I don't have to completely take on board what you're saying.

<Internals\Research cycle 2\b. Follow up\Lane End\Ben> - Improvements

:: It changes that dynamic, that relationship between us. Because it also takes away that... with children where, you know you do it for me, and I'm not you know. The object is to solve the problem, but you or the TA will usually write the answer for me. And I don't have to completely take on board what you're saying.

Examples of coded interview data (by code: Talking)

Once all the interview data is encoded, the software enables you to extract for further analysis all the data from multiple interviewees for any particular code. Further analysis might involve merging codes into broader categories.

The following examples are interview data, from Research Cycle 2, Lane End school, encoded 'Talking'.

<Internals\Research cycle 2\b. Follow up\Lane End\Ben>

:: Straightaway he fires through it and you can see, he's thinking it through and shooting through the screens. "OK, so do you know what you're doing?" "Yes, I'm doing this, this and this."

:: It usually starts, "Well what did you do? What was the previous calculation, how did you solve that?" And then they think, "OK I did this, this and this." And they try to repeat that process. So it's getting them to think what they initially did and how that helped them solve this.

:: It's scaffolding, I often say to them, well you've got to do, what you did before, you can't just throw all that away. You've still got to apply the same thing because it's there. I think sometimes they need reminding of that, so sitting next to him, "Look, you did this before, why don't you try that again?", and he says "yeah, OK". I'm using the game as a way of reinforcing the process.

:: It's useful getting [Christian] to explain things, because he's got to engage with me, which he avoids engaging with anyone, which is quite tricky for him. He's quite willing to let the world go by. So getting him to talk to you about he's done and why he's done it, to show you what he's done and why he's done it. He can show me what he did on a previous level, and I can say, "So why are you not doing that again?" "Oh right, OK, I'll try that, Oh it works." "So what are we going to do on this one." "Well I'll just try it shall I?" "OK let's see how that one works out." So it's actually going through that process with him. You just say, "OK, so what are you going to do this time?"

<Internals\Research cycle 2\b. Follow up\Lane End\Hannah>

:: I just try to hover around, I'll just now and again mention something, I don't try to follow it up. I'm not with them all the time, so they can just get on with it, in their own way, but it's also – it's nice to hear what they are learning while they are doing it. Just for them to reinforce it by speaking to me, about what they've learned from it and I'll walk away. [Kaitlin] for example, had been stuck. I'd rather one of the other ones help her, so they're learning together, so it's a peer thing, rather than a teacher coming and get.... I like to hear them say what they're learning.

:: I think that they're getting a lot from the games, and it's a kind of reinforcing the help that I'm trying to give. Rather than just play the games, I sometimes feel that [Christian], I checked up on him a bit more

because I don't think that he quite.... But then I was discussing with him, "So what do you think it's asking you to do?" Rather than him just doing random things on the game, it's just trying to focus him a bit more, about what the game is expecting him to do. Particularly with the blocks, he was just trying random things. "So, what do you think you should be doing here?" Get them to pause and think for a bit. Helping them to progress from there.

:: I think when the child can tell you what they're doing, or tell another child, it's just another reinforcing the learning, and it's finding out what's going on in their mind as well, rather than just see what they're doing in the game. I think if they can explain something to you then that's just reinforcing the learning that they're getting from the game and from the maths questions that they're doing. It's just an extra thing, in addition to when they're writing things, and helping them to communicate better.

:: When I have been working with them, it's all about, with maths it's all about what do these numbers represent, and it gives an opportunity to talk about it. Whereas when you're in class, it's not quite the same. When they're using the game, they're distracted and they'll just talk about the maths.

<Internals\Research cycle 2\b. Follow up\Lane End\Kaitlin>

:: Well it depends what we're talking about, if we're talking about the maths it helps, if we're talking about something else... we were talking about what different games we'd played, what we've done and stuff.

<Internals\Research cycle 2\b. Follow up\Lane End\Sam>

:: I think it's quite good, because if there's something you don't understand, and they understand it, you could ask them. It's more helpful than getting a teacher to help. I was just asking on that when you're supposed to collect the key, the first time I played it I didn't understand so I just asked [Kaitlin] what you're supposed to do and she told me and I got it right.

