

The Development of Executive Function in Childhood



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Table of Contents

<i>Acknowledgements</i>	iii
<i>Publications arising from this thesis</i>	iv
<i>Short Abstract</i>	v
<i>Long Abstract</i>	vi
Chapter 1: General introduction	1
Chapter 2: Shifting development in mid-childhood: The influence of conflict, tasks and time	20
Experiment 1	30
Experiment 2a	46
Experiment 2b	55
Chapter 3: Stimulus and response conflict in task-switching	66
Chapter 4: Self-ordered pointing as a test of working memory in typically developing children.....	99
Chapter 5: Go or no-go? Developmental improvements in the efficiency of response inhibition in mid-childhood	121
Chapter 6: Neural correlates of successful and partial inhibitions in children: An ERP study	141
Chapter 7: The bigger picture: Relationships and trajectories in executive function	169
Chapter 8: General discussion	189
<i>References</i>	208
<i>Appendices</i>	221

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Short Abstract

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The experiments in this thesis explored the development of executive function in 5- to 11-year-old children. Developmentally-appropriate versions of the task-switching paradigm, go/no-go task and self-ordered pointing test were used to measure shifting, inhibition and working memory respectively. These executive skills were examined independently using within-task experimental manipulations to explore both the executive and non-executive processes that influenced children's performance. This allowed the investigation of not only when, but also how, executive function develops.

Children's ability to shift their attention was highly influenced by the specific tasks switched between and the conflict created by the overlap between the tasks, as well as by previous task experience. Working memory for pictures was also influenced by previous experience and task difficulty, however the predicted relationship between the ability to remember nameable objects and language ability was not found. Inhibition on the go/no-go paradigm appeared to be driven by an improvement in the efficiency of response inhibition, which allowed older children to inhibit their response at an earlier stage during the movement.

Shifting, inhibition and working memory all showed developmental improvements during mid-childhood, demonstrating the protracted development of executive function. Shifting and working memory showed a similar pattern of development whereas inhibition reached a stable level of performance at an earlier age. There were no correlations between the three executive skills studied in this thesis, supporting the fractionation of executive function.

Long Abstract

The Development of Executive Function in Childhood

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This thesis explored the development of executive function, specifically shifting, inhibition and working memory, in 5- to 11-year-old children using new developmentally-appropriate measures. The thesis was organised around the principle that executive function can be fractionated, with two chapters devoted to shifting, one to working memory and two to inhibition. Within-task experimental manipulations were used to examine the executive and non-executive factors affecting task performance with an aim to investigate not only when, but also how executive processes develop. The final experimental chapter took a more general approach to examine the relationships between shifting, inhibition and working memory and compared their developmental trajectories.

Chapter 2 reported three experiments exploring the development of shifting. Experiment 1 used a version of the task-switching paradigm in which 5- to 11-year-olds had to shift between deciding either what colour, or what pattern, shirt a footballer was wearing. Shifting performance improved with age, and all children found it easier to switch to the pattern task than the colour task, demonstrating an asymmetry in switch costs. As the stimulus-response mappings for the two tasks overlapped, this made it possible to examine the influence of conflicting task-irrelevant information on shifting. All children were slower when the responses for the two tasks were incongruent, suggesting that they were influenced by the task-

irrelevant information. They were particularly slow on incongruent switch trials, presumably because the now irrelevant task had been relevant on the previous trial. Furthermore, the younger children showed a larger congruence effect than the older children and also experienced more interference on trials that did not involve a switch, including pure trials where the irrelevant task was not even performed during that block. This suggests that the ability to ignore the task-irrelevant information improved with age.

Experiments 2a and 2b, also reported in Chapter 2, explored the reliability of the task-switching paradigm. Experiment 2a investigated the parallel form reliability of the paradigm, comparing the Football version used in Experiment 1 to a new version which required making decisions about the colour or shape on the top of a cake. Unexpectedly, the switch costs for both versions were very small, which seemed to be because the children tested had previously taken part in Experiment 1. Experiment 2b confirmed this by directly comparing the switch costs from the two sessions of Experiment 1 to the switch costs from Experiment 2a. The switch costs were relatively stable over a few days but greatly reduced one year later, particularly for the younger children. The fact that switch costs are not reliable over long periods of time cautions the use of the task-switching paradigm in longitudinal studies investigating the development of shifting in children.

Chapter 3 extended the findings from Experiment 1, investigating the influence of overlapping stimulus-response mappings on shifting performance. In the typical task-switching paradigm the tasks overlap at both the level of the stimulus and the level of the response, however we systematically manipulated the degree of overlap at both the stimulus and response level, hypothesising that reducing the overlap would result in reduced conflict between the tasks. Interestingly, separating

the stimuli actually increased stimulus conflict rather than decreasing it as intended, particularly when colour was the irrelevant dimension. This made it difficult to draw general conclusions about stimulus and response conflict but revealed the complex interplay of factors that affect children's shifting performance: The results were highly dependent on the task being performed, and also the order in which the conditions were experienced. This experiment provided further evidence that the ability to ignore task-irrelevant information improves with age as the older children were less susceptible to interference from the colour task and also more receptive to manipulations aiming to reduce response conflict.

Chapter 4 moved away from shifting and investigated working memory development using the self-ordered pointing test (SOPT; Petrides & Milner, 1982). This is a measure of non-spatial executive working memory which requires the ability to generate and monitor a sequence of responses. One version of the task used pictures of familiar objects and the other hard-to-verbalise abstract designs. Performance improved between the ages of 5 and 11 years, although did not reach adult levels of performance. The children and adults appeared to be differentially affected by task repetitions. The children seemed to experience interference from previous games on the object version of the task, which was not apparent in the adults, suggesting that the ability to overcome this interference improves with age. In contrast, the adults' performance improved over repetitions with the abstract stimuli whereas the children's performance did not, suggesting that the adults may have been making a conscious effort to encode the abstract stimuli.

All participants found the object stimuli easier to remember than the abstract stimuli, suggesting that they were using verbal labels to help encode the stimuli where possible. It was predicted that there would be a relationship between verbal

ability and task performance in the children, such that those children with superior verbal skills would be more able to recruit language to help remember the stimuli. Furthermore, it was hypothesised that there would be a greater difference between the object and abstract conditions in the older children than the younger children, based on evidence that children above 8-years-old use verbal rehearsal strategies to aid memory performance (Halliday, Hitch, Lennon, & Pettipher, 1990; Hitch & Halliday, 1983). However, neither of these predictions were supported.

Chapters 5 and 6 used a modified version of the go/no-go paradigm to test the hypothesis that response inhibition becomes more efficient with age as children become able to inhibit a response at an earlier stage during the movement. The novel task used a home key and separate target key to record partial inhibitions: trials on which a response was initiated (home key released) but inhibited before the response was completed (target key pressed). The results from Chapter 5 showed that 9- to 11-year-olds made more successful inhibitions than 5- to 7-year-olds, inhibiting a response before any movement was made. In turn these younger children were more likely to make partial inhibitions, supporting the hypothesis that response inhibition becomes more efficient with age. The effect of inducing time pressure by narrowing the allowable response time was also examined, however this did not reduce the inhibitory demands of the task for either age group.

Chapter 6 reported an experiment in which event-related potentials (ERPs) were recorded while 7- and 9-year-olds performed the modified go/no-go paradigm. The N2 and no-go P3 components, linked to response inhibition, and the go P3 component, related to target detection, were examined for correct go trials (hits) and successful and partial inhibitions. The behavioural results were similar to those found in Chapter 5, with an increase in successful inhibitions and a decrease in

partial inhibitions in the 9-year-olds compared to the 7-year-olds, however the difference was not significant. Developmental changes were apparent in the latency of the N2 component, reflecting an increase in the efficiency of response inhibition with age. The N2 was also later on partial inhibitions than successful inhibitions, suggesting that inhibition occurred later on these trials. The amplitude of the N2 was larger in the 9-year-olds than the 7-year-olds on successful inhibitions and appeared to be related to better response inhibition in the 7-year-olds. However this relationship was not found in the 9-year-olds, making these results difficult to interpret. The amplitude of the no-go P3 component was not enhanced on no-go trials compared to go trials as is typically found in adults, and did not show developmental differences. The no-go P3 did differ between partial and successful inhibitions however. While the reason for this difference is not clear, it suggests that there may be differences in processing between these two types of trial, rather than just a difference in when the response is stopped. The go P3 was larger in the 9-year-olds than the 7-year-olds, particularly on partial inhibitions and possibly indicates that the partial inhibitions were processed differently by the two age groups.

Chapter 7 explored the developmental trajectories and relationships between different executive skills. The new measures were first validated against existing standardised tests to ensure they were tapping into the constructs they were designed to measure. Once this was established, performance on the shifting, inhibition and working memory measures was compared in the same group of children. These executive processes appeared to be independent from each other, supporting the fractionation of executive function. There was also no evidence of a strong link between executive function and general intelligence. Shifting and working memory

showed a strikingly similar development with a substantial increase in performance between the ages of 7 and 10 years. Interestingly, development either side of this spurt was non-linear, with a slight decrement in performance between the ages of 6-7 and again at 10-11 years. This finding needs replicating to confirm the extent to which it is specific to this sample. In contrast to shifting and working memory, inhibition showed less development during mid-childhood, reaching a stable level of performance at an earlier age. Thus, it appears that at least some executive functions mature at different rates.

In summary, this thesis combined the detail of experimental adult executive function research with a developmental approach emphasising child-friendly tasks and procedures. The findings show that executive skills are complex and influenced by a variety of factors, both executive and non-executive. This extends our understanding of the protracted development of executive function, not only the specific skills of shifting, inhibition and working memory, but also how these processes fit together under the umbrella of executive function.

Chapter 1: General introduction

This chapter provides a general overview of the literature addressing the development of executive function in children. One of the main issues discussed is the fractionation of executive function into separable components. The thesis is structured around this idea, with separate chapters devoted to the executive processes of shifting, working memory and inhibition. Literature reviews relating to these specific processes are included in the separate chapters, while this introduction focuses on more general issues such as the measurement of executive function in children and the developmental trajectories of executive skills. Theories of executive development are also discussed. The chapter ends with a brief overview of the aims of this thesis.

Executive function (EF) is the name given to the group of processes that allow us to respond flexibly to our environment and engage in deliberate, goal-directed, thought and action. Executive function forms the basis of abilities such as problem solving and flexible thinking and is most likely to be used in the absence of external guidance or when a situation is novel. The study of executive function originated from observations of adults with damage to the frontal lobe. These patients typically exhibit a lack of control and often show impulsive, inflexible, or erratic behaviour (Damasio, 1993; Fuster, 1997; Mesulam, 2002; Stuss & Benson, 1986). The study of these patients has led to a very strong link in research between executive processes and frontal lobe function. However, it is also possible to characterise executive function as a purely psychological concept, without any reference to anatomical underpinnings (V. Anderson, 1998; Baddeley, 1996; Stuss, 1992).

The study of executive function in children was long overlooked as it was thought that the frontal lobes were non-functional prior to adolescence (Golden, 1981). We now know that this is not the case. The frontal lobes are active early on in infancy (Bell & Fox, 1992; Chugani & Phelps, 1986) yet continue to develop well into the second decade of life (Casey, Giedd, & Thomas, 2000; Durston & Casey, 2006; Segalowitz & Davies, 2004). This physiological maturation is accompanied by a protracted development in the ability to control attention and behaviour. The focus of this thesis will be on these behavioural and cognitive changes in executive function, rather than the physiological changes that accompany them.

Executive skills are among the last cognitive abilities to mature and show a protracted development throughout childhood and adolescence. It is important to understand the development of executive function as it plays a vital role in the change from a child, who often ‘acts without thinking’, to a mature, responsible adult able to plan and control their actions. Furthermore, executive dysfunction has been implicated in a range of developmental disorders such as autism (Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004; Happé, Booth, Charlton, & Hughes, 2006; Hill, 2004; Ozonoff, South, & Provencal, 2005; Pennington & Ozonoff, 1996), attention deficit hyperactivity disorder (Barkley, 1997; Geurts et al., 2004; Happé et al., 2006; Pennington & Ozonoff, 1996; Scheres et al., 2004; Shue & Douglas, 1992) and phenylketonuria (Diamond, Prevor, Callender, & Druin, 1997; Smith, Klim, & Hanley, 2000). To obtain an accurate picture of the executive deficits present in these disorders it is essential that we fully understand the typical development of executive function, against which to compare these special populations.

Fractionating executive function

The term executive function is somewhat misleading as it is now generally acknowledged that it is simply an umbrella term for a number of separable processes including planning, working memory, inhibition and cognitive flexibility (shifting). Damage to the frontal lobes can produce a wide-ranging variety of deficits, suggesting that EF can be fractionated (Fuster, 1997; Mesulam, 2002; Stuss et al., 2002; Stuss & Benson, 1986). Neuroimaging studies support this, showing that different areas of the frontal lobe support different executive functions (Aron, Robbins, & Poldrack, 2004; Crone, Wendelken, Donohue, & Bunge, 2006; Fassbender et al., 2004). Behaviourally, the use of factor analysis and similar methods has shown that executive processes can be separated. Miyake, Friedman, Emerson, Witzki and Howerter (2000) used latent variable analysis with healthy young adults to determine the extent to which ‘updating’- actively manipulating relevant information in working memory, ‘inhibition’- the deliberate, controlled suppression of prepotent responses, and ‘shifting’- shifting back and forth between multiple tasks, operations or mental sets, are unitary or separable functions. Three measures of each executive function were used which had the same target processing requirement but differed in their non-executive demands. A latent analysis was used to avoid the task impurity problem commonly found in executive tasks. This ‘extracted’ what was common across the tasks and analysed the relationships among different executive functions in terms of these purer factors, rather than more superficial task demands. The model which best fitted the data showed that updating, inhibition and shifting are clearly distinguishable, but also moderately correlated constructs. This indicates both the unity and diversity of executive functions.

Measuring executive function

A range of psychological tests are sensitive to frontal lobe damage and as such have come to be seen as standard measures of executive function. These are largely validated only on the basis that frontal lobe patients perform badly on them and while attempts have been made to propose what these complex tests actually tap into, these assumptions are rarely tested. A brief description of some of these tests and the proposed executive skills they involve are presented in Table 1.1.

Table 1.1: Description of standard measures of executive function

Test	Description	Executive Processes
Wisconsin Card Sorting Test	Cards are sorted by colour, shape or number on the basis of feedback from the experimenter. After ten consecutive correct trials the sorting rule is changed without warning.	set-shifting, flexibility, rule induction, inhibition, problem-solving, categorisation
Tower of Hanoi/ London (TOH/TOL)	Three discs of varying sizes (TOH) or three balls (TOL) on three pegs have to be rearranged into a configuration specified by the experimenter in a prescribed number of moves.	planning, problem-solving, inhibition
Verbal fluency	As many words as possible either belonging to a particular category (e.g. animals) or starting with a specific letter have to be generated in a fixed amount of time.	flexibility, working memory
Colour-word Stroop	The colour of the ink that a colour word is written in has to be named; e.g. for blue say 'red'.	inhibition, conflict resolution, mental flexibility

Miyake et al. (2000) investigated the role of updating, inhibition and shifting in some of these standard executive tasks; the WCST, Tower of Hanoi (ToH), random number generation and an operation span task (a prevalent measure of verbal working memory capacity). They found that updating, inhibition and shifting

contributed differentially to performance on these commonly used executive tasks. Perseverative errors on the WCST seemed largely related to shifting ability, while inhibition was the most important factor in the ToH. Inhibition also contributed to random number generation whereas updating was implicated in both random number generation and the operation span task. This supports the notion that EF is not homogenous. Furthermore, it goes some way towards determining what abilities complex executive tasks are actually measuring.

Early studies of executive function in children used many of the standard tasks designed for adults and looked for behaviours similar to those found in adults with frontal lobe damage. Chelune and Baer (1986) found a developmental improvement in 6- to 12-year-olds on the Wisconsin Card Sorting Test (Grant & Berg, 1948), a widely used measure of executive function in adults. In this test participants are given a deck of cards displaying 2-4 coloured shapes. They have to sort the cards first according to one dimension and then switch to sort by a different dimension. The participant is not told when the rule changes but has to infer this using feedback given by the experimenter. Chelune and Baer found that 6-year-olds showed a tendency to perseverate and continue to sort by the initial rule despite receiving negative feedback. This is a characteristic feature of frontal lobe damage (Milner, 1963). Kirk and Kelly (1986) reported that on executive tasks such as the WCST younger children made the kinds of perseverative errors seen in adults with dorsolateral prefrontal damage, but that errors diminished gradually between the ages of 6 and 11 years. A reduction in perseverative errors in this age group was also shown by Passler, Isaac & Hynd (1985), particularly between 6- and 8-years-old. Improvements in inhibition also seem to take place between these ages. Becker, Isaac & Hynd (1987) showed a developmental improvement in motor inhibition and

temporal ordering in 6- to 12-year-olds, with a notable improvement in performance between the ages of 6 and 8 years.

As these studies show, standard adult measures of EF are sensitive to developmental change. However, the application of the neuropsychology model to development, using tasks designed for adults and looking for deficits in children similar to those found in adults with frontal lobe damage, is problematic for a number of reasons. Firstly, even if poor executive performance in children is linked to immaturity of the frontal lobe, this is not the same as the kind of damage sustained in adults, and therefore it is not necessarily the case that children will show similar behaviours to adult patients. The result of damage sustained to a fully-developed adult brain where brain-behaviour relationships are well established is very different to the behaviour subserved by the developing, changing brain of a child and it is crucial to take the process of development itself into account when studying this behaviour (Bishop, 1997; Karmiloff-Smith, 1998; Scerif, 2006).