:: I think it's quite good [to chat with friends] because if you're not sure you can ask them and they sometimes help when you're stuck on playing the game. It's useful having an adult kind of to help you.

:: I've been using the games at home, which has been working fine, because at home if I get a little stuck I can ask my mum for help or my dad. Sometimes if my mum's not busy she'll sit with me and help me, but if she's busy and my dad's busy then I'll do it on my own. I prefer doing it with my mum or my dad but sometimes it's quite good to do it on my own. It's fun sharing it. She thinks that it's quite good that I use it.

<Internals\Research cycle 2\b. Follow up\Lane End\Christian>

:: [We talked with each other], sometimes. I asked for help once. A few times. It's good to chat with our friends because if they're stuck on a question but I know it, we can help each other. I think that helps people to learn.

:: It was helpful, because he was giving me like, because I was wondering how to do this question when there was no numbers, and [Ben] said, "What was the number for the last one?" He was getting me to think a different answer. It helped me, because if someone gave me a problem like that I would be able to find it easier, to work it out.

--

Research ethics approval

SOCIAL SCIENCES & HUMANITIES
INTER-DIVISIONAL RESEARCH ETHICS COMMITTEE

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Co-ordinator of the IDREC
Social Sciences Divisional Office



Ref. SSD/2/3/IDREC

02 June, 2011

Wayne Holmes
Department of Education

Dear Mr Holmes,

Research Ethics Approval

Ref No.: SSD/CUREC2/11-12

Title: Investigating the use of digital gameplay as a means by which to better understand and support the learning needs of children who struggle with numeracy.

The above application has been considered on behalf of the Social Sciences and Humanities Inter-divisional Research Ethics Committee (IDREC) in accordance with the procedures laid down by the University for ethical approval of all research involving human participants.

I am pleased to inform you that, on the basis of the information provided to the IDREC, the proposed research has been judged as meeting appropriate ethical standards, and accordingly approval has been granted.

Should there be any subsequent changes to the project, which raise ethical issues not covered in the original application, you should submit details to the IDREC for consideration.

A handwritten signature in black ink that reads 'Chris Ballinger'.

Dr Chris. Ballinger

cc: Dr Rebecca Eynon, Department of Education
Education Research Office, Department of Education

CAJB

Participants' information

Information for parents and carers:

DEPARTMENT OF EDUCATION
15 Norham Gardens, Oxford, OX2 6PY
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general.enquiries@education.ox.ac.uk
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Investigating the use of digital gameplay as a means by which to better understand and support the learning needs of children who struggle with numeracy.

INFORMATION FOR PARENTS AND/OR CARERS OF PARTICIPATING CHILDREN

Invitation

Your daughter/son is being invited to take part in a research study, looking at the use of computer games to support their numeracy.

Before you agree that your child may take part, it is important that you have an opportunity to understand the purpose of the research and what your child's participation will involve. This document aims to give you all the information that you need to make an informed decision. Please take all the time that you need to read it.

Please do not hesitate to ask if there is anything about the project that is unclear or if you would like more information. Please take all the time that you need to decide whether or not you are happy for your daughter/son to take part in this research.

What is the purpose of the study?

This study investigates ways in which computer games might be used to better understand and support the learning needs of children who struggle with numeracy. I am undertaking this study as part of my Doctor of Philosophy (DPhil) studies at the University of Oxford.

Why have your daughter/son been chosen?

Your daughter/son has been suggested by their school as someone whose numeracy skills might benefit from additional support.

What will your participation involve?

The research project will involve your daughter/son answering some brief questions and playing a computer game designed to support their numeracy. This will take place at their school during normal school hours as part of their numeracy support. Their progress playing the game will be monitored and what they say while they are playing and answering questions might be audio recorded.

Does your daughter/son have to take part?

No. It is entirely your decision whether to permit your daughter/son to take part in this study.

Leveraging the pedagogical affordances of digital games to better understand and support the learning needs of children who struggle with numeracy.

INFORMATION FOR PARENTS AND CARERS

What are the risks and benefits of taking part?