Secondly, the construct validity of standard executive tests is poor. Tests such as the WCST are largely validated on the basis that they are sensitive to frontal lobe damage, and therefore the precise nature of the executive processes implicated in the tasks are not well specified (Miyake et al., 2000). One of the characteristics of executive function is that it co-ordinates lower-level processes. Therefore, in addition to control processes, executive tasks also involve a number of other processes such as language, visuo-spatial skills and sustained attention. If children have difficulty with one of these lower-level process then they will do badly on the test, whether they can cope with its executive demands or not. Furthermore, executive tests used with adults need to be complex in order to tap into high-order executive processes. Potentially therefore, children could be failing simply because

they find these tests too difficult. Indeed, Becker et al. (1987) reported that 6-year-olds were unable to do a temporal ordering task and often lapsed into stereotypic response patterns. This gave the appearance of perseverative responding, characteristic of adult frontal lobe damage, simply because the task was too difficult. A related point is that children may find these tests unappealing and uninteresting. As a result they may not be motivated to perform at their best, again underestimating their executive abilities.

Several researchers have highlighted the importance of using well-designed, developmentally appropriate tests of executive function so that executive skills are measured accurately in children (P. Anderson, 2002; V. Anderson, 1998; Hughes & Graham, 2002; Welsh & Pennington, 1988). This has been successful for preschool populations. The Dimensional Change Card Sort test (DCCS; Frye, Zelazo, & Palfai, 1995; Zelazo, Frye, & Rapus, 1996), a simplified card sorting test, has replaced the WCST, and more appealing versions of the Stroop task have been designed to replace the colour-word version (e.g. Animal stroop: Wright, Waterman, Prescott, & Murdoch-Eaton, 2003; Day/night stroop: Gerstadt, Hong, & Diamond, 1994). A variety of inhibition measures have been developed for preschoolers based on simple games, e.g. Simon says, taking turns to build a tower or by requiring children to wait for a treat (Kochanska, Murray, Jacques, Koenig, & Vandegest, 1996). In addition, a new test battery has been developed which taps a range of executive functions using a simple storybook format (Espy, 1997). Performance on these tasks improves rapidly during the pre-school years, demonstrating executive development. However, on most of these measures, ceiling performance is reached around 4- to 5-years and so these tasks are not suitable for use with older children. This has led to the continued use of adult paradigms with school-age children, even

though they may not be suitable. One of the aims of this thesis was to develop developmentally appropriate tasks for use with school-age children. There is a need for tasks to be developed that are sensitive to developmental changes in executive function without including unnecessary processing demands that might compromise performance.

The development of executive function

While there is evidence for separable executive processes in adults, this does not necessarily mean these processes are distinct during development. A number of studies have used factor analysis to investigate the fractionation of EF in children (Brocki & Bohlin, 2004; Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003; Levin et al., 1991; Pennington, 1998; Welsh, Pennington, & Groisser, 1991). Most studies using factor analysis find three factors, demonstrating that EF is fractionated in children. These three factors vary slightly across studies depending on the tasks used, however dissociable components relating to working memory (Brocki & Bohlin, 2004; Lehto et al., 2003; Pennington, 1998), inhibition (Brocki & Bohlin, 2004; Lehto et al., 2003; Levin et al., 1991; Pennington, 1998), shifting (V. Anderson, Levin, & Jacobs, 2002; Pennington, 1998), planning (Levin et al., 1991; Welsh et al., 1991), concept formation (Levin et al., 1991) and in some cases speed of responding/arousal (Brocki & Bohlin, 2004; Welsh et al., 1991) have been identified.

Particularly in early studies (Levin et al., 1991; Welsh et al., 1991), the measures used in these factor analyses were often complex and hindered by task impurity, e.g. WCST. As such, factors may have been created because tasks shared common non-executive demands rather than the same executive process. Furthermore, in many cases, the tasks were not chosen to measure a specific aspect

of EF and so interpretation of the factors was discretionary, a particular problem given that exploratory factor analysis is data-led rather than theory-led.

Huizinga, Dolan and van der Molen (2006) avoided these problems by using a latent variable analysis of tasks chosen to index updating, inhibition and shifting processes, following Miyake et al. (2000). Using a sample of 7-, 11-, 15- and 21-year-olds they found similar factors relating to updating and shifting, however in contrast to Miyake et al. the correlation between their inhibition measures was low. This may be because of a difference in the test materials used. Huizinga et al. used a stop-signal task and Stroop task to measure inhibition, as Miyake et al. did, however they changed the Stroop task from a colour-word version to a more developmentally appropriate colour-orientation task using 'smileys'. Furthermore, they replaced the anti-saccade task used by Miyake et al. with an Eriksen flanker task. Huizinga et al. suggested the tasks they used did not correlate because of differences in task format. Another possibility for why the inhibitory tasks did not correlate is that they tapped into different types of inhibition. It has been suggested that inhibition can be split down into more specific processes such as motor or response inhibition and interference suppression (Friedman & Miyake, 2004; Kipp, 2005; Nigg, 2000). Therefore one could argue that while the stop-signal task requires response inhibition, the flanker task and Stroop are dependent on interference suppression processes. The Stroop and stop-signal task correlated in Miyake et al.'s study. However, this could indicate that different types of inhibition are more distinct in children than in adults. In addition, Huizinga et al. found that the switching and updating factors did not correlate in the children, while they did in the 21-year-olds. Again, this suggests that these executive processes may be more separable in

children than in adults. Overall, the results from Huizinga et al. support the idea that executive functions are separable processes throughout development.

Huizinga et al. also administered the WCST and Tower of London (ToL) tasks. In contrast to Miyake et al., they found that updating rather than shifting predicted perseverative errors on the WCST. This could be due to differences in task instructions on the WCST as suggested by Huizinga et al., but may also be evidence that children approach the same tasks in a very different manner to adults, such that the same task taps different processes in the different age groups. ToL performance in adults was related to the Stroop task, suggesting the involvement of inhibitory processes (Miyake et al., 2000). However, none of the factors predicted ToL performance in children. Again, this suggests that children and adults may be approaching the same task in different ways.

Further evidence that EF is fractionated in development comes from studies comparing the developmental trajectories of inhibition, working memory, shifting and planning (Brocki & Bohlin, 2004; Huizinga et al., 2006; Levin et al., 1991; Luciana, 2003; Luciana & Nelson, 2002; Welsh et al., 1991). Some studies suggest that response inhibition, as indexed by the go/no-go task, develops relatively early around the ages of 7 to 9 years (Becker et al., 1987; Brocki & Bohlin, 2004; Levin et al., 1991). However, Huizinga et al. (2006) found that performance on the stop-signal task, which measures the speed of response inhibition, improved until age 15. This implies that even once children can accurately inhibit a response, the efficiency of this inhibition continues to improve. Huizinga et al. also found that adult levels on the flanker task weren't reached until the age of 15 years, suggesting that other forms of inhibition may develop later.

The age at which shifting reaches adult levels seems to depend on the task that is used. While perseverative errors on the WCST were shown to reach adult levels around 10 years (Levin et al., 1991; Welsh et al., 1991) and mature performance on the intradimensional/extradimensional shift task from the CANTAB battery was reached at 7 years (Luciana & Nelson, 2002), performance on task-switching paradigms was found to mature at 15 (Huizinga et al., 2006), and by 13 years, children had still not reached adult levels on a task that required shifting response mappings (Davidson, Amso, Anderson, & Diamond, 2006). This discrepancy in results may be due to a difference in how performance is measured. Children may be able to accurately switch to a new task relatively early, yet continue to get faster at shifting throughout childhood and into adolescence.

Some aspects of working memory (Brocki & Bohlin, 2004; Huizinga et al., 2006; Luciana, 2003; Luciana & Nelson, 2002), as well as higher-order executive functions such as planning (Huizinga et al., 2006; Levin et al., 1991; Luciana, 2003; Luciana & Nelson, 2002; Welsh et al., 1991), also seem to develop later and continue to improve in adolescence. Davidson, Amso, Anderson, & Diamond (2006) investigated the developmental trajectories of different executive skills by presenting children, adolescents and adults with a range of tasks that varied in their working memory, inhibition and shifting demands. The youngest children (4 to 6 years) were more affected by the inhibition manipulations. Once these had matured however, the older children and adolescents were more affected by working memory manipulations. This suggests that the two processes show different patterns of development, with inhibition maturing earlier than working memory.

These studies confirm that EF has a protracted development and show that separate executive processes mature at different ages. Despite the inconsistencies, it

does seem as if inhibitory processes develop first, followed by shifting, working memory and planning. However, although these processes are often measured in the same children, the trajectories for different skills are not directly compared. This is important in order to confirm that executive processes mature at different ages. Nevertheless, these studies give us a relatively good understanding of when executive functions develop. Yet it is important that we also address what is driving the improvement with age to understand *how* these executive processes develop.

Theories of executive development

The relationship between different aspects of executive function is clearly complex. Factor analyses have shown that they can be separated and they appear to develop at different rates, yet they are also highly related. In some ways, it may be easier to separate processes or propose causal relationships conceptually, yet it is difficult to test these distinctions empirically, particularly given the complex nature of many executive tasks. This may be one reason why this area is not strongly driven by theoretical motivations. However, there are a number of theories which have been proposed to explain executive development. These have largely focussed on the roles of inhibition and working memory and whether an improvement in one or both of these processes is sufficient to explain developmental change on all executive tasks.

One of the most influential theories of the role of inhibition in development was proposed by Barkley (1997). Although originally a theory of ADHD, it can also been applied to typical development. Barkley defined inhibition as the ability to inhibit a prepotent response, stop an ongoing response, and avoid distraction from competing events and responses. He suggested that executive abilities such as working memory, self-regulation of affect, motivation and arousal, and the use of

rule-governed behaviour and problem solving by the internalisation of speech, are partially dependent on inhibition. This is because inhibition provides a delay in the decision to respond, which gives these other executive functions the opportunity to control the eventual response that is made. In developmental terms, as the ability to inhibit a response improves, it creates a chance for other executive functions to develop.

Inhibition is treated as a single construct by Barkley (1997). However, Dempster (1992; 1993) proposed that inhibition has a variety of characteristics that vary on temporal (e.g. proactive, coactive, and retroactive), formal (motoric, perceptual, and linguistic), and spatial (internal, external) dimensions. He suggested that resistance to interference (the capacity for inhibition) is a major factor in cognitive development, but that the varieties of inhibition have different developmental trajectories, with motoric interference being the first to mature, and linguistic interference the last. Dempster argued that developmental changes in resistance to interference explain age-related improvement on many different tasks, including the WCST, Stroop, selective attention measures and many Piagetian tasks, including the A-not-B task.

An alternative view is that inhibition or interference control alone is not sufficient to solve these tasks. Roberts and Pennington (1996) argued that children also need to determine the correct strategies and responses, using general knowledge and working memory, to ensure successful task performance. Many executive tasks can be considered to involve the concurrent demands of holding information in working memory while also inhibiting a prepotent response. Diamond (Davidson et al., 2006; Diamond, 2002; Diamond & Goldman-Rakic, 1989) argued that it is the combination of these requirements that makes executive tasks difficult. Although

these abilities emerge and can be combined in infancy (Diamond, 1985; Diamond & Doar, 1989; Diamond & Goldman-Rakic, 1989) as children get older they become able to do this in increasingly more complex situations (Davidson et al., 2006; Diamond, 2002; Gerstadt et al., 1994).

The interaction between inhibition and working memory was considered in a theory by Bjorklund and Harnishfeger (1990) who proposed that inefficient inhibitory processes results in less mental space for the processing and storage of task-relevant information (working memory). Therefore, as inhibition becomes more efficient during development, less irrelevant information enters working memory and thus the efficiency and functional processing capacity of working memory increases. This theory suggests that development of inhibition drives improvements in working memory. In contrast, Roberts and Pennington (1996) proposed the opposite view—that it is working memory that influences inhibition. They suggested that when working memory processes are successfully implemented, then alternative actions are automatically inhibited. Following this logic, if working memory demands are increased then there should be a decrease in inhibition and therefore an increase in the probability of committing incorrect prepotent responses. Supporting this theory, Roberts, Hager, and Heron (1994) found that increasing working memory demands on an anti-saccade task by adding a concurrent task did in fact result in more errors. Importantly, this did not interfere with performance on a prosaccade task in which inhibition was not required. This theory is also consistent with connectionist models of working memory which suggest that when a prepotent response is stronger or conflict is greater, stronger working memory traces are required to counteract it (Miller & Cohen, 2001; Morton & Munakata, 2002; Munakata, 2001).

Both Bjorklund and Harnishfeger (1990) and Roberts and Pennington (1996) suggest that working memory and inhibition are highly interactive processes. Beveridge, Jarrold and Pettit (2002) adopted a novel approach to test the interactive relationship between inhibition and working memory by manipulating inhibitory and memory demands within the same task. While increasing working memory and inhibition demands independently resulted in a decrease in performance, these manipulations did not interact. This suggests that working memory and inhibition are independent processes and do not rely on a common limited processing capacity. Despite this, there is clearly a strong relationship between the two processes, as shown by the fact that children who do well on measures of working memory also perform well on tests of inhibition (Archibald & Kerns, 1999; Davidson et al., 2006).

Compared to the focus on inhibition and working memory in the developmental literature, until recently, shifting has been neglected. It is interesting that even though shifting has been found to be an independent component in factor analyses (V. Anderson et al., 2002; Huizinga et al., 2006; Pennington, 1998), it is often explained in terms of inhibition and working memory demands. For example, developmental improvements on the DCCS, a popular shifting measure used with preschoolers, have been explained in terms of an improvement in aspects of inhibition (Kirkham, Cruess, & Diamond, 2003; Muller, Dick, Gela, Overton, & Zelazo, 2006), working memory (Morton & Munakata, 2002; Munakata & Yerys, 2001) and rule use (Zelazo & Frye, 1998; Zelazo et al., 1996; Zelazo, Muller, Frye, & Marcovitch, 2003), but not in terms of a specific improvement in switching task set. By using tasks which required varying levels of inhibition and working memory, but also introduced shifting demands, Davidson et al. (2006) examined the effects of combining these three executive functions. They showed that 4- to 6-year-olds could

hold information in mind, inhibit a prepotent response and combine these as long as both demands remain constant. However, if the task contingencies changed, so that they had to switch between rules or between inhibiting a response, and not inhibiting that response, then the task became much more difficult, and even 13-year-olds struggled. This suggests that shifting simply increases the demands placed on inhibition and working memory. These developmental studies contrast with the adult task-switching literature, where it has been proposed that a separate ability in exogenously reconfiguring a task-set is required (Meiran, 1996; Rogers & Monsell, 1995). Therefore it seems that the construct of shifting as an independent executive skill is not well-specified in children.

Aims of the thesis

It is important to understand the development of executive function as it plays a vital role in becoming a mature, responsible individual who has control over their actions. Executive function in preschoolers is relatively well understood: There are a range of suitable executive tests available for this age group and these have been manipulated in interesting ways to elucidate the early development of executive skills (Brooks, Hanauer, Padowska, & Rosman, 2003; Carroll, Apperly, & Riggs, 2007; Diamond, Carlson, & Beck, 2005; Espy & Bull, 2005; Kirkham et al., 2003; Kloo & Perner, 2005; Perner & Lang, 2002; Simpson & Riggs, 2005, 2006; Zelazo et al., 2003). Although we know that executive function continues to develop into adolescence, less attention has been devoted to executive skills in older children. When school-age children are studied they are often given large batteries of executive tests, many of which have been designed for adults (Archibald & Kerns, 1999; Becker et al., 1987; Brocki & Bohlin, 2004; Huizinga et al., 2006; Lehto et al., 2003; Levin et al., 1991; Luciana & Nelson, 1998; Luciana & Nelson, 2002;

Pennington, 1998; Welsh et al., 1991). While these can tell us about the general developmental paths of executive skills, they cannot provide detailed information about what factors affect performance on executive tasks and what might be driving developmental improvement.

This thesis investigates the development of executive function in a large sample of school-aged children between the ages of 5 and 11 years. A timeline of the data collected for this thesis is presented in Appendix VII. The executive processes of working memory, inhibition and shifting are examined as these appear to be three of the fundamental executive functions, and have received the most attention in the developmental literature. These processes are tested independently using within-task experimental manipulations to investigate the factors driving developmental improvement. Given the problems in using adult tasks with a developmental population, an overall aim of this thesis was to use tasks that were appropriate and appealing for children so that they would be motivated to perform at their best, thus giving us an accurate picture of their executive skills.

While the current literature presents a picture of how children of different ages are likely to perform on various executive tasks, the exact way in which these executive processes and how these processes might develop, is far from understood. In this thesis we aim not only to track the improvement of these executive processes with age, but also to investigate what is driving developmental change. In addition to executive factors, the issues of task impurity and the role of non-executive or task-specific factors in performance are addressed.

Chapters 2 and 3 focus on the development of shifting. This has been identified as an independent executive skill in factor analyses and the adult shifting literature. In contrast, shifting in preschoolers is often explained in terms of

inhibition and working memory demands. A task-switching paradigm, originally developed to measure shifting in adults, was used to try and reconcile the differences between the adult and developmental literature. We were interested not only in how shifting develops but also how the influence of overlapping stimulus-response mappings, one of the key features of the task-switching paradigm, affects children's shifting performance. As executive tasks are notoriously unreliable, the reliability of the task-switching paradigm across superficial changes in stimuli and also over time was examined in two follow-up experiments. The first experiment revealed that the interference from conflicting stimulus-response mappings showed interesting changes in performance across development. These were investigated further in a follow-up experiment (Chapter 3) which manipulated the overlap of the stimulus-response mappings.

Chapter 4 reports findings from a working memory task, the self-ordered pointing task. This has previously been used with children but the factors that improve during development have not been examined. To look in more detail at how performance improved with age we investigated the influence of task manipulations that have been overlooked in previous developmental studies. The extent to which language was used to help task performance was also explored.

Chapters 5 and 6 address the development of inhibition using a go/no-go task. This task has been widely used in the developmental literature, however we modified the task to include a more sensitive measure of performance which recorded the stage at which a response was inhibited. This allowed us to investigate how, rather than just when, inhibition improves. In Chapter 6 event-related potentials (ERPs) were used to examine the neural correlates of this modified go/no-go task.

After investigating shifting, inhibition and working memory independently, the final aim in Chapter 7 was to examine the relationships between these processes in school-age children. We were interested in the extent to which these processes can be separated, but also the links between them, particularly the extent to which inhibition and working memory predicted shifting ability. The developmental trajectories of these three executive processes were also compared to see if they develop at different rates and if response inhibition does mature earlier than switching and working memory, as has been found in the previous literature.

To summarise, this thesis aimed to build on existing knowledge about *when* the skills of working memory, inhibition and shifting develop and begin to investigate *how* these processes improve. The executive skills were tested independently using developmentally appropriate tasks that would get the best performance possible from the children. Within-task experimental manipulations were used to gain a better understanding of both the executive and non-executive factors affecting performance on executive tasks. Finally, the relationships between working memory, inhibition and shifting were investigated and their developmental trajectories in mid-childhood were compared.

Chapter 2: Shifting development in mid-childhood: The influence of conflict, tasks and time

This chapter reports three experiments describing 5- to 11-year-olds' performance on a developmentally-appropriate version of the task-switching paradigm. Experiment 1 charted the development of the ability to (i) switch attention between different tasks and (ii) to inhibit irrelevant stimulus-response mappings. Performance was partly dependent on the tasks used, as the children found it easier to switch to a decision about pattern than a decision about colour. Practice also affected children's performance, reducing switch costs overall while equalling out the switch costs for the two tasks (colour vs. pattern). Practice had an interesting effect on interference from the irrelevant response mappings, increasing rather than decreasing interference on some trials.

Experiment 2a attempted to replicate the findings from Experiment 1 and to assess its reliability, using the same version of the paradigm and a parallel version with different stimuli. Although the same version yielded a similar pattern of results, switch costs were greatly reduced compared to Experiment 1. In the parallel version the pattern of results was different, yet as for the same version, the switch costs were small and unreliable. One explanation for this is that the same children participated in both Experiments 1 and 2a, albeit a year apart. Therefore, the low switch costs could be a result of long-term carryover effects from previous task exposure. To test this hypothesis, Experiment 2b compared the switch costs from Experiments 1 and 2a. Switch costs were much smaller one year after the initial testing session and the results suggest that, in addition to maturational factors, prior testing experience affected children's performance on the subsequent re-test. These findings caution use of the task-switching paradigm in longitudinal studies of shifting development.

The ability to shift attentional set is a necessary skill to be able to respond flexibly to changes in the environment. Selecting the appropriate response for a given situation requires the correct configuration of mental resources, or ‘task set’ to be in place before the task can be performed. It has been argued that intentional executive control is needed in order to select the appropriate task set (Meiran, 1996; Rogers & Monsell, 1995). This is particularly important when the same stimulus requires different responses depending on the context or situation, such as adding or subtracting the same two numbers depending on what is required. Typical tests of set shifting simplify this concept by using stimuli which vary along two or more dimensions, such as colour and shape. The stimuli remain the same across tasks; however the participant is required to switch their attention between these dimensions depending on the task being performed.

The WCST as a measure of shifting in children

One of the most widely used tests of set shifting is the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948). In this test, there are a set of four target cards each showing a stimulus that varies along three dimensions; shape, colour and number. The participant is given a stack of test cards and has to sort them to match the target cards on the required dimension, indicated by the examiner’s feedback. After ten correct sorts the rule changes and the cards have to be sorted according to a different dimension.

The WCST has been used as a measure of set-shifting and executive function in typically developing children (Arffa, Lovell, Podell, & Goldberg, 1998; Bull & Scerif, 2001; Chelune & Baer, 1986; Levin et al., 1991; Somsen, in press; Welsh, Pennington, & Groisser, 1991) and performance is thought to reach adult levels around 10 years of age (Chelune & Baer, 1986; Welsh et al., 1991). However, this

test may underestimate set-shifting ability in children. In addition to shifting attentional set, the WCST requires the correct rule to be determined through trial and error and held in working memory, while any currently irrelevant rules are inhibited. Children may be failing the task because of immature skills in these other areas, rather than a specific problem with shifting set. The length and complexity of the test may also mean that children are unmotivated and do badly because of a lapse in attention.

Attempts have been made to simplify the WCST to make it more appropriate for children. Cinan (2006) used 12 target cards, each displaying an example of only one of the dimensions (colour, shape or number) instead of the usual four target cards each varying on all three dimensions, thus separating the tasks at a perceptual level. As the standard WCST was not administered it cannot be determined if this improved children's level of performance. However, even with these modifications the children still struggled, especially the youngest group (mean age = 6.5 years) who made significantly more perseverative errors than 8.5 and 11.5 year-olds. Cinan (2006) also showed that children have difficulty with the number dimension as the children did better when number was represented using the number of digits (e.g. four 4s) compared to a single digit. Zelazo, Craik and Booth (2004) went one step further and removed the number dimension completely in a computerised version of the task that cued the participant as to which task to perform. Even with only two dimensions, 8- to 9-year-old children struggled to switch attentional set, making more perseverative errors than young adults. Moreover, the authors noted that difficulty on the task was not restricted to switch trials, suggesting that there were other aspects of the task that the children found difficult in addition to set-shifting.

As mentioned earlier, one problem with the WCST is that it may not appeal to children and therefore they may not perform at their best. Schouten, Oostrom, Peters, Verloop and Jennekens-Schinkel (2000) replaced the stimuli used in the standard WCST paradigm, with more developmentally-appropriate animal stimuli (type of animal, colour, and facial expression). Performance in 4- to 10-year-olds was markedly improved in the adapted version, particularly in 4- to 6-year-olds, suggesting that the complexity of the WCST does lead it to underestimate children's ability. Furthermore, Schouten et al. found that perseverations were not the predominant error type. From this they argued that the children were not having a problem in disengaging their attention from the previous set but that the error patterns demonstrated a 'trial and error' approach to shifting set.

As well as shifting attention to a different dimension of the test card, the WCST also involves switching stimulus-response mappings. Crone, Ridderinkhoff, Worm, Somsen and van der Molen (2004) simplified the WCST by using a task that required switching stimulus-response mapping rather than an extra-dimensional shift to a different stimulus dimension. This provided a purer index of those errors caused by a specific difficulty in switching response mappings. The pattern of findings was largely comparable to age-related changes in WCST performance, with adult levels of performance reached by 11-12 years of age on most scoring measures. However, a condition in which the rule change was indicated attenuated perseverative behaviour in the 8- to 9-year-olds. This suggests that perseverative errors in the WCST may reflect children's failure to monitor performance feedback when switches are not explicitly cued, rather than a failure to switch attention away from the previous task. Crone et al. showed that as well as having difficulty switching task, children also had difficulty in maintaining the correct task rule once a switch

had been made. The ability to keep the relevant task-rule online appeared to follow a separate developmental trajectory to task-switching, and also seemed to mature later. This was supported by Huizinga and van der Molen (2007) who showed that on a standard version of the WCST, set-shifting reached adult levels at 11 years whereas set-maintenance did not mature until 15 years. This demonstrates that the WCST is a complex task and that children may fail for reasons other than a problem shifting attentional set. In sum, these findings question the use of the standard WCST as a measure of set-shifting behaviour in children.

The DCCS as a measure of shifting in children

A more successful variation of the WCST for children, the Dimensional Change Card Sort test (DCCS) was pioneered by Zelazo and colleagues (Frye, Zelazo, & Palfai, 1995; Zelazo, Frye, & Rapus, 1996) and is now a widely used measure of set-shifting ability in preschool children. This test has only two target cards which vary along the dimensions of colour and shape – for example a red boat and a blue rabbit. The test cards match the targets on one of these dimensions, e.g. blue boats and red rabbits. The test cards first have to be sorted according to either colour or shape, and then by the other category during the post-switch phase. It has consistently been shown that 3-year-olds have difficulty in the post-switch phase and struggle to shift set and sort by a new dimension, while 4-year-olds succeed (Kirkham, Cruess, & Diamond, 2003; Perner & Lang, 2002; Zelazo et al., 1996). A number of theories have been put forward to explain this phenomenon, such as the Cognitive Complexity and Control (CCC) theory (Zelazo & Frye, 1998). This proposes that the improvement in performance in 4-year-olds can be attributed to a change in the maximum hierarchical complexity of the rules that children can formulate and use when solving problems (in this task the if-then rules for sorting in

each dimension have to be embedded under more complex if-if-then rule that selects the relevant task). It has also been proposed that 3-year-olds have difficulty because of negative priming; by ignoring the conflicting colour information when sorting by shape, they then have difficulty activating colour rules in the post-switch phase (Muller, Dick, Gela, Overton, & Zelazo, 2006; Perner & Lang, 2002). A similar explanation is that by selectively attending to one dimension in the pre-switch phase, there is a pull to continue attending to it in the post-switch phase, and therefore a difficulty inhibiting this pull once it becomes irrelevant. This has been termed the 'attentional inertia' account (Kirkham et al., 2003). Alternatively, it may be that 3-year-olds do not understand that an object can be re-described in a different way (Kloo & Perner, 2005). Neural network models of the DCCS suggest a further explanation (Morton & Munakata, 2002), not incompatible with the attentional inertia theory (Yerys & Munakata, 2006). According to this account, behaviour in the DCCS is determined by competition between the latent representation of the pre-switch rule, representing habits, and an active representation of the current rule, representing working memory. When habits are stronger than working memories perseveration occurs, whereas when working memories are stronger than habits, flexible switching occurs. As yet there is no consensus as to which of these explanations is most likely; indeed given the complexity of the task it is likely that a number of these processes are involved.

Although 4-year-olds can successfully perform DCCS, even adults are affected by a switch in task if RT is used as the dependent variable. Diamond and Kirkham (2005) used a computerised version of the DCCS to show that adults' responses were slower on the first two trials following a change in sorting rule. Responses were slowed even further when the task switched on a trial-by-trial basis.

Diamond and Kirkham also found a differential performance between the two tasks depending on which dimension was relevant first, with faster RTs throughout the testing session when the adults were sorting by the initially relevant dimension.

The task-switching paradigm as a measure of shifting in children

The results of Diamond and Kirkham (2005) are consistent with the large body of literature using the task-switching paradigm in adults (see Monsell (2003) for a review). In this paradigm participants must switch between making decisions about one of two dimensions of the same stimuli, such as its colour and shape, on a trial by trial basis. The difference in RT between trials in which the task differs from the previous one, and trials in which the task stays the same is calculated as a measure of the time taken to complete the cognitive processes required to reconfigure the appropriate task set. Responses are slower when the task switches compared to when the task stays the same, indicating that it takes more effort to reconfigure a new task set.

Two different types of switching costs can be identified. The first are general, or mixing costs, which are believed to reflect the difficulty in maintaining and selecting among two or more different potential response sets (Reimers & Maylor, 2005). Mixing costs are calculated by comparing the difference between RT on blocks containing just one type of task and either non-switch trials within a block of mixed trials, or all trials within a mixed block. The second, typically referred to as the switch cost, represents the difficulty in reconfiguring a new task and response set, and is calculated by comparing switch and non-switch trials within a mixed block of trials. The switch cost seen in adults is partly thought to represent the executive process of shifting (Meiran, 1996; Rogers & Monsell, 1995), yet this contrasts with explanations for the DCCS, which is largely explained in terms of working memory

or inhibitory processes. Using the task-switching paradigm with children may help resolve this discrepancy and determine if shifting is an independent executive process in children.

Lifespan development studies (Cepeda, Kramer, & Gonzalez de Sather, 2001; Kray, Eber, & Lindenberger, 2004; Reimers & Maylor, 2005) have shown larger switching costs in school-age children than in adults. However it is not clear which aspects of performance on the task-switching paradigm improve during childhood. Kray, Eber and Lindenberger (2004) compared the switching ability of 8- to 10-year-old children, young adults and older adults and showed that the children had larger mixing costs than the young adults, suggesting a difficulty in maintaining and manipulating two task sets in working memory, however there was no difference in switch costs. Reimers and Maylor (2005) also showed a developmental improvement in mixing costs but not in switch costs between 10 and 18 years of age. In contrast, Cepeda, Kramer and Gonzalez de Sather (2001) found that children and older adults showed significantly longer switch costs than the young adults, even when baseline speed was controlled. However, it is not clear which age groups are included in these categories. The youngest age group (7 to 9 years) were not included in the main analyses and the group classed as children may have included those between the ages of 13 and 20 in addition to 10- to 12-year-olds.

There are a number of reasons that may explain the difference in findings between these lifespan studies. Kray et al. (2004) compared only a single age group of children with both young and old adults in the same analysis. Potentially, the use of such a large age-range may have masked any developmental changes in switch costs. Both Reimers and Maylor and Cepeda et al. only included children over 10 years, although only Cepeda et al. found a developmental improvement in switch

costs; Reimers and Maylor suggested that their data may have been too noisy to detect an improvement in switch costs in children.

A major problem with these lifespan studies is that the tasks were not designed specifically for use with a young population. The children may have found the stimuli unappealing and had trouble with the written cues, meaning they were not performing at their optimum level. Given the large number of trials and speeded responses needed to gain a reliable and accurate measure of RT for each condition in this paradigm, it is important that the children are sufficiently motivated to maintain optimum performance throughout the task.

Two studies have used a version of the task-switching paradigm more appropriate for use with children to examine developmental changes within childhood. Dibbets and Jolles (2006) designed a task in which 4- to 13-year-olds were required to choose an orange house in the context of a daytime sky and a blue house in the context of a night sky. The left and right position of the two houses varied over trials. They found that all children were slower when the task switched, but that overall the older children were faster and made fewer errors. There was no interaction between trialtype and age group, for either mixing or switch costs, suggesting that task *switching* performance did not improve with age. Importantly however, although the procedure of this experiment was similar to the task-switching paradigm, the task itself had more in common with an object reversal task (e.g. Overman, Bachevalier, Schuhmann, & Ryan, 1996) simply requiring the opposite stimulus to become correct on switch trials. This does not involve the same executive switch in task set as the extra-dimensional shift demanded by the standard task-switching paradigm, which may explain why age-related improvements in shifting set were not observed.

Consistent with this suggestion, a study adapting a standard adult task-switching paradigm for children did find a developmental improvement in set-shifting ability during childhood. Cohen, Bixenman, Meiran and Diamond (2001, as cited in Diamond (2002)) presented 5- to 11-year-olds and adults with a smiley face in one quadrant of a square. The participants had to say whether the face was on the left or right, or top or bottom, depending on the current task. This is known as a spatial task-switching paradigm as participants have to switch how they represent the location of the stimulus in space, rather than between two perceptual dimensions of the stimulus. Accuracy rather than RT was used as the dependent variable but a difference in error rate was shown between pure blocks and mixed blocks (mixing cost) and between switch and non-switch trials (switch cost). Furthermore, the difference in error rate decreased with age. While switch costs in RT were not reported for this study, Huizinga, Dolan and van der Molen (2006) found a reduction in RT switch costs between the ages of 7 and 15 years on three versions of the task-switching paradigm adapted from the adult literature, demonstrating a developmental improvement in the ability to switch between tasks during mid-childhood.

The existing literature on the development of set-shifting in children is rather inconsistent and the findings do not always agree. Therefore, Experiment 1 attempted to replicate Cepeda et al. (2001) and Huizinga et al. (2006) and show a developmental improvement in switch costs using an object version of the task-switching paradigm with stimuli appropriate for children. The tasks required switching between perceptual dimensions of the same stimulus, facilitating comparison with both the WCST and DCCS which work on a similar principle. As a result, this experiment aimed to further our understanding of the development of set-

shifting ability by providing data for school-aged children to complement the work using the DCCS in preschoolers and WCST and task-switching paradigm in adults.

Experiment 1

A number of factors which may affect children's performance on the task-switching paradigm were examined. The first of these was the tasks themselves. Ellefson, Shapiro and Chater (2006) found that when 7-year-old children and young adults were asked to match blue or red circles or triangles by either colour or shape, they showed larger mixing and switch costs on colour trials than on shape trials, despite being faster and more accurate on colour trials, suggesting they found this task easier. This asymmetry was similar for both age groups. A larger switch cost on a 'stronger' more familiar task compared to a weaker task has also been found in the adult task-switching literature (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000; Wylie & Allport, 2000), although only under certain conditions (Monsell, Yeung, & Azuma, 2000; Yeung & Monsell, 2003b). A good example is the colour-word Stroop task in which a large switch cost is seen for word-reading (strong task) compared to colour-naming (weak task). This may seem counter-intuitive, but one explanation is that when performing the weaker task, extra activation of the weaker task and greater inhibition of the stronger task is needed in order to overcome interference from the stronger task. This positive priming of the weaker task and negative priming of the stronger task then has to be overcome when the stronger task is switched to. In contrast, the weaker task does not interfere with performance of the stronger task and so there is less priming to overcome when it is switched to (Allport et al., 1994). With these issues in mind, the tasks in Experiment 1 involved attending to either the colour or shape of a stimulus. Following Ellefson et al., we

predicted that the children would find the colour task easier and therefore show larger switch costs in this condition.