There are no known risks to your daughter/son's participation in this study. You can withdraw your child from the study at any time. Your child will only be questioned and their use of the computer game observed under the supervision of a school staff member. In addition, I have been CRB (full disclosure) checked.

The research information gathered during this study will only be made available to my supervisor, Dr Rebecca Eynon, and the Catch Up organisation. Data about the progress in numeracy made by your daughter/son will be shared only with their school's staff. In any reports, all names will be anonymised and every effort will be taken to protect the identity of the participants.

The maintenance of confidentiality of all information gathered as a part of this research is subject to normal legal requirements.

What will happen to the results of this research?

The results of this research will form the basis of my DPhil thesis, which will be submitted for assessment to the University of Oxford.

Who is funding the research?

The research is partly funded by the not-for-profit charities Catch Up and The Esmée Fairbairn Foundation.

Contact for further information or follow-up

Should you have any further questions about this research study, please do not hesitate to contact me:

- Wayne Holmes (wayne.holmes@education.ox.ac.uk) (07973 506106), Department of Education, University of Oxford, 15 Norham Gardens, Oxford, OX2 6PY

Alternatively, you can contact my DPhil Supervisor:

- Dr Rebecca Eynon (rebecca.eynon@oii.ox.ac.uk), Department of Education, University of Oxford, 15 Norham Gardens, Oxford, OX2 6PY (01865 274024)

Or you can contact the Deputy Director of Catch Up:

- Dr Graham Sigley (graham.sigley@catchup.org.uk), Catch Up, Keystone Innovation Centre, Croxton Way, Thetford, IP24 1JD (01842 752297)

THANK YOU FOR TAKING THE TIME TO READ THIS INFORMATION

Information for school staff:

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Investigating the use of digital gameplay as a means by which to better understand and support the learning needs of children who struggle with numeracy.

INFORMATION FOR SCHOOL STAFF

Invitation

You and some of the children with whom you work are being invited to take part in a research study, looking at the use of computer games to support children's numeracy.

Before you agree to take part, it is important that you have the opportunity to understand the purpose of the research and what your participation will involve. This document aims to give you all the information that you need to make an informed decision. Please take all the time that you need to read it.

Please do not hesitate to ask if there is anything about the project that is unclear or if you would like more information. Please take all the time that you need to decide whether or not you are happy to take part in this research.

What is the purpose of the study?

This study investigates ways in which computer games might be used to better understand and support the learning needs of children who struggle with numeracy. I am undertaking this study as part of my Doctor of Philosophy (DPhil) studies at the University of Oxford.

Why have you been chosen?

You have been suggested by your school as someone who is working with children whose numeracy skills might benefit from additional support.

What will your participation involve?

The research project will involve you answering some brief questions and supporting some of the children with whom you work as they play a computer game designed to support their numeracy. This will take place in school during normal school hours as part of the children's numeracy support. The children's progress playing the game will be monitored and what you and they say while they are playing might be audio recorded.

Do you have to take part?

No. It is entirely your decision whether to take part in this study.

Investigating the use of digital gameplay as a means by which to better understand and support the learning needs of children who struggle with numeracy.

INFORMATION FOR SCHOOL STAFF

What are the risks and benefits of taking part?

There are no known risks to your participation in this study. You and the children can withdraw from the study at any time. I will only work with the children under your supervision (or supervision by another staff member). In addition, I have been CRB (full disclosure) checked.

The research information gathered during this study will only be made available to my supervisor, Dr Rebecca Eynon, and the Catch Up organisation. Data about the progress in numeracy made by the participating children will be shared only with you. In any reports, all names will be anonymised and every effort will be taken to protect the identity of the participants.

The maintenance of confidentiality of all information gathered as a part of this research is subject to normal legal requirements.

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THANK YOU FOR TAKING THE TIME TO READ THIS INFORMATION

Participants' consent

Consent form for parents and carers:

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**Informed Consent Form**

FOR PARENTS AND CARERS

'Investigating the use of digital gameplay as a means by which to better understand and support the learning needs of children who struggle with numeracy' is a research project being undertaken by Wayne Holmes as part of his Doctor of Philosophy studies at the University of Oxford.

The project aims to investigate ways in which computer games might be used to better understand and support the learning needs of children who struggle with numeracy..