Another factor that may influence task-switching performance is the overlap of the stimulus-response mappings for the two tasks. Within the task-switching paradigm the same two response keys are generally used for both tasks. This creates some trials where the responses for the two tasks are incongruent, i.e. when the currently relevant task calls for one response (e.g. left response key) and the currently irrelevant task calls for a different response (e.g. right response key). Typically, RTs are significantly longer for incongruent than congruent trials, and this difference is larger on switch than on non-switch trials (Monsell et al., 2000). Cepeda et al. (2001) examined the effects of the response mappings, or congruence effects¹, on switching performance and found that the interaction between switch costs and congruence was larger for children than for adults. They argued this showed that children find it harder to inhibit interference from the irrelevant task. We predicted that congruence effects would show a developmental improvement within childhood with larger congruence effects in younger children.

Practice has been found to reduce switch costs (Meiran, 1996; Rogers & Monsell, 1995), with the largest improvement shown by younger age groups (Cepeda et al., 2001; Schouten et al., 2000). Therefore, Experiment 1 tested children across two sessions at least a day apart. We predicted smaller switch costs in the second session, with a greater difference between sessions in the younger children.

In summary, the aim of this experiment was to design a developmentally-appropriate task-switching paradigm to investigate the development

¹ The term compatibility rather than congruence was used by Cepeda et al. however the principle is the same.

of set-shifting abilities in 5- to 11-year-old children. It was predicted that both mixing and switch costs would get smaller with age. Furthermore, following Ellefson et al. we predicted larger switch costs for the colour task than the shape task. In addition, it was predicted that the influence of incongruent stimulus-response mappings would reduce with age. Performance was re-tested in a second session a few days later. It was predicted that the influence of practice would result in improved performance in the second session, particularly for the younger children.

Method

Participants

Ninety children participated in this experiment. Data were collected from 15 children in each of the following British school year groups: Year 1 (5-6yrs); Year 2 (6-7yrs); Year 3 (7-8yrs); Year 4 (8-9yrs); Year 5 (9-10yrs) and Year 6 (10-11yrs). These were later grouped into two age groups: Younger Children (Years 1-3) and Older Children (Years 4-6). All of the children attended state primary schools and were selected at random by class teachers, although bilingual children and those with a statement of special educational needs were excluded from the study. Informed parental consent was received for all children that participated. Background information for all participants is presented in Table 2.1.

Table 2.1: Background information for participants

<u>Age Group</u>	<u><i>n</i></u>	<u>Gender</u>		<u>Age (yrs)</u>	
		Male	Female	<i>M</i>	<i>SD</i>
Year 1	15	7	8	6.01	0.33
Year 2	15	7	8	6.81	0.25
Year 3	15	8	7	8.13	0.28
Younger Children	45	22	23	6.98	0.93
Year 4	15	9	6	9.15	0.24
Year 5	15	7	8	10.1	0.32
Year 6	15	7	8	11.0	0.24
Older Children	45	23	22	10.1	0.80

Materials and Procedure

The experiment was carried out in a quiet area of the school. The experimental tasks were created and controlled using e-prime software and run on a Dell laptop computer. This was connected to an ELO touchscreen placed approximately 270mm from the edge of the table with an ergonomic mouse mat centred in front of it which acted as a hand-rest. The participants sat within comfortable reaching distance of the touchscreen and were asked to begin by placing their dominant hand on the hand-rest.

The children were seen across two sessions at least a day apart. The task-switching paradigm was split equally between the sessions and the blocks were interspersed with other tasks to keep motivation levels high. The order in which the sessions were completed was counterbalanced across participants.

The paradigm was introduced as a football match scenario in which the child had to choose which team a player was on. The target stimuli were footballers

presented in the centre of the screen, one at a time. All of the footballers were identical apart from the shirts which they were wearing. These were either spotty or stripy and could either be pink or yellow. The two tasks entailed making a decision based on either the colour or the pattern of the shirt.

On each trial, participants first saw the ‘football stadium’ (Figure 2.1) which consisted of a wall with two doors. Between each door and the edge of the screen were two ticket offices. After 1000ms the cue indicating which task should be performed on that trial appeared. The cues were rectangles superimposed on the ticket offices. For the colour task this consisted of a pink rectangle on the left hand ticket office and a yellow rectangle on the right, while for the pattern task this was a spotty rectangle on the left and a stripy rectangle on the right. 500ms after the cue the footballer would appear in the centre of the screen. The cue squares remained on the screen when the target appeared and a response was made by touching one of the cue rectangles. The computer recorded the accuracy and latency of the response.

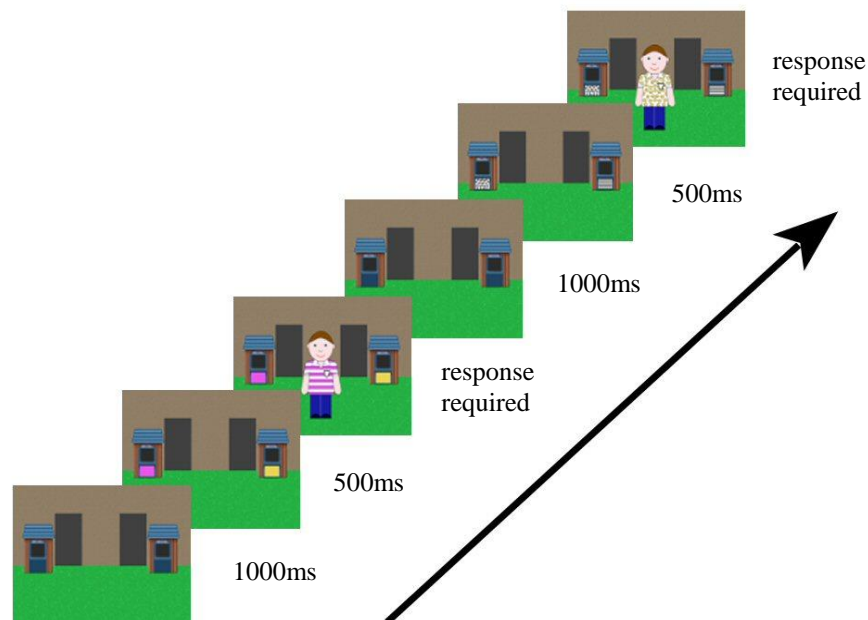


Figure 2.1: Example of a colour trial followed by a pattern trial. In this example the pattern trial is a switch trial

At the start of each session the children completed two pure blocks, one of colour trials and one of pattern trials. The order in which these blocks were performed was counterbalanced across participants. If the colour block was completed first in session one then the shape block was completed first in session two. The children were introduced to the task with screen shots of the football stadium and the cues and told that in this game either the pink team would be playing the yellow team or the spotty team would be playing the stripy team, depending on which task was performed first. It was then explained that they had to send the player through the correct door by touching the rectangle which matched his shirt. They were asked to do this as fast as they could and then return their hand to the hand-rest. After the task had been explained eight practice trials were performed. This was followed by 64 test trials. Half-way through and at the end of each block a feedback screen was displayed telling the child how many correct responses they had made.

In addition to the pure colour and pattern blocks, the participants also performed mixed blocks in which the task (colour or pattern) and the target were selected randomly with equal probabilities. The children completed two mixed blocks of 64 trials in each session (four in total). In the mixed blocks the children were told that this time, instead of a football match there was a football tournament, so that sometimes the pink team were playing the yellow team, but that sometimes the spotty team were playing the stripy team. It was explained that they could tell which teams were playing by looking at the cues on the ticket offices, and that all they had to do was to match the player's shirt to the correct rectangle. The participants were then shown four different target stimuli, one for each possible response (pink, yellow, spotty and stripy). For the first two they were told which

door was correct; e.g. “He is wearing a pink shirt so he goes in here” (point to the pink rectangle). For the second two, the participant had to show the experimenter the correct rectangle to make sure that they understood the task. The procedure then continued as for the pure blocks.

Switch trials were defined as trials in which the task differed from the previous trial whereas non-switch trials occurred when the task repeated. As the responses overlapped for the two tasks it was also possible to look at congruence effects. Pink cues and spotty cues were always on the left, and yellow and stripy cues were always on the right. This meant that football shirts with pink spots and those with yellow stripes were congruent stimuli due to the fact that the response was the same regardless of the dimension attended to. Pink stripy shirts and yellow spotty shirts were incongruent as the two dimensions (colour and pattern) indicated different responses.

Results

The first two trials of each block of the task switching paradigm were treated as ‘warm-up’ trials and were not analysed. In addition, any trial on which more than one touchscreen response was recorded was treated as an equipment failure and not included in the data analysis. There were 965 such trials, which amounted to 2.12% of the total number of trials. The dependent variable in this task was RT, measured from the time the target stimulus appeared until a response was made. The median RT was calculated for each participant in each condition. Overall error rates were low, amounting to only 0.98% across age groups and conditions and as a result were not analysed further. Error trials were excluded from the RT analysis.

There was no effect of gender or the order in which the blocks were completed ($F(1, 88) < 1$, *ns*, for both gender and order) as shown by two mixed-

measures ANOVAs with trialtype (pure, non-switch, switch) as a within-subject factor and either gender (male, female) or order (colour first, shape first) as a between-subjects factor. Therefore gender and order were not included as factors in further analyses. The analyses were initially performed comparing all six age-groups of children; however the pattern of results showed that the children fell into two groups. As such the results were reanalysed comparing younger children (Years 1-3) to older children (Years 4-6).

To analyse the RTs a five-way mixed-measures ANOVA was performed with Task (colour, pattern) Trialtype (pure, non-switch, switch), Congruence (congruent, incongruent) and Session (session one, session two) as within-subject factors and Age (younger children, older children) as a between-subjects factor. For clarity, the results for switch costs and congruence effects were considered separately and the effect of age and practice on each of these factors is addressed in turn. The Greenhouse-Geisser correction was used in all ANOVAs. Means for all conditions can be found in Appendix I.

Speed

Overall, all children were slightly faster on the colour task ($M=1034\text{ms}$, $SD=268$) than the pattern task ($M=1080\text{ms}$, $SD=281$) as shown by a significant main effect of Task, $F(1, 88)=34.3$, $p<.001$, $\eta^2=.281$. As shown in Figure 2.2, one of the most obvious differences between the different age groups was an overall difference in response speed. There was a significant main effect of Age, $F(1, 88)=58.9$, $p<.001$, $\eta^2=.401$, as the older children ($M=886\text{ms}$, $SD=139$) were significantly faster to respond than the younger children ($M=1228\text{ms}$, $SD=265$). This shows that RT decreased with age. Because of this, any interactions between Age and other conditions could be driven by this difference in overall speed, for example, a 20%

increase in RT in both age groups would result in a larger absolute difference in the younger children. The analyses were repeated using mean log RTs which are less sensitive to baseline differences in performance (Kray, Li, & Lindenberger, 2002; Kray & Lindenberger, 2000; Meiran, 1996). These analyses showed the same pattern of results as the medians, suggesting that any group differences were not due to a difference in overall speed. The log RT analyses will only be mentioned when they add something to the median analyses on the raw data.

Performance was faster in the second session ($M=1022$, $SD=265$) than the first session ($M=1092$, $SD=292$) as shown by a significant main effect of Session, $F(1,88)=28.0$, $p<.001$, $\eta^2=.241$. This demonstrates that practice improved overall response speed. The Session x Age interaction was not significant, $F(1,88)=3.61$, ns , showing that practice affected response speed to the same extent for both age groups.

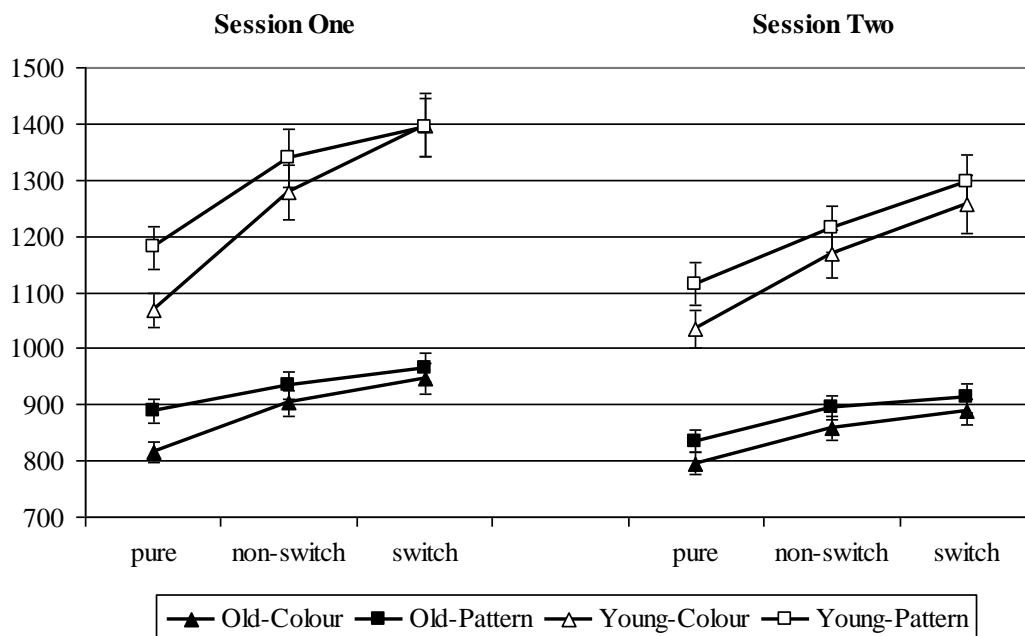


Figure 2.2: Mean RT (*SE*) of each trialtype for colour and shape tasks. Filled shapes = older children, unfilled shapes = younger children

Switch Costs

The main effect of Trialtype for pure, non-switch and switch trials was significant, $F(1.24, 110)=136.6$, $p<.001$, $\eta^2=.608$. A test of simple effects showed this was due to reliable differences between all three trialtypes. Performance was fastest in the pure trials ($M=966\text{ms}$, $SD=217$). All children were slower on the non-switch trials in mixed blocks ($M=1074\text{ms}$, $SD=284$) than trials in the pure blocks, demonstrating a mixing cost. They were slowest of all on the switch trials in the mixed blocks ($M=1132\text{ms}$, $SD=325$).

The significant difference between non-switch and switch trials demonstrates an overall switch cost, however this was qualified by a Trialtype x Age interaction, $F(1.24, 110)=24.9$, $p<.001$, $\eta^2=.220$. All trialtypes were significantly different from each other in both age groups; however there was a larger difference between trialtypes in the younger children. This demonstrates that the older children showed smaller mixing and switch costs, suggesting that they found it easier to maintain two task and response sets in working memory and to flexibly switch between two tasks.

There was a small but significant Trialtype x Session interaction, $F(1.37, 121)=4.53$, $p<.05$, $\eta^2=.049$, with smaller switch costs in the second session. Mixing costs (Session 1: 126ms; Session 2: 89ms) seemed to be more affected by practice than switch costs (Session 1: 62ms; Session 2: 54ms). There was also a Trialtype x Task interaction, $F(1.86, 164)=11.1$, $p<.001$, $\eta^2=.112$, as there was a greater difference between trialtypes for colour trials, suggesting an asymmetry in switch costs. However, a significant Task x Trialtype x Session interaction, $F(1.98, 174)=3.07$, $p=.05$, $\eta^2=.034$, showed that this was only true in session one.

Congruence

Participants were slower on incongruent trials ($M=1075$, $SD=281$) than congruent trials ($M=1039$, $SD=265$) as shown by a significant main effect of Congruence, $F(1,88)=52.5$, $p<.001$, $\eta^2=.374$. This shows that the children responded faster when the two dimensions of the target indicated the same response than when they indicated conflicting responses. As shown in Figure 2.3, this was qualified by a significant Congruence x Age interaction ($F(1,88)=9.07$, $p<.01$, $\eta^2=.093$) which occurred because of larger congruence effects in the younger children than in the older children. There was a significant Congruence x Trialtype interaction ($F(1.47,129)=15.4$, $p<.001$, $\eta^2=.149$) showing that the influence of congruence had a greater effect on RT in switch trials than in non-switch trials.

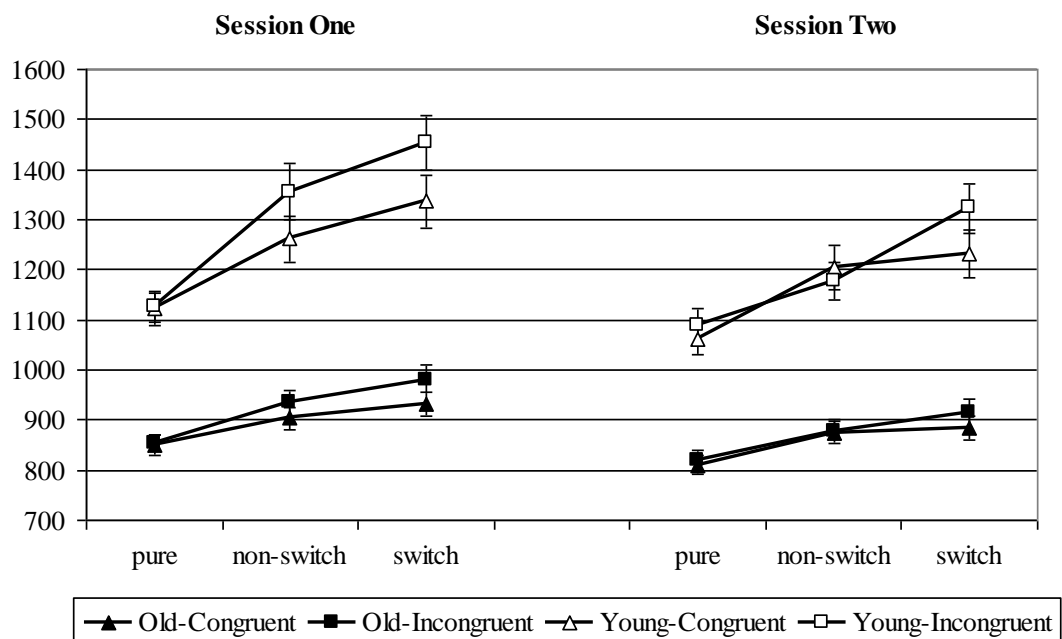


Figure 2.3: Mean RT (*SE*) for congruence effects at each trialtype. Filled shapes = older children, unfilled shapes = younger children.

A significant Congruence x Session interaction $F(1,88)=14.8$, $p<.01$, $\eta^2=.144$, showed that practice reduced the congruence effect. Tests of simple effects showed that overall, performance was faster on congruent trials than incongruent trials in session one but that this difference was smaller in session two. This suggests that interference from response mappings had less of an effect on performance in session two. There was also a significant three-way interaction between Congruence, Session and Trialtype, $F(1.49, 131)=8.48$, $p<.001$, $\eta^2=.088$. Tests of simple effects showed significant congruence effects on switch costs in both sessions. In addition, in session one there were also congruence effects on non-switch trials, while in session two there were congruence effects on pure trials. The presence of congruence effects in a pure block is particularly interesting as it suggests that after experience with both tasks, the response mappings for the irrelevant task interfere, even when it is not being performed within that block.

When the median RT was used as the dependent variable congruence effects on trials other than switch trials were only present in the younger children, as shown by significant Age, Trialtype and Congruence ($F(1.47,129)=3.48$, $p=.05$, $\eta^2=.038$) and Age, Trialtype, Congruence and Session interactions, $F(2.20, 194)=5.45$, $p<.01$, $\eta^2=.058$. However, using the mean log RT, the older children also showed a significant congruence effect on pure trials in the second session.

The congruence results show that children's responses are influenced by the stimulus-response mappings of the task. The congruence effect interacted with the switch costs, such that responses were slowest on incongruent trials that also required a switch in the task being performed. The congruence effects on switch trials were slightly reduced in the second session, suggesting that practice reduced the interference from irrelevant response mappings on switching performance.

However, the congruence effect on pure trials in the second session indicates that once the children had become familiar with both tasks, the unattended dimension interfered with performance even when it was not required within the block. This demonstrates the pervasive influence that overlapping responses has on children's performance in the task-switching paradigm. Overall, the younger children were more strongly influenced by interference from the irrelevant task suggesting that the ability to inhibit irrelevant information develops during mid-childhood.

Discussion

This experiment used a developmentally-appropriate task-switching paradigm to investigate the effects of task, stimulus-response mappings and practice on children's ability to shift attentional set. All children who participated found the task appealing and were motivated to perform at their best. Despite marked methodological differences to earlier task-switching paradigms, i.e. more complex stimuli and the use of a touchscreen to make responses, significant switch costs were present. This suggests that this task-shifting paradigm is a useful tool to measure the set shifting in children.

The results showed a developmental improvement in task-switching within mid-childhood, with younger children (5- to 8-years-old) showing significantly larger mixing and switch costs than older children (9- to 11-years-old). This shows that the ability to maintain two task sets in working memory, and also the ability to flexibly shift between them, develops between the ages of 5- and 11-years-old. Some researchers have argued that a global improvement in processing speed is responsible for all improvements during development (Hale, 1990; Kail, 1986, 1991). However, the difference in switch costs between the two age groups in this experiment remained significant even when differences in baseline speed were taken

into account, suggesting that a general improvement in processing speed was not driving the age-related changes in shifting attentional set.

The results from this experiment are consistent with the growing body of literature documenting the improvement of set-shifting abilities in childhood (Chelune & Baer, 1986; Cinan, 2006; Crone et al., 2004; Dibbets & Jolles, 2006; Schouten et al., 2000; Welsh et al., 1991). Together, these findings further our understanding of the development of set-shifting, filling in the gap between the DCCS literature in pre-schoolers and the task-switching and WCST literature in adults.

Given that our results support the findings of Cepeda et al. (2001) in showing developmental changes in switch costs during childhood, it is necessary to consider why these effects were not found by Kray et al. (2004) and Reimers and Maylor (2005). The switch costs presented by Kray et al. were small for all age groups (around 20ms), possibly because the participants had taken part in a previous experiment using the same stimuli and were thus well practised at the task. The switch costs may also have been affected by a secondary task that was introduced during the cue-target interval. An alternative explanation is that Kray et al. used a larger set of 32 possible target stimuli, rather than the four used in this experiment and by others (Cepeda et al., 2001; Reimers & Maylor, 2005). Kray and Eppinger (2006) found age differences in switch costs between younger and older adults with a stimulus-set size of four, but not with a set of 96 stimuli. This is consistent with other studies that have found a difference in switch costs between older and younger adults if a small set size is used (Mayr, 2001; Meiran, Gotler, & Perlman, 2001) but not if a large set size is used (Kray & Lindenberger, 2000). It is possible that developmental changes in childhood are also affected by the size of the stimulus set;

however this has not yet been specifically investigated. One possible problem with this interpretation is that Reimers and Maylor (2005) used a small stimulus-set size yet did not find a developmental change in switch costs. However, they suggested that a problem with noisy data, probably due to the fact that their data were collected over the internet, may explain why they did not find significantly larger switch costs in children.

There was some evidence of asymmetrical switch costs, with a larger cost on the easier colour task, consistent with the findings of Ellefson et al. (2006). However, the asymmetry between the two tasks was not present in the second session. This suggests that practice on the tasks may reduce the unequal interference of the colour task on the pattern task. Practice has also been shown to affect asymmetrical switch costs in adults (Yeung & Monsell, 2003a). In this case however, recent practice on one of two initially equal tasks led to a larger cost when switching to this practised task.

In addition to studying the ability to shift attentional set, the task-switching paradigm can also be used to explore the influence of conflicting stimulus-response mappings on task-switching performance by examining the congruence effects. As the stimuli and responses for the two tasks overlapped there were some trials on which the tasks indicated conflicting responses. As a result, the response associated with the irrelevant task needed to be ignored, which may have involved processes of inhibition. Cepeda et al. (2001) showed that children found it harder to ignore information from the irrelevant task than adults did. We added to this result by showing that the ability to inhibit irrelevant stimulus-response mappings improves during mid-childhood, as shown by smaller congruence effects in the older children. The ability to ignore irrelevant information depended on the type of trial. Overall,

the children found this more difficult on trials in which the task switched, presumably because the information they needed to inhibit had been relevant on the previous trial. In addition, the younger children were more susceptible to interference on incongruent trials where a task switch was not involved. This included trials in pure blocks in the second session during which the irrelevant task was never performed. This suggests that there was interference from the irrelevant task even when it was not being actively maintained as a possible response mapping for trials in that block, implying that the younger children were having greater difficulty inhibiting irrelevant information. The congruence effects in task-switching are explored further in Chapter 3.

The switch task was performed across two sessions enabling the effects of practice on performance to be examined. This has not been done with this age group before. Unsurprisingly, overall response speed was faster in the second session. Switch costs and mixing costs were reduced but not eliminated by practice. Moreover, practice seemed to have a greater effect on maintaining two task sets in working memory (mixing costs) than on improving the ability to switch between them (switch costs). Practice had a complicated effect on the influence of conflicting response mappings. Interference from irrelevant response mappings on switch trials was reduced by practice for both age groups. However, experience with the two tasks appeared to introduce this interference in pure blocks in which the irrelevant task was not even being performed.

In conclusion, this experiment used a novel, developmentally-appropriate task-switching paradigm to show that the ability to shift attentional set improves during mid-childhood. In addition, the ability to inhibit task-irrelevant information showed a striking improvement during childhood. Practice reduced but did not

eliminate switch costs, however the effect of practice on congruence effects was more complicated, reducing conflict on switch trials but introducing it in pure blocks of trials.

Experiment 2a

An important factor in the use of all psychological tests is their reliability. Poor reliability limits the sensitivity of a test when used on its own but also the extent to which it can be expected to correlate with other measures (Lowe & Rabbitt, 1998). Reliability is also important when a task is used to detect changes in ability over time, such as in longitudinal studies of development or to measure individual differences.

The reliability of executive tasks in children is often overlooked (Kuntsi, Stevenson, Oosterlaan, & Sonuga-Barke, 2001). Yet in order to provide an accurate picture of the development of executive functions it is important to find reliable measures that yield consistent results across changes in stimuli and repeated administrations. Understanding the reliability of the task-switching paradigm in children helps to determine the extent to which differences across studies are simply due to the fact that the measure is unreliable, or if more important changes in task parameters are responsible.

Given that different groups of researchers use similar tasks but often vary the exact stimuli that are used, it is also important to examine the extent to which these superficial changes affect task performance. As mentioned earlier, differences in the tasks used can affect performance on the task-switching paradigm. For example, using two tasks that are unequal in strength (e.g. colour naming and word reading; Allport et al., 1994; Allport & Wylie, 2000; Wylie & Allport, 2000) creates asymmetric switch costs that are not present when more equivalent tasks are used

(odd/even decision for numbers and vowel/consonant decision for letters (Rogers & Monsell, 1995)). However, less is known about how simple changes in stimuli affect task-switching performance. Huizinga et al. (2006) found that three task-switching measures using different stimuli showed a similar pattern of development and loaded onto a single latent variable for shifting that could be used in structural equation modelling. In a similar task, the DCCS, consistent results have been found across studies which use the same tasks (colour and shape) but vary the colours and objects used (Kirkham et al., 2003; Perner & Lang, 2002; Zelazo et al., 1996). These findings suggest that changes in superficial task features do not influence set-shifting performance.

To examine the reliability of our version of the task-switching paradigm we carried out a second experiment using an identical version of the test and also a parallel form using new stimuli but similar colour and shape tasks. Using the identical paradigm we hoped to replicate the findings from Experiment 1. The parallel form was included to determine if set-shifting performance was robust across different stimuli, i.e. if those children who performed well with one set of stimuli also performed well with new stimuli.

Method

Participants

Seventy-one of the original sample of 90 children participated in a second experiment, carried out one year later. The oldest age group from Experiment 1 could not be included as they had now left primary school. In addition, four other participants had moved away from the area. At this time-point the children had all moved up one school year. To avoid confusion with Experiment 1, the new year

groups were labelled with T2 to indicate that this was the school year they were in at Time 2.

Materials and Procedure

As for Experiment 1, the children were seen for two 30 minute testing sessions at least a day apart. Two versions of the task-switching paradigm were administered, counterbalanced across sessions. The Football version was the same as Experiment 1. In addition a parallel form of the task using cakes as stimuli was included (Figure 2.4).

In the Cake version the background was a plain dark-red screen and shopping baskets replaced the ticket offices. The target consisted of a cupcake with a coloured shape on top. This was either a purple or green flower or star. Cues similar to those used in the Football version were presented on the shopping baskets indicating whether the colour or shape task was to be performed. The procedure for both tasks was identical to that for Experiment 1 except that the pure block of shape/pattern trials was always presented first and each version was performed in one session instead of two.

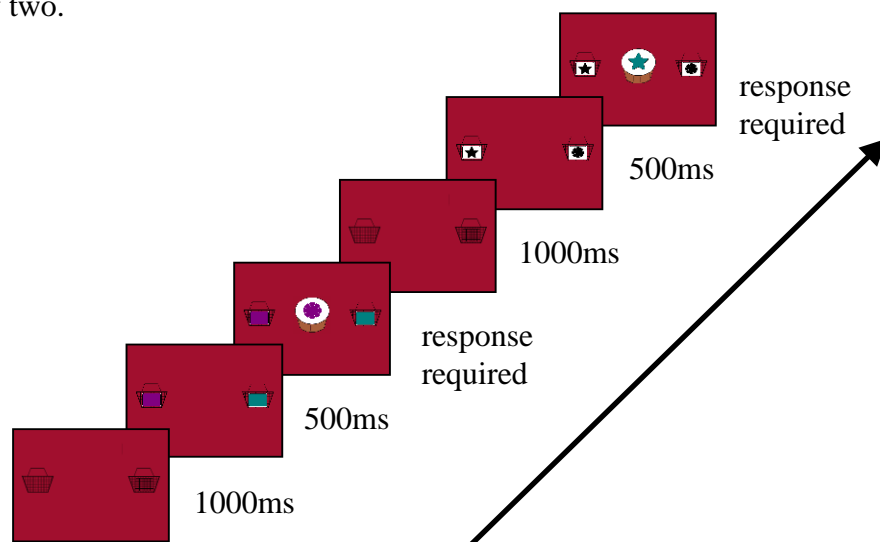


Figure 2.4: Example of a colour trial followed by a shape trial in the Cake version of the task-switching paradigm. In this example the shape trial is a switch trial

Results

Two sets of analyses were performed. The first used ANOVAs to examine the switch costs and congruence effects for the Football and Cake versions of the task-switching paradigm separately. The second set of analyses investigated the degree of correlation between the two versions.

RTs were treated in the same way as in Experiment 1. For both the Football and Cake versions error rates were below 0.01% and the number of trials excluded due to equipment failure was less than 0.1%. There was no effect of gender or order ($F(1, 69) < 1$, *ns*) for either version as shown by two mixed-measures ANOVAs with Trialtype (pure, non-switch, switch) and Version (Football version, Cake version) as within-subject factors and either Gender (male, female) or Order (Football version first, Cake version first) as between-subject factors. Gender and order were not included as factors in further analyses. The analyses were also performed with mean log RT as the dependent variable. These analyses were generally consistent with the median and will only be mentioned when they add additional information. The Greenhouse-Geisser correction was used in all analyses. Means for all conditions can be found in Appendix I.

In Experiment 1, the six year groups were collapsed in to two age groups for analysis. In this experiment however, only five year groups participated, compared to six year groups in Experiment 1. This introduced a dilemma as how to divide the age groups. Inspection of performance across trialtypes for each year group showed that Year 2_{T2} and Year 3_{T2} showed a similar pattern of RTs and overall speed of responding, as did Years 5_{T2} and 6_{T2}. Year 4_{T2} showed an intermediate pattern that did not immediately fit with either group. There was an argument for including Year 4_{T2} with the older children, following the break between Years 3 and 4 used in

Experiment 1. Alternatively, as the children in Years 2-4 formed the original younger group in Experiment 1 there was an argument for keeping them together again in Experiment 2. An alternative was to use a median split on chronological age to divide the children in two. However, as many of the Year 4_{T2} children were of the median age (9 yrs, 2 months) this did not seem appropriate. It was finally decided to keep Year 4_{T2} as a separate group to see whether they were more similar to the older or younger children. Although the analyses could have been performed to compare all year groups separately, it was decided to combine the year groups where appropriate to provide more power and ease interpretation of results. The analyses were also run comparing all year groups separately and the results were very similar. Therefore, the children were split into 3 age groups; 6- to 8-year-olds ($n=28$, $M=7.30$, $SD=.53$), 9-year-olds ($n=15$, $M=9.08$, $SD=.28$) and 10- to 11-year-olds ($n=28$, $M=10.6$, $SD=.53$).

Football version

The Football version of the paradigm was analysed using a four-way mixed-measures ANOVA with Task (colour, pattern) Trialtype (pure, non-switch, switch) and Congruence (congruent, incongruent) as within-subject factors and Age (7- to 8-year-olds, 9-year-olds and 10- to 11-year-olds) as a between-subjects factor. All means are shown in Figure 2.5.

There was a significant main effect of Age, $F(2, 68)=18.6$, $p<.001$, $\eta^2=.353$, as the 6- to 8-year-olds were significantly slower than the 9-year-olds and 10- to 11-year-olds who did not differ. Overall, all children were slightly faster on the colour task than the pattern task as shown by a significant main effect of Task, $F(1, 68)=57.6$, $p<.001$, $\eta^2=.459$. The gap between the two tasks decreased with age as

shown by a marginally significant Task x Age interaction, $F(2, 68)=3.604$ $p=.055$, $\eta^2=.082$.

There was a significant effect of Trialtype, $F(1.52, 104)=12.1$, $p<.001$, $\eta^2=.151$, showing significant mixing and switch costs. However, this was qualified by a Trialtype x Age interaction, $F(3.05, 104)=4.13$, $p<.01$, $\eta^2=.108$, as only the 6- to 8-year-olds showed these costs. The 10- to 11-year-olds showed no significant costs, while the 9-year-olds only showed a difference between pure and switch trials. This pattern was replicated in the log RT analyses, $F(2.99, 102)=4.46$, $p<.01$, $\eta^2=.116$, showing that these difference were not simply driven by a difference in overall speed. The log RT analysis also showed an interaction between task and trialtype, $F(1.92, 131)=4.45$, $p<.05$, $\eta^2=.061$, due to a greater difference between the two tasks on pure trials compared to the other trialtypes.

There was a main effect of Congruence, $F(1, 68)=18.8$, $p<.001$, $\eta^2=.217$, however a Congruence x Trialtype interaction, $F(1.72, 117)=6.13$, $p<.01$, $\eta^2=.083$, showed that there was only a congruence effect on switch trials. Furthermore, a significant Trialtype x Congruence x Age interaction, $F(3.45, 117)=2.55$, $p<.05$, $\eta^2=.070$, demonstrated that only the 6- to 8-year-olds and 9-year-olds showed this congruence effect. The log RT analysis replicated these findings and also showed a significant Congruence x Task interaction, $F(1, 68)=1.54$, $p<.01$, $\eta^2=.119$, due to a congruence effect on colour trials only when log RT was used as the dependent variable.

In sum, the results for the Football version of the task show a similar pattern of results to Experiment 1 except that switch costs and congruence effects are no longer apparent in the oldest children.