- **I have read and understood the accompanying 'Information for the parents and/or carers of participating children' and have had the opportunity to ask questions and get satisfactory answers.**
- **I understand that I can withdraw my daughter/son from the study without any consequences at any time simply by informing the researcher of my decision.**
- **I understand who will have access to any information that I provide and what will happen to the data at the end of this project.**
- **I understand that this project has been reviewed by, and received ethics clearance through, the University of Oxford Central University Research Ethics Committee**

I agree that my daughter/son may participate in this study.

Daughter/son's name:

Your name:

Date:

Your signature:

Consent form for school staff:

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**Informed Consent Form****FOR SCHOOL STAFF**

'Investigating the use of digital gameplay as a means by which to better understand and support the learning needs of children who struggle with numeracy' is a research project being undertaken by Wayne Holmes as part of his Doctor of Philosophy studies at the University of Oxford.

The project aims to investigate ways in which computer games might be used to better understand and support the learning needs of children who struggle with numeracy..

- I have read and understood the accompanying 'Information for participants' and have had the opportunity to ask questions and get satisfactory answers.
- I understand that I can withdraw from the study without any consequences at any time simply by informing the researcher of my decision.
- I understand who will have access to any information that I provide and what will happen to the data at the end of this project.
- I understand that this project has been reviewed by, and received ethics clearance through, the University of Oxford Central University Research Ethics Committee

I agree to participate in this study.

Name:

Date:

Signature:

Online questionnaires

The questions asked for Lickert scale responses and provided opportunities for extended text responses.

Teaching staff (pre-intervention):

- How confident are you that you know how best to support children who have difficulties with numeracy?
- How confident are you that you have sufficient resources to fully support children who have difficulties with numeracy?
- If you have used a computer game to support children who are receiving Catch Up Numeracy support...
 - What computer games have you used?
 - How effective on average have these computer games been?
 - In what ways were these computer games effective?
 - In what ways were these computer games not effective?
 - Have you used the games in individual and/or group sessions?
 - Were the games also used by parents to support their children?
- How useful do you think it would be for children who are receiving Catch Up Numeracy support to play computer games designed to complement Catch Up Numeracy?

Participating children (pre-intervention):

Answered by the member of teaching staff:

- For how many months has the child received Catch Up Numeracy support?
- What is the child's Catch Up Numeracy level for each of the following components? Remembered facts. Estimation. Derived facts.

Answered by the child, while supported by the member of teaching staff:

- How good are you at maths?
- How happy are you when doing maths calculations on paper?
- How happy are you when doing maths calculations in your head?
- When you have difficulties in maths, how unhappy or worried does it make you?
- How well can you understand maths instructions given by your teacher?
- How do you feel in the maths classroom?
- If your teacher asks you to answer a maths question in class, how happy are you?
- If you have not understood something in your maths lessons, how worried does it make you?
- How much do you agree with the following statements?
 - You can't change how clever (intelligent) you are.
 - If you work hard, you can become cleverer (more intelligent).
 - You can learn new things, but you can't make yourself any cleverer (more intelligent).
 - Being clever is more important than working hard.
- When I'm doing maths, if I get things wrong...
 - ...I get upset and want to give up.
 - ...I don't worry because I know I can do better.
 - ...I know I can improve by getting help or working harder.
 - ...I know I'm not clever enough to do any better.
- How much do you enjoy playing computer games?
- How much do you enjoy playing computer games with friends, sisters or brothers?
- How much do you enjoy playing computer games with parents or carers?
- How effective do you think computer games can be helping you to learn?
- How much do you think computer games might help you with your maths?
- How much would you like to play computer games designed to help you with your maths?