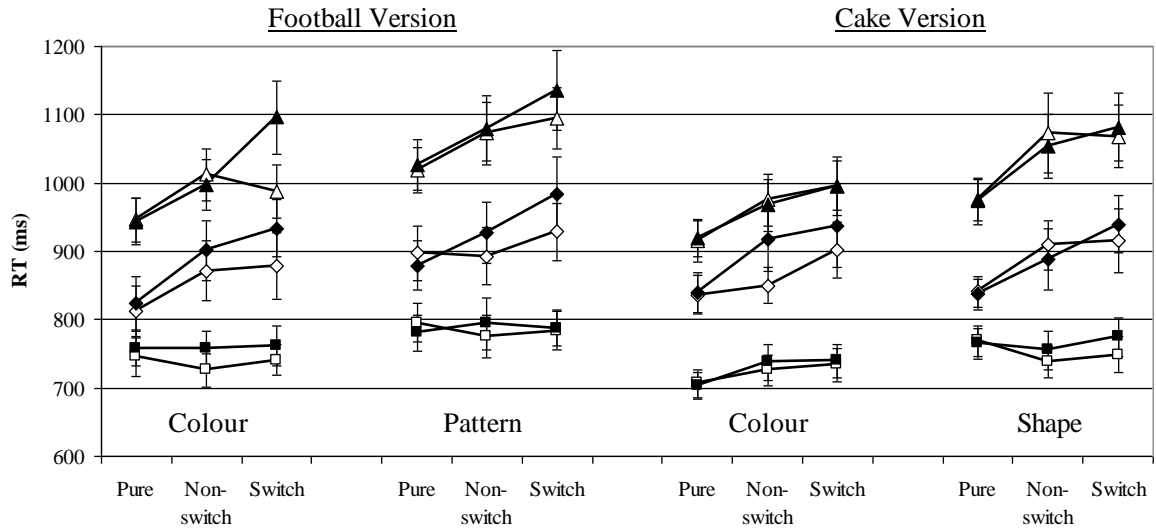


Figure 2.5: Mean RT (*SE*) for all conditions in the Football and Cake versions of the task-switching paradigm. ■ = 10- to 11-year-olds, ◆ = 9-year-olds, ▲ = 6- to 8-year-olds. Filled shapes = incongruent, unfilled shapes = congruent.

Cake version

An identical analysis was performed for the Cake version using a four-way mixed-measures ANOVAs with Task (colour, shape) Trialtype (pure, non-switch, switch) and Congruence (congruent, incongruent) as within-subject factors and Age (7- to 8-year-olds, 9-year-olds and 10- to 11-year-olds) as a between-subjects factor. All means are shown in Figure 2.5.

There was a significant main effect of Age, $F(2, 68)=19.6$, $p<.001$, $\eta^2=.366$, as the 10- to 11-year-olds were significantly faster than the 6- to 8-year-olds and 9-year-olds who did not differ. A significant main effect of Task, $F(1, 68)=27.3$, $p<.001$, $\eta^2=.287$, showed that responses were faster on the colour task than the shape task. However, a significant Task x Age interaction, $F(2, 68)=7.00$ $p<.01$, $\eta^2=.171$, showed that there was no difference between tasks for the 9-year-olds.

Overall there were significant mixing and switch costs, as shown by a significant effect of Trialtype, $F(1.33, 90.1)=17.3$, $p<.001$, $\eta^2=.203$. However, a Trialtype x Age interaction, $F(2.65, 90.1)=3.68$, $p<.05$, $\eta^2=.098$, revealed an interesting pattern of results. Tests of simple effects showed that while the 10- to 11-year-olds showed no significant costs, the 9-year-olds showed a significant switch cost and the 6- to 8-year-olds a significant mixing cost. Both the 6- to 8-year-olds and 9-year-olds showed a difference between pure and switch trials. This pattern of results was replicated in the log RT analysis.

Overall, responses were slightly faster on congruent trials than incongruent trials ($F(1, 68)=6.40$, $p<.05$, $\eta^2=.086$), however this did not interact with Trialtype ($F(1.90, 129)=1.68$, *ns*). There was a trend towards a Congruence x Age interaction, $F(2, 68)=2.76$, $p=.070$, $\eta^2=.075$, which tests of simple effects indicated was because only 9-year-olds were showing a significant congruence effect. However this was not significant when log RT was used as the dependent variable. The log RT analysis showed a significant Task x Congruence interaction, $F(1, 68)=4.87$, $p<.05$, $\eta^2=.067$, due to a congruence effect on colour trials only when log RT was the dependent variable.

The results for the Cake version of the task-switching paradigm differ from those found for the Football version. Both switch costs and congruence effects appeared more fragile in the Cake version and the 9-year-olds showed a different pattern of results from the other two age groups. This suggests that the results from the task-switching paradigm vary depending on the stimuli used.

Comparison of Football and Cake versions

The similarity between the Football and Cake versions was assessed using Pearson product-moment correlations. There was a small correlation between switch

costs in the two parallel forms, $r(71) = .292$, $p < .05$. However this disappeared when outliers greater than 3 *SD* above the mean for each condition (1 in each condition) were removed ($r(69) = .145$, *ns*). Given the different patterns of results found in the previous analyses, it is perhaps not surprising that the switch costs in the two parallel forms were dissimilar. Overall the results suggest that the reliability of the task-switching paradigm across changes in stimuli is poor.

Discussion

Two versions of the task-switching paradigm were included in Experiment 2a in an attempt to replicate Experiment 1 but also to see if task-switching performance was similar when different stimuli were used. The Football version showed a similar pattern of results to Experiment 1, with switch costs and congruency effects decreasing with age. However, overall the switch costs were smaller, to the extent that they were non-existent, or even negative, in the 9-year-olds and 10- to 11-year-olds. The Cake version did not show a similar pattern of results to Experiment 1. Switch costs varied between age groups and congruence effects did not decrease with age. This difference between the two versions was not explained by the order in which the two versions were performed (cake first or football first). Therefore, task-switching performance in this group of children was altered by changing the stimuli used. This is in contrast to the versions of the task-switching paradigm used by Huizinga et al. (2006) and the DCCS (Kirkham et al., 2003; Perner & Lang, 2002; Zelazo et al., 1996) which are shown to be reliable across changes in stimuli.

These findings suggest that the task-switching paradigm does not have good reliability across parallel forms and is not robust to superficial changes in the stimuli used. However, switch costs in both versions were very small, and were even negative in some cases. If it was simply the case that the switch costs were small and

unreliable only on the Cake version of the task then it could be assumed that this version was not a good measure of task-switching ability. Yet as the switch costs were also reduced on the Football version, it suggests that the children's performance was affected by having previously performed the Football version of the task-switching experiment one year earlier. This result was surprising given that we had not expected there to be any lasting effects from performing the task after this length of time. In consequence, this is not a fair test of parallel form reliability. The two versions of the task-switching paradigm should be re-administered in a new sample of children who have not performed either of the tasks previously to determine the extent to which task-switching performance is stimulus-specific.

To investigate exactly how switch costs were affected by previous performance, we carried out a further experiment directly comparing the switch costs for the Football version in the original testing session and follow-up session a few days later (reported in Experiment 1) to the same Football version administered one year later (reported in Experiment 2a).

Experiment 2b

This experiment examined how repeated administration of our task-switching paradigm to the same group of children affected their performance over time. It also aimed to determine if children's performance in Experiment 2a had been affected by taking part in Experiment 1 one year earlier. An issue raised by examining performance over time is the distinction between practice effects and test-retest reliability. Performance over time is usually examined by looking at *either* practice effects (usually within the same testing session or sessions no more than a few days apart) or test-retest reliability over a longer period of time. A distinction between practice effects and reliability could be made on the basis of the amount of time

between the two testing sessions: A repetition after a few hours or days is likely to be influenced by familiarisation with specific features of the task as it will still be relatively well remembered. With increasing time between tests it is likely that the specific features will be forgotten but other more general aspects of the task may have been retained. However, it is not quite that simple. Practice effects focus on participants' performance whereas test-retest reliability is more concerned with the task used. Furthermore, practice effects are expected to be highly linked to the original testing session, usually demonstrating an improvement in performance in the second session. In contrast, test-retest reliability examines, to some extent, whether a second testing session can be considered as a stand-alone measure of performance at that point in time. To complicate matters further, the two are difficult to separate given that test-retest reliability is likely to be affected by practice effects, and practice effects will not be reliable if the task used is not measuring the same processes at both points in time.

The test-retest reliability of executive tasks is a particular concern as it is often poor (Hughes & Graham, 2002; Lowe & Rabbitt, 1998; Miyake et al., 2000). The control and self-regulatory processes employed by executive tasks are particularly relevant when a task is novel (Burgess, 1997; Lowe & Rabbitt, 1998). As a task is repeated it becomes less novel and so these processes are no longer required for successful performance. From this it could be argued that previous practice has a huge effect on the reliability of executive tasks.

Mixed results have been found in the few studies examining the test-retest reliability of executive tasks in children (Archibald & Kerns, 1999; Isquith, Crawford, Espy, & Gioia, 2005; Kuntsi et al., 2001). Isquith, Crawford, Espy and Gioia (2005) gave preschoolers two executive tasks, Shape School and TRAILS-P,

which tapped response suppression and cognitive switching to varying degrees in different conditions. They found that the test-retest reliability for the tasks was acceptable but that it varied across the different conditions. With older school-age children, tests of working memory and stroop-like interference have shown the highest reliability (Archibald & Kerns, 1999; Kuntsi et al., 2001), while the stop-signal task, a measure of response inhibition, and a dual-task paradigm showed poor reliability after 2 weeks (Kuntsi et al., 2001). Poor test-retest reliability has also been shown for the Tower of Hanoi, a measure of planning, after an interval of 30-40 days (Bishop, Aamodt-Leeper, Cresswell, McGurk, & Skuse, 2001). Importantly however, this differs from task-switching in that once the strategy is understood, the task becomes much easier, such that performance may suddenly improve substantially. In contrast, as the cued task-switching paradigm involves relatively unconscious processes, performance may be more stable across testing sessions with more continuous effects of practice.

These studies show that test-retest reliability is highly variable depending on the task and the processes involved. Another factor that affects test-retest reliability is the amount of time after the initial experiment that performance is re-tested. While most studies retest performance either after hours or days to examine practice effects, or investigate reliability over a longer period of weeks or months, we were able to investigate both the short- and long-term effects of previous task experience in the same sample.

In this experiment we compared performance on the Football version of the task-switching paradigm at three time points. As this was administered across two sessions in Experiment 1, performance one or two days later could be examined allowing short-term practice effects, when the task is still consciously familiar, to be

assessed. In addition the same children performed the task one year later allowing long-term repetition effects to be examined. This is a much longer time interval than most studies examining test-retest reliability (Archibald & Kerns, 1999; Bishop et al., 2001; Isquith et al., 2005; Kuntsi et al., 2001; Lowe & Rabbitt, 1998). This adds a further complication in that after a year, performance on the task is likely to have changed simply by virtue of the fact that the children are a year older. The maturational changes can be separated from practice effects by comparing children of the same age who either have or have not performed the task before.

We expected that performance would improve in the short-term while the task was still easily recalled. We had originally hypothesised that one year later, when the task was no longer actively familiar, the influence from previous testing sessions would have declined, which is why we carried out Experiment 2a on the same group of children as Experiment 1. However, the fact that not all age groups demonstrated switch costs in Experiment 2a suggest that switch costs were greatly reduced. As children of the same age showed switch costs in Experiment 1 but not 2a we predicted that, in addition to maturational factors, having performed the task previously would also affect children's task-switching performance one year later.

Method and Results

For each child who participated in both Experiments 1 and 2a ($n=70$) switch costs (mean RT on switch trials – mean RT non-switch trials) were calculated for session 1 of Experiment 1 (Time 1a), session 2 of Experiment 1 (Time 1b), and the Football version from Experiment 2a (Time 2). Four outliers with switch costs greater than 3 *SD* above the mean were identified, three at Time 1b and one at Time 2. The analyses were performed both with and without these participants but as the pattern of results did not change they were kept in the analyses. The switch costs

were entered into a mixed-measures ANOVA with Time (Time 1a, Time 1b, Time 2) as a within-subject factor and Year Group at Time 2 (Year 2_{T2}, Year 3_{T2}, Year 4_{T2}, Year 5_{T2}, Year 6_{T2}) as a between-subjects factor.

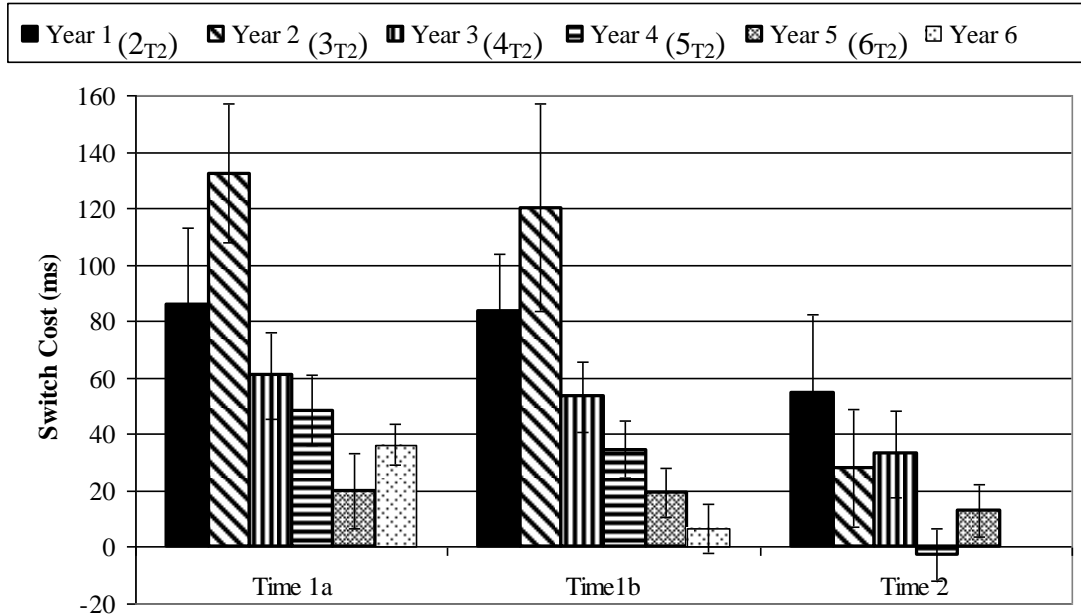


Figure 2.6: Mean (SE) switch costs at each time point. Years represent age at Time 1 with age at Time 2 in brackets

As shown in Figure 2.6, switch costs reduced with age, $F(4, 65)=6.22$, $p<.001$, $\eta^2=.277$. A significant main effect of Time, $F(1.96, 127)=9.39$, $p<.001$, $\eta^2=.126$, showed that switch costs also reduced over time. Tests of simple effects showed that switch costs at Time 2 were smaller than at both Time 1a and Time 1b. There was no Time x Year Group interaction, suggesting a reduction in switch costs over time for all age groups.

The reduction in switch costs over time may be due to prior experience on the task, but it could also be because the children were a year older. To try and separate these factors, switch costs for each year group at Time 2 were compared to the switch costs at Time 1a shown by children of the same age (see Table 2.2). This

compares children of the same age performing the task for the first vs. third time.

For example Year 3_{T2} would be compared with Year 4_{T2} who would have been in Year 3 at Time 1.

Table 2.2: To determine the relative contribution of age and experience on switch costs at Time 2, the performance of each year group at Time 2 was compared to how the year group above them performed at Time 1a. Time 1a shows the year group who were performing the task for the first time. Time 2 shows the year group performing the task for the second time.

<u>Time 1a</u>			<u>Time 2</u>		
Year Group	<u>Switch Cost</u>		Year Group (Group at Time 1)	<u>Switch Cost</u>	
	<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>
Year 2	132	88.7	Year 2 _{T2} (Year 1)	54.9	103
Year 3	60.8	58.6	Year 3 _{T2} (Year 2)	27.9	74.8
Year 4	48.6	46.2	Year 4 _{T2} (Year 3)	33.1	59.8
Year 5	20.1	49.7	Year 5 _{T2} (Year 4)	-2.71	34.2
Year 6	36.4	28.8	Year 6 _{T2} (Year 5)	13.1	35.1

As the same groups of children contributed to the switch cost at Time 1 in one year group, but to Time 2 in another year group, the data were analysed using separate independent t-tests for each year group. These demonstrated that switch costs were reduced at Time 2 compared to Time 1a for children in Year 2_{T2}, ($t(25)=2.09$, $p<.05$), although there was also a trend towards this for Year 6_{T2} ($t(27)=1.96$, $p=.06$). There were no significant differences for the other year groups (Year 3_{T2}: $t(26)=1.28$; Year 4_{T2}: $t(27)=0.78$; Year 5_{T2}: $t(26)=1.42$).

These results suggest, that for some age groups at least, the effects of performing the task previously lasted over a very long period of time, and that the differences between Times 1 and 2 are not simply due to the fact that the children are older. This is supported by the occurrence of negative switch costs seen in many

children at Time 2, which were very rarely observed at Time 1a. Interpretation of these results is difficult however, given that if the Bonferroni correction for multiple comparisons is applied, none of these results would remain significant. This conservative approach may lead to a Type II error however, especially as detecting differences between time points is made difficult by the huge amount of variability in switch costs within age groups.

These results show that as a group, switch costs were much smaller one year later. To examine the stability of individuals' switch costs across the different time points, Pearson product-moment correlations were used. Switch costs between Time 1a and Time 1b correlated ($r(70) = .31, p < .01$), however there was no relationship between Time 1a and Time 2, ($r(70) = .14, ns$). Performance at Time 1b and Time 2 ($r(70) = .31, p < .01$) correlated, although this was no longer significant when the outliers greater than 3 *SD* above the mean for each condition were removed ($r(66) = .23, ns$). This suggests that while performance on the same task-switching paradigm is relatively stable over a few days, using the test with the same stimuli a year later does not give a reliable measure of switching performance.

Discussion

Experiment 2b sought to examine the stability of task-switching performance in the same group of individuals over time. The results confirmed our suspicions, raised in Experiment 2a, in showing that switch costs were greatly reduced at Time 2 compared to Time 1a and Time 1b. These results suggest that the task-switching paradigm may be similar to other executive tasks in that the executive skills involved in performing the task are most important when the situation is novel. The results also support our argument in the discussion of Experiment 1 that Kray et al. (2004)

found small switch costs at all ages, and therefore no significant differences between the groups, because they had already completed the task in a previous experiment.

The reduction in switch costs at Time 2 could simply be due to the fact that the children were a year older. However, even the oldest group in Experiment 1 showed a significant switch cost, while the oldest group in Experiment 2a did not. This suggests that effects of prior testing were also playing a role. To investigate this, children of the same age were compared performing the task for the first or the third time. While the ANOVA suggested a reduction in switch costs over time for all age groups, the t-test analyses showed that task repetition effects played a significant role in reducing switch costs for the youngest and oldest groups of children. The large reduction in switch costs between Time 1a and Time 2 for the 5- to 7-year-olds supports Schouten et al.'s (2000) finding that younger children benefit most from practice. Furthermore, these results are consistent with findings from the older adult literature which show that practice is, counter-intuitively, greater for less able than more able individuals (e.g. Lowe & Rabbitt, 1998). The significant difference for Year 6_{T2} may have been driven by the relatively large switch costs shown by the year 6 children at Time 1a (see Figure 2.6), who did not take part in Experiment 2.

A significant difference between the children performing the test for the first compared to the third time was not found for Years 3_{T2} to 5_{T2}; however this may have been due to a lack of power. It is important to note that the analyses used in this experiment to separate the effects of age and practice were not ideal because each year group at Time 1 contributed as the control group for the previous year at Time 2. This meant that separate analyses had to be performed for each year group, reducing the power of the analyses. It was not feasible to recruit a separate control group at Time 2 for this experiment; however this would have been the best way to

confirm that practice effects were partly responsible for the reduction in switch costs one year later.

We were surprised to find that there were lasting effects of prior testing on the task-switching paradigm one year later. While a re-test interval this long has not been used with executive tests before, M. Anderson, Reid and Nelson (2001) tested children on an inspection time task five minutes after the initial testing session and again one year later. They found that performance had greatly improved one year later compared to both the initial testing session and the second session five minutes later. They showed that this was largely due to the effects of prior testing rather than maturational factors. As with our experiment, after a year it is unlikely that the effect of prior experience is due to familiarisation with specific features. It is not clear what is causing these large year-long carryover effects: Anderson et al. suggested that exposure to a particular class of tasks may result in slow changes and reorganisation in underlying knowledge and strategic behaviour. Potentially, these factors may also underpin the long-term effects seen in this experiment.

While these results inform us about the changes in group performance over time, they do not shed any light on how consistent individual subjects were. To do this, the test-retest reliability of individual subjects' switch costs were also examined. Compared to the first session, switch costs for the Football version were moderately stable after a few days, although this would not be accepted as a satisfactory level for test-retest reliability (Kuntsi et al., 2001). There was no correlation between switch costs after a year, which is perhaps not surprising given the vast reduction in switch costs during this time. The results from this experiment suggest that as performance on the task-switching paradigm is affected by repeated administrations, it should be

used cautiously in longitudinal studies to measure the development of children's ability to shift attentional set.

General Conclusions

The experiments reported in this chapter examined the development of task-switching performance in mid-childhood. Experiment 1 extended the findings of lifespan studies and demonstrated that the ability to maintain two task and response sets in working memory, as well as to flexibly shift between them, improves during mid-childhood, consistent with the growing body of literature charting the development of set-shifting performance using a variety of experimental tasks (Chelune & Baer, 1986; Cinan, 2006; Crone et al., 2004; Dibbets & Jolles, 2006; Huizinga et al., 2006; Schouten et al., 2000; Welsh et al., 1991). Furthermore, an important related skill in this paradigm, inhibiting irrelevant information, also showed considerable improvement during this period as demonstrated by a reduced congruency effect in older children. It was particularly striking that the children showed interference from incongruent information not only on switch trials, but also in pure blocks where the irrelevant task was never performed. This was especially true for the younger children and suggests that they experience a larger amount of interference from the irrelevant task. Again this shows that there is a developmental improvement in the ability to ignore irrelevant information, which is an important aspect of successful task-switching performance. The role of irrelevant information, and the level at which it interferes, is explored further in Chapter 3.

Performance on the task improved with practice, and surprisingly experience with the task still had an effect on performance one year later, as shown in Experiment 2b. This has important implications for using the task as part of a longitudinal study, as switch costs one year later are greatly reduced. It suggests that

the task-switching paradigm may be similar to other executive tests in that it is most likely to tap into executive processes when the task is novel. While this may limit its use in longitudinal studies, if the benefits of experience with the task extend to other situations where set-shifting is required then it may suggest a possible use of the task-switching paradigm in training the ability to flexibly shift and control attention.

These experiments suggested that the task-switching paradigm does not conform to the standard criteria for a reliable test as performance was affected by a change in stimuli (Experiment 2a) and repeated administrations (Experiment 2b). However, given that the same group of children participated in all the experiments reported here, further experiments with a new sample are needed to confirm whether changes in stimuli affect task-switching, and also to clearly dissociate the relative contributions of age and experience on re-test performance.

Chapter 3: Stimulus and response conflict in task-switching

Experiment 1 showed that interference from the irrelevant task decreased with age. This suggests that as children get older they are better at resolving the conflict created by the tasks' overlapping stimulus-response mappings. However, as the tasks overlap at both the level of the stimulus and the level of the response it is difficult to determine the relative contribution of stimulus and response conflict. In this experiment we systematically manipulated the degree of overlap at both the stimulus and response level to investigate the independent and combined effects of stimulus and response conflict on children's task-switching performance. Task and order had a significant effect on children's performance. Furthermore, reducing the stimulus overlap increased stimulus conflict rather than decreasing it as intended. This made it difficult to draw general conclusions about stimulus and response conflict but demonstrated the complex interplay of factors that affect children's shifting performance.

The task-switching paradigm is a widely used measure of executive control that involves flexibly switching between two simple tasks. Switching to a new task results in a cost in RT as typically responses are slower when a new task is switched to than when a task is repeated. This is known as a *switch cost*. If an indication of the upcoming task is given in advance with enough time to prepare then the switch cost is reduced. This has been taken as evidence for an endogenous control system that can actively reconfigure the appropriate configuration of mental resources, or *task-set*, in advance (Rogers & Monsell, 1995). However, even with long preparation times, switch costs are rarely eliminated completely, leaving what is known as a *residual switch cost*. Rogers and Monsell (1995) argued that this is the result of a

second endogenous process that cannot take effect until triggered by stimulus attributes associated with the task.

An alternative explanation for the residual cost is that there are exogenous ‘bottom-up’ processes related to interference and priming of the stimuli and responses used for the tasks (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000; Koch & Allport, 2006; Waszak, Hommel, & Allport, 2003; Wylie & Allport, 2000). For example, there is likely to be persisting interference from the competing stimulus-response (S-R) mappings that were relevant on the previous trial (Allport et al., 1994). Increasing the time between a response and the subsequent trial allows the activation from the previous task to dissipate, thus reducing the switch cost (Allport et al., 1994; Cepeda, Kramer, & Gonzalez de Sather, 2001). In addition to this persisting interference, competing task demands can also be retrieved from memory, cued by the presentation of stimuli previously associated with these demands (Allport & Wylie, 2000; Koch & Allport, 2006; Waszak et al., 2003; Wylie & Allport, 2000). These bottom-up processes may be particularly important when a small set of stimuli is used, as there should be stronger links between specific stimuli, tasks and responses than if a large stimulus-set is used (Kray & Eppinger, 2006).

The specific tasks that are used in a task-switching paradigm can have an interesting effect on switch costs. If the two tasks differ in their familiarity or difficulty then a larger switch cost is often seen when switching to the stronger task. This has been found for word reading compared to colour naming in the colour-word Stroop task (Allport et al., 1994; Allport & Wylie, 2000; Wylie & Allport, 2000) and also for decisions based on the colour of an object compared to its shape (Ellefsen, Shapiro, & Chater, 2006). This counter-intuitive finding has been attributed to

greater persisting interference from the stronger task than the weaker task, such that extra inhibition of the stronger task is needed in order to perform the weaker task. This inhibition then has to be overcome when the stronger task is switched back to, resulting in a longer reaction time (Allport et al., 1994).

One of the main features of the task-switching paradigm is that the stimuli and responses are *bivalent*. In other words, the same stimuli and responses are used for both tasks. Attention has to be switched between two dimensions of the same stimulus, such as the colour and shape, and the same two response keys are then used to make decisions on both of these dimensions, creating conflict between the two tasks. The influence of conflicting response mappings on switch costs is well established in the task-switching literature. Overlapping stimulus-response mappings creates some trials on which responses are *congruent*, where both tasks indicate the same response, and some that are *incongruent*, where conflicting responses are involved. Responses are typically faster on congruent trials than on incongruent trials. This is taken as evidence that stimulus-response mappings for both tasks are activated, even though one is irrelevant. Furthermore, this *congruence effect* interacts with the switch cost, with larger switch costs on incongruent trials. This suggests that switching task is harder when there is increased response conflict.

There is some evidence to suggest that children are particularly susceptible to interference from these lower-level processes in task-switching. Cepeda, Kramer and Gonzalez de Sather (2001) found that while adults benefited from increasing the time between the response and the subsequent trial, children did not, suggesting that children experience difficulty overcoming interference from previous S-R mappings. This was supported by their finding that children experience greater congruence effects. We report a similar finding in Experiment 1, which showed that the

influence of incongruent response mappings decreased with age during mid-childhood. Further evidence that children experience greater interference from irrelevant stimulus-response mappings comes from a study by Crone, Bunge, van der Molen and Ridderinkhof (2006). They found that children show a greater reversed repetition effect than adults as they find it harder to switch to a new task when repeating the same response, compared to switching both task and response. Crone et al. suggested this is because children experience greater carry-over effects from the previously activated S-R associations.

The ability to switch to a different task is clearly greatly affected by bottom-up interference and priming effects. Indeed, switch costs seem largely dependent on the conflict created by bivalent stimuli and responses as they are greatly reduced when there is no overlap between the two tasks (Kray & Eppinger, 2006; Mayr, 2001; Rogers & Monsell, 1995). As tasks typically conflict at the level of both the stimulus and the response, it is difficult to determine the relative contribution of stimulus and response related conflict in switching tasks. However, studies manipulating the extent of either stimulus or response conflict have attempted to answer this question.

Stimulus and response conflict in adults

Meiran (2000) proposed that stimulus and response conflict have independent effects on task-switching. He put forward a model whereby representations of stimuli and responses contributed to independent task sets; a stimulus task set that controls the representation of the target stimuli, emphasising the relevant dimension compared to the irrelevant dimension, and also a response task set that controls the representation of available responses. Response selection is then achieved via the interaction of stimulus and response codes. Moreover, Meiran argued that stimulus

and response sets affect different components of the switch cost. He suggested that the preparatory component of the task-switching cost reflects the reconfiguration of the stimulus task set, which can be done in advance prior to task execution. In contrast the reconfiguration of the response set is only completed after responding and therefore contributes to the residual task-switching cost component. To test this model, Meiran performed a series of experiments manipulating the valency of both the stimuli and responses. In one experiment he inter-mixed univalent with bivalent task stimuli so that on univalent trials the task was unambiguous. When either the current or previous stimulus, or both, was univalent the switch cost was relatively small and not influenced by the preparation interval suggesting that on these trials the stimulus task set does not need to be reconfigured. A further experiment showed that the residual switch cost was reduced when separate response keys were used for both tasks, suggesting that the response mappings do not have to be reconfigured in this situation. Meiran's model has received some support in the literature (Brass et al., 2003; Crone et al., 2006; Koch & Allport, 2006; Sohn & Anderson, 2003) although evidence from fMRI has suggested that response recoding may not be independent from task preparation (Brass et al., 2003).

Further evidence that conflict at the level of the stimulus affects the time taken to switch to a new task comes from Allport and colleagues (Allport & Wylie, 2000; Koch & Allport, 2006; Waszak et al., 2003) who showed that stimulus-based priming of a competing task contributes to the switching cost. Allport and Wylie (2000) found that switch costs were much greater in response to stimuli that had also appeared in the context of the irrelevant task than those which had not. Furthermore, Waszak, Hommel and Allport (2003) found that stimulus-based priming occurred for congruent as well as incongruent stimuli suggesting that priming occurs at the task

level and is not confined to specific S-R associations. Consistent with Meiran's (2000) model, Koch and Allport (2006) found that stimulus priming was affected by manipulations of the preparation interval but not of the response-stimulus interval.

In contrast to these findings, Rubin and Meiran (2005) did not find an effect of stimulus conflict on switch costs when they compared univalent and bivalent target stimuli. They suggest the discrepancy in findings may be because Waszak et al. (2003) and Allport & Wylie (2000) used the alternating runs paradigm, however this explanation does not extend to Koch and Allport's (2006) results. An alternative explanation is that Rubin and Meiran used univalent responses in contrast to the typical bivalent responses used in the other studies. This suggests that there may be something important about concurrent conflict at both a stimulus and response level.

While they did not find any effects of switch costs, Rubin and Meiran (2005) did show an effect of stimulus conflict on mixing costs, the difference between RT in blocks of pure trials and blocks where both tasks were performed. Mixing costs are thought to reflect processes involved in the dual-task situation in general (Crone et al., 2006). From these results they argued that activation from the competing task in bivalent stimuli interferes with a task decision process that takes place on every trial in mixed blocks, including non-switch trials. This is consistent with Liston, Matalon, Hare, Davidson, and Casey (2006) who found that increased stimulus conflict slowed both switch and repeat trials, whereas increasing response conflict only affected switch trials.

Mayr (2001; Mayr & Bryck, 2007) proposed that separating tasks at a physical level makes task set representation more distinct, and as a result between-task interference is reduced. By manipulating both stimulus and response valence within the same paradigm, Mayr (2001) found that stimulus ambiguity had only a

small effect on switch costs, whereas response-set overlap did not affect switch costs. Stimulus and response valence had a greater effect on global selection costs, which are similar to the mixing costs described earlier. However, in this case, Mayr defined global selection costs as the difference between blocks of univalent and bivalent stimuli with two tasks performed in both conditions, rather than comparing blocks in which a single task is performed to blocks in which two tasks are performed, which is how global or mixing costs are usually calculated. Mayr found that older adults showed a greater difference between bivalent and univalent stimulus conditions than younger adults but only when the responses for the tasks were bivalent. Thus only when both the stimulus and response mappings for the two tasks overlapped, giving no information to help keep the task sets apart, did the older adults' most severe problems arise. This again suggests that it is the combination of stimulus and response conflict that is important.

A similar definition for global set selection costs was used by Mayr and Bryck (2007) who compared bivalent and univalent stimuli in a task with either overlapping or separate responses. Responses were made on a touchscreen by pressing one of two small squares inside a larger rectangle which served as the target stimulus. In one condition the stimulus was always presented in the same location, creating a situation where the responses overlapped for both tasks. In a second condition the location of the stimulus covaried with the task so that the responses were separate. Congruency effects for the bivalent stimuli were reduced in the second condition showing that separating the response locations for the two tasks reduced the conflict between them. There was a greater difference between bivalent and univalent stimuli in the single object condition, supporting Mayr's (2001) finding that greater global set selection costs are seen when the response locations

overlap. Again, the manipulations seemed to have less of an impact on switch costs: The switch cost in error rate was reduced on bivalent trials by separating the stimulus and response locations but this pattern was not found in the RT cost. One important confound in this study is that separating the response locations also involved separating the locations of the target stimulus, which may have independently contributed to reducing task-set conflict.

In summary, the adult task-switching literature provides mixed results as to the influence of stimulus and response conflict on switching task. Given that manipulations in parameters such as the stimuli used and the timing of events within a trial are known to influence the time taken to switch task, and these often vary between studies, it is not surprising that there are variations in findings. Nevertheless, the literature does show that under certain conditions processes at the level of the stimulus, and at the level of the response, contribute to the cost involved in switching to a different task.

Stimulus and response conflict in children

Although few studies to date have used the task switching paradigm with children, a similar test, the Dimensional Change Card Sort test (DCCS) is widely used with preschoolers. This involves sorting cards according to either the colour or shape of the picture on the card. There is only one switch involved in the DCCS, and it has been shown that while 4-year-olds have no problem sorting according to a new dimension, many 3-year-olds continue to sort using the previous rule (Kirkham, Cruess, & Diamond, 2003; Perner & Lang, 2002; Zelazo, Frye, & Rapus, 1996). The stimuli and responses for the two tasks overlap in a similar manner to the task-switching paradigm. A number of studies have addressed the effect of stimulus and response conflict on preschoolers' ability to switch and sort the cards by a new rule.

Reducing conflict at the stimulus level has been shown to help performance on the DCCS. Perner and Lang (2002) showed that compared to the standard version, children had no problem in a 'same-silly' game using univalent cards displaying one of two objects of the same colour. In the pre-switch 'same' game 3- and 4-year-olds had to match the card to the correct object but in the post-switch 'silly' game they had to reverse this response mapping. More children passed this task than the standard DCCS. Perner and Lang argued this was because the children no longer needed to re-describe the cards according to the new dimension. Findings from the intradimensional/extradimensional shift sub-test of the CANTAB battery also suggest that children are able to complete a reversal of response mappings within one dimension before they are able to switch their attention to a new dimension (Luciana & Nelson, 1998; 2002)

Brooks, Hanauer, Padowska and Rosman (2003) argued that there is a confound in Perner and Lang's experiment because as well as removing the need to re-describe the cards, they also reduced the complexity of the stimuli, which may have made it easier to selectively attend to the relevant dimension. Brooks et al. found that if the target stimuli varied on the irrelevant colour dimension, accuracy on the 'same-silly' game decreased. They argued that this is because children's difficulty lies in selectively attending to the relevant dimension rather than in re-describing the stimulus in a new way.