Teaching staff (post-intervention):

- How confident are you that you know how best to support children who have difficulties with numeracy?
- How confident are you that you have sufficient resources to fully support children who have difficulties with numeracy?
- How did you use the Catch Up Numeracy games? (please tick all that apply)
 - In Catch Up Numeracy individual sessions
 - As individual play whilst another child had a Catch Up Numeracy session
 - As a talking point (between me and the children)
 - In group sessions
 - Allowed children to discuss their play
 - In other sessions
 - Whenever we could fit it in
 - When it was timetabled
 - Gave parents access
- How did you fit the games into your school/class?
- On average, how many times did the children play the games each week?
- On average, for how many minutes did the children play the games in a single session?
- In what ways were the games effective?
- In what ways were the games not effective?
- How might the games be made more effective?
- How familiar were the children with the computer game format?
- How useful was it that the mathematics was situated in a computer game format?
- How useful was it that the mathematics started with objects before using numbers?
- How useful or worthwhile was it for the children to play the games?
- How likely are you to use the games in the future with other children?
- How useful is it that...
 - ...the children can make several attempts to complete a task?
 - ...the games are not just about drawing on existing knowledge?
 - ...the games spiral up from very simple numbers to higher numbers?
 - ...the children's names appear on the leader board (does it matter that the other names on the leader board are not real)?
- How useful is the repetition (the same task first as objects, then as labelled objects, then as numbers)?
- How easy did the children find progressing from the objects to the labelled objects, and from the labelled objects to the numbers?
- How often did the children use the objects to work out the numbers?
- How often did the children use the numbers to work out the objects?
- How effectively did the repetition (objects, labelled objects, numbers) help the children to consolidate their mathematical understanding?
- How useful was watching the children play the games (did watching the children give you opportunities to learn about their mathematical understandings)?
- How useful were conversations between you and the children about their gameplay (did the conversations give you opportunities to learn about the children's mathematical understandings)?
- How useful for you were conversations between the children about the games (did the conversations give you an opportunity to learn about the children's mathematical understandings)?
- How useful for the children were conversations with the other children while they played (did the conversations help the children with their mathematical understandings)?
- How useful were conversations between you and the teacher or classroom assistant about the children's gameplay?
- How useful were conversations between you and the children's parents about the children's gameplay?

*Participating children (post-intervention):**Answered by the member of teaching staff:*

- What is the child's Catch Up Numeracy level for each of the following components? Remembered facts. Estimation. Derived facts.

Answered by the child, while supported by the member of teaching staff:

- How good are you at maths?
- How happy are you when doing maths calculations on paper?
- How happy are you when doing maths calculations in your head?
- When you have difficulties in maths, how unhappy or worried does it make you?
- How well can you understand maths instructions given by your teacher?
- How do you feel in the maths classroom?
- If your teacher asks you to answer a maths question in class, how happy are you?
- If you have not understood something in your maths lessons, how worried does it make you?
- When I'm doing maths, if I get things wrong...
 - ...I get upset and want to give up.
 - ...I don't worry because I know I can do better.
 - ...I know I can improve by getting help or working harder.
 - ...I know I'm not clever enough to do any better.
- How much did you enjoy playing the Catch Up Numeracy games?
- How much do you think playing the Catch Up Numeracy games helped you with your maths?
- How much would you like to continue playing the Catch Up Numeracy games?
- How easy did you find the maths tasks in the Catch Up Numeracy games?
- How easy did you find using the Catch Up Numeracy games (apart from the maths)?
- How much did you enjoy working out the right answers to the tasks?
- How much did you like being able to try as often as you liked?
- How important is it knowing immediately if you get an answer wrong?
- How much did you like using the games to practise your maths?
- How much did you like the way the game gave you each task three times (firstly as objects, then as objects and numbers, then as only numbers)?
- How much did you like the look of the games?
- How much did you like collecting coins?
- How much did you like being able to change your avatar?
- How much did you like the glowing character talking?
- How useful did you find what the glowing character said?
- How much did you like the leader board?
- How much did you like being able to choose which games to play?
- How much did you like talking about the games, as you played them, with (the adult)?
- (If appropriate) How much did you like talking about the games, as you played them, with other children who were playing the games?
- (If appropriate) How much did you like talking about the games, as you played them, with your parents/carers/brothers/sisters?

Report of the Examiners on the Thesis submitted for the Degree of Doctor of Philosophy by Mr Wayne Holmes, Wolfson College.

Level Up! A Design-based Investigation of a Prototype Digital Game for Children who are Low-attaining in Mathematics

Examiners: Prof. C. Lewin and Dr C. Davies

The candidate underwent a *viva voce* examination on September 4th, 2013, during which all aspects of the thesis were explored and discussed in considerable depth. The candidate showed a firm knowledge of all aspects of his work, and made a strong case for its contribution to knowledge. Given our positive view of the thesis itself, and the high quality of his performance in the viva, we are pleased to recommend the award of DPhil as the thesis stands, with the attendant recommendation that he carries out a small number of minor corrections.

This thesis presents a design-based research (DBR) approach to investigating the design and impact of a digital game to support children who are judged to be low-attaining in mathematics. It demonstrates a considerable amount of work over a considerable period of time, and a quite ambitious project on the part of the candidate. It displays maturity and expertise in terms of awareness of the field of educational tools broadly, and educational games in particular, and also of approaches to supporting maths interventions for learners experiencing difficulties in this area. It shows a good awareness of relevant theory, and is diligent in its efforts to ground the work in that theory. Methodologically, the thesis shows a high level of understanding of what is involved in DBR work, and a conscientious and rigorous approach to keeping the complex roles of researcher and innovator well-balanced throughout.

The research reported is extensive and quite properly is conducted through multiple (three) cycles. There are two over-arching research questions which ensure that the argument is presented coherently throughout the thesis. Each of the three cycles has its own specific research sub-questions offering more focus and ensuring that each phase informs the next, supporting development of the prototype game. These cycles involve quite distinctive approaches to managing the research, and allow for on-going development of the tool being researched. The second cycle is perhaps the most revealing and illuminating, but there are clearly important lessons to be learned from the final cycle, over which the researcher deliberately exercised less direct control, in order to observe how the tool functioned in the wild so to speak.

The presentation and structure are very clear (with very few typographical errors). The level of signposting throughout is excellent. The thesis has been a pleasure to read, being informative and engaging.

The thesis makes an important contribution to knowledge and understanding in relation to the integration of learning theory in games-based learning (GBL) design, combining constructivist and behaviourist approaches, how such a tool is used and adapted in the classroom, the importance of such a tool as a mediating artefact for mediating dialogue, and the experience and impact for students who are low-attaining in mathematics. The results could inform future GBL design and classroom practices, providing useful insights into the complexities of GBL adoption in learning and teaching.

Chapter 2 presents a rationale for the development of the game through consideration of six research premises. This is a solid review of the relevant literature, evidencing critical engagement and demonstrating a sound grasp of: numeracy interventions for low-attainers, GBL and appropriate learning theories. Chapter 3 presents the methods, focussing primarily on the DBR approach, with sections on sampling, data collection and ethics. The review of DBR is thorough and informative. The section on data collection is relatively concise but the candidate talked knowledgeably during the viva about his use of observation, interviews and questionnaires and the issues faced. Chapters 4-6 present the prototype design, implementation overview and findings for each of the cycles. These chapters reflect the thorough and substantial work undertaken. Chapter 7 presents an interesting discussion of the key outcomes, and includes the introduction of new literature in relation to dialogic approaches in the classroom. This seems relevant (although some might argue that literature should be presented altogether rather than brought in when deemed appropriate) and supports the story unfolding at this point. The conclusion is relatively short and focuses on summarising the contributions to knowledge and understanding.

In the end, it is evident that the outcomes of the explorations of the digital game with learners were mixed. Learners appear to have benefited from their experience of it, and the candidate argues strongly in favour of the learning benefits of the social interactions that occurred between teachers and learners around the game. But there were clearly frustrations in achieving the full understanding and co-operation of teachers in working with the tool, and the candidate reports these honestly and thoughtfully. This does not anyway suggest that the research itself was a failure, as design-based research can, if conducted and written up properly, reveal as much (in terms of theory) from failure as success. Whilst this tool clearly did not fail, it is clear that the complexities of conducting the research resulted in mixed outcomes to some extent. But it seems to us that the candidate explores and discusses these with openness and intelligence, and is able to learn from the fieldwork very well.

Overall, the candidate has demonstrated good knowledge of the field of GBL to support low-attaining children and has presented a scholarly piece of work, presenting a clear argument underpinned by the literature selected and the data. The abstract is satisfactory. As outlined above the thesis makes a significant and substantial contribution to the field.