The findings of Brooks et al. (2003) have not always been replicated (Kloo, Perner, & Dabernig, 2007) However, several studies have shown that children are greatly affected by variation on an irrelevant dimension of a stimulus when making speeded classifications on another dimension, known as the Garner interference effect (e.g. Garner, 1970; Garner & Felfoldy, 1970). The interference from the

irrelevant dimension reduces with age (Ridderinkhof, van der Molen, Band, & Bashore, 1997; Shepp & Barrett, 1991; Strutt, Anderson, & Well, 1975), suggesting a developmental improvement in attentional control.

Interference from the irrelevant dimension is generally found to decrease if it is a property of a separate object, rather than a feature of the same stimulus as the relevant dimension (Garner & Felfoldy, 1970; Shepp & Barrett, 1991). Ridderinkhof, van der Molen, Band and Bashore (1997) found the typical pattern of increased interference and congruence effects for integrated compared to separated stimuli when colour was the relevant dimension. However, when colour was the irrelevant dimension, there was increased interference and congruence effects if colour was part of a separate object than if it was integral with the relevant orientation dimension. This suggests that interference effects are sensitive to the specific stimulus dimensions used and may not generalise from one stimulus dimension to the next.

The idea that separating stimulus dimensions onto separate objects reduces interference was used by Kloo and Perner (2005) to test the theory that children have problems in re-describing stimuli in the DCCS. They used cards where an outline of an object was presented next to a coloured circle so that the two dimensions were no longer properties of the same object. Kloo and Perner argued that in this condition there was no need to re-describe the stimulus as the children could switch their attention from the object with the relevant shape to the object of the relevant colour. There were three conditions in which the stimuli were (i) separated only on the cards to be sorted (test cards), (ii) separated only on the cards that marked the correct response locations (target cards) or (iii) separated on both the test and target cards. They found that performance improved when the dimensions on the test cards were

separated, but not when the target cards were separated. In contrast, Zelazo, Müller, Frye and Marcovitch (2003; Experiment 6) found that separating the test cards in a similar manner did not improve performance. In this case however, the stimuli were only separated on the test cards and not on the target cards that marked the correct response locations. Differences in the instructions used or the fact that Zelazo et al. only used one type of test card may explain the discrepancy in results.

The attentional inertia theory (Diamond & Kirkham, 2005; Kirkham et al., 2003; Kirkham & Diamond, 2003) is similar to the re-description theory (Kloo & Perner, 2005; Perner & Lang, 2002) in that it proposes that once children have thought of a stimulus in terms of one dimension, e.g. its shape, they have great difficulty in disengaging from this dimension. Diamond, Carlson and Beck (2005) proposed that if the two dimensions were not properties of the same object then this difficulty would be reduced. They included a condition whereby a black object was presented on a card with a coloured background. This was a more stringent test than that used by Kloo and Perner (2005) as there was less separation between the dimensions, meaning that the use of spatial attention was not as easily available as a strategy to select the relevant dimension. In addition, colour was a property of the background, surrounding the object on all sides, rather than a feature of a separate object. The dimensions were separated on both test and target cards. While there was no difference for 2½-year-olds, the performance of 3- and 3½-year-olds was significantly improved when the dimensions were separated. This supports the findings of Kloo and Perner (2005) suggesting that preschoolers find switching task easier when the same object does not have to be seen in two ways i.e. when stimulus conflict is reduced.

It should be noted that in these studies, even when the stimuli on the target cards were separated, the same two response locations were used for both tasks. Towse, Redbond, Houston-Price and Cook (2000) included a condition in the DCCS whereby four response locations were used so that responses for the two tasks did not overlap. Although this did not improve performance, this finding is difficult to interpret as the majority of children (91%) passed the standard version, meaning that there was not much room for improvement. However, in a sample of a similar age but with only a 10% pass rate on the standard condition, Rennie, Bull and Diamond (2004) also found that using univalent responses did not significantly improve performance. Taken together, these studies show that reducing response conflict does not help preschoolers to switch task on the DCCS.

The findings from the DCCS differ from adults in that separating the response locations for the two tasks does not appear to help switching performance in young children as it does in adults. In contrast, stimulus conflict does seem to play a large role in preschooler's ability to switch to a new dimension. Little is known about the influence of stimulus and response conflict on school age children's ability to flexibly switch attention, particularly in the task-switching paradigm. As mentioned earlier, Cepeda et al. (2001) and Crone et al. (2006) suggested that school-age children may be more influenced by interfering stimulus-response mappings than adults. These findings are supported by Ridderinkhof et al. (1997) who found that interference from both irrelevant stimulus dimensions and incongruent response mappings decreased with age. In Experiments 1 and 2a we showed that the influence of overlapping stimulus-response mappings in the task-switching paradigm had a smaller effect on the older children's performance. However, the relative contributions of stimulus and response conflict are unknown.

This experiment orthogonally manipulated stimulus and response conflict by varying the overlap of stimulus dimensions and response mappings in a version of the cued task-switching paradigm. The effects on both switching costs and congruency effects were examined. Our initial predictions were that stimulus and response conflict would have independent effects, so that separating stimulus and response dimensions would both reduce switch costs. Furthermore we predicted that these would have an additive effect so that performance was most improved when there was no conflict at either level between tasks. We also predicted that reducing response conflict would reduce the congruency effect as this is largely caused by overlapping response mappings. To determine if the effects of stimulus and response conflict change with age during this period we compared two groups of children, 5- to 7-year-olds and 9- to 11-year-olds. We expected that switch costs and congruency effects would be smaller in the older age group and that greater age-differences would be seen at high levels of stimulus and response conflict.

Method

Participants

Sixty children took part in the experiment, thirty 5- to 7-year-olds and thirty 9- to 11-year-olds. All children attended state primary schools in England. Bilingual children were excluded from the study and informed parental consent was obtained for all children who participated. Background information for all participants is presented in Table 3.1.

Table 3.1: Background information for participants

	<u><i>n</i></u>	<u>Gender</u>		<u>Age (years)</u>	
		Male	Female	<i>M</i>	<i>SD</i>
5- to 7-year-olds	30	14	16	6.37	0.58
9- to 11-year-olds	30	15	15	10.35	0.60

Materials and Procedure

The experimental task was created and controlled using e-prime software and run on a Dell laptop computer. The participants responded using an ELO touchscreen connected to the computer. The touchscreen was placed 270mm from the edge of the table with an ergonomic mouse mat centred in front of it which acted as a hand-rest.

The target stimulus was a picture of a cupcake presented on a dark red screen along with a number of shopping baskets which served as the response locations. A response was made by touching the basket that matched the cake. The cakes varied on two dimensions: colour (purple or green), and the shape on top of the cake (flower or star). As shown in Figure 3.1, the level of overlap for the two stimulus dimensions was manipulated so that either the shape itself was coloured and the top of the cake was white (integrated stimulus: SI) or the top of the cake was coloured and the shape on top was white (separated stimulus: SS). This was similar to the stimulus separation used by Diamond et al. (2005) where the shape is a property of the foreground and the colour a property of the background.

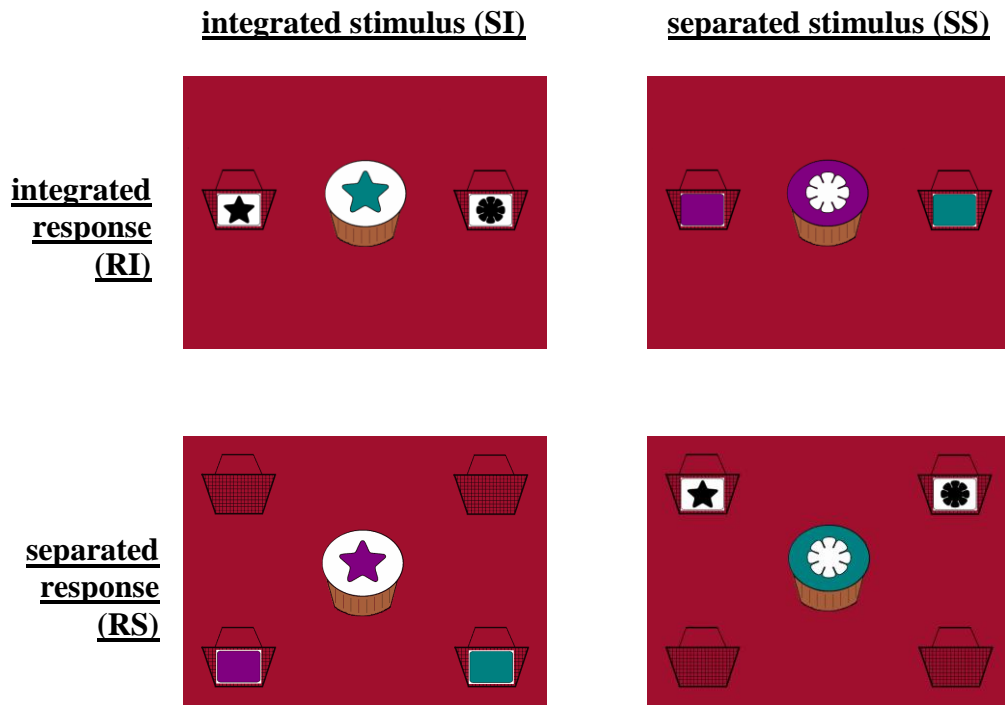


Figure 3.1: Example of the four conditions used in the experiment

The cake was matched to a basket on the basis of either its colour or its shape according to a cue presented at the start of the trial. The cues consisted of rectangles superimposed on the shopping baskets at the possible response locations. Response overlap for the two tasks was also manipulated. In the integrated response (RI) condition there were only two shopping baskets, presented centrally either side of the cake. In the separated response (RS) condition four shopping baskets were presented, one in each corner of the screen. If the cake was to be matched on colour then in the RI condition a purple rectangle was displayed on the left basket and a green rectangle on the right. In the RS condition the colour cues were displayed on the bottom two baskets. If the cake was to be matched on its shape then a solid black star was displayed on a white rectangle on the left basket, and a solid black flower was displayed on a white rectangle on the right basket. In the RS condition these were presented on the top two baskets.

The experiment was carried out in a quiet area of the child's school and split across two sessions at least one day apart. The four conditions were combined to create four blocks of trials:

- separated stimulus, separated response (SS, RS)
- separated stimulus, integrated response (SS, RI)
- integrated stimulus, separated response (SI, RS)
- integrated stimulus, integrated response (SI, RI)

In Session A the SI, RS block was administered first followed by the SI, RI block. The two blocks were separated by approximately ten minutes during which time other tasks (not reported in this chapter) were administered. In session B the SS, RI block was followed ten minutes later by the SS, RS block. The order in which the two sessions were completed was counterbalanced across participants so that half the children completed Session A followed by Session B (order one), and the other half completed Session B first (order two). Unlike Experiments 1 and 2 the children did not complete any pure blocks of trials in which only one task was performed.

At the start of each block a series of instruction screens were presented to the child to explain the task: The baskets were displayed first followed by a cue for one of the tasks. Two target stimuli were then shown in succession, one matching each basket, and the child had to show the experimenter which basket that cake matched. This was then repeated for the other task.

During the testing phase the baskets were always present on the screen. At the start of a trial the cues appeared for 500ms, followed by the target stimulus. The task (colour, shape) and the target were selected randomly with equal probability on each trial. The cues remained on the screen after the target appeared and a response was then made by touching the cue that matched the cake as fast as possible. In the

RS condition it was emphasised to the child that they must touch a basket that had a picture on it and not an empty basket. The interval between the response and the start of the next trial was 1000ms and the children were asked to return their hand to the hand-rest during this time. The children completed eight practice trials followed by 112 test trials in each block. Halfway through and at the end of each block a feedback screen displayed how many correct responses the child had made.

Results

Switch trials were defined as trials on which the task differed from the task on the previous trial. Non-switch trials were defined as trials on which the task was the same as the previous trial. The trials were also coded for response congruence. Even when response locations were separated, stars and purple stimuli always required a response on the left hand side of the screen, while flowers and green stimuli always required a response on the right hand side of the screen. A congruent trial was defined as a trial where both dimensions of the target required a response on the same side of the screen. An incongruent trial was defined as a trial where the two dimensions indicated responses on opposite sides of the screen.

The first two trials of each block were treated as 'warm-up' trials and were not analysed. In addition, any trial on which more than one touchscreen response was recorded was treated as an equipment failure and excluded. There were 205 such trials, which amounted to 0.75% of the total number of trials. Overall, errors were rare, and only occurred on 0.96% of trials. As such error rates were not analysed further and error trials were excluded from RT analysis. The RT was measured from the time the target appeared until the response was made. The median RT was calculated for each participant for each condition. Means for all conditions are presented in Appendix II.

To explore the effects of gender and order on performance a five-way mixed-measures ANOVA was performed with Age Group (5- to 7-year-olds, 9- to 11-year-olds), Gender (male, female) and Order (one, two) as the between-subject factors, and Response Overlap (RI, RS) and Stimulus Overlap (SI, SS) as the within-subject factors. There was no effect of Gender on performance, $F(1, 52)=.204$, *ns*. While there was no main effect of Order, $F(1, 52)=.217$, *ns*, both Response Overlap and Stimulus Overlap interacted with Order separately (Response Overlap: $F(1, 52)=22.5$, $p<.001$, $\eta^2=.302$; Stimulus Overlap: $F(1, 52)=15.5$, $p<.001$, $\eta^2=.230$). For the Response Overlap by Order interaction, those who did Session A first were faster at RI blocks ($M=1049$, $SD=282$) than RS blocks ($M=1087$, $SD=284$), while those who did Session B first were faster at RS blocks ($M=999$, $SD=278$) than RI blocks ($M=1043$, $SD=278$). Thus it appears that the children were slower in the type of response condition that they completed first. This may indicate practice effects with an increase in overall speed as the children gained more experience with the tasks. For stimulus overlap there was no significant difference in speed between SS ($M=1055$, $SD=303$) and SI ($M=1087$, $SD=274$) blocks for those children who did Session A first while for those who completed Session B first were slower on SS blocks: ($M=1061$, $SD=273$) than on SI blocks ($M=978.6$, $SD=268$). This suggests that the children were also slower in the stimulus overlap condition they completed first if this was the SS condition.

A significant main effect of Age Group, $F(1, 52)=61.7$, $p<.001$, $\eta^2=.54$, showed that the 9- to 11-year-olds ($M=852.6$, $SD=139$) responded significantly faster than the 5- to 7-year-olds ($M=1249$, $SD=228$). There was also a significant interaction between Response Overlap, Stimulus Overlap and Age Group, $F(1, 52)=4.31$, $p<.05$, $\eta^2=.077$, due to slightly different patterns of response times across

the four conditions for the two age groups. Separate two-way ANOVAs comparing Response Overlap and Stimulus Overlap for each age group showed no difference between blocks for the younger children $F(1, 29) < 1$, *ns*, but a significant Response Overlap by Stimulus Overlap interaction for the older children, $F(1, 29) = 13.0$, $p = .001$, $\eta^2 = .310$. This was due to slightly faster RTs in the SI, RI block ($M = 824.5$, $SD = 28.0$) than the SS, RI ($M = 872.1$, $SD = 26.4$) and the SI, RS ($M = 858.8$, $SD = 29.2$) blocks.

Switch costs and congruence

The effects of response and stimulus overlap on switch costs and congruence were first analysed using a five-way mixed-measures ANOVA. The between-subjects variable was Age Group (5- to 7-year-olds, 9- to 11-year-olds) and the within-subject variables were Trialtype (switch, non-switch), Congruence (congruent, incongruent), Response Overlap (RI, RS) and Stimulus Overlap (SI, SS). As the effects of Age Group on performance have already been discussed, they will not be mentioned in this section, apart from where they interact with other factors. An additional ANOVA including Order as a between-subjects variable was also performed. However as it had no effect on performance in addition to those already mentioned it has not been included as a factor in the following analyses.

There was a significant main effect of Trialtype, $F(1, 58) = 62.1$, $p < .001$, $\eta^2 = .517$, showing that all children were faster on non-switch trials ($M = 1032$, $SD = 263$) than on switch trials ($M = 1070$, $SD = 286$), as would be expected in a task of this nature. The Trialtype effect interacted with Age Group, $F(1, 58) = 18.1$, $p < .001$, $\eta^2 = .238$, due to a larger difference between switch and non-switch trials (switch cost) in the younger children (57 ms) than the older children (17ms). Switch costs for both age groups were significant. It is possible that this difference occurred solely due to

the baseline differences in speed between the two groups. Therefore the analyses were also performed with mean log RT as the dependent variable as this is less affected by baseline differences in performance (Kray, Li, & Lindenberger, 2002; Kray & Lindenberger, 2000; Meiran, 1996). The log RT analysis also showed a significant Trialtype x Age Group interaction, $F(1, 58)=7.6$, $p<.01$, $\eta^2=.116$, suggesting that the age difference was not just due to differences in baseline speed. Overall the log RT analyses showed a similar pattern of results and will only be mentioned further where they add to the median analyses.

Contrary to our predictions, manipulations of either response overlap or stimulus overlap alone had no effect on switch costs. There was a trend towards a three-way interaction between Response Overlap, Stimulus Overlap and Trialtype, $F(1, 58)=3.57$, $p=.064$, $\eta^2=.058$. However, this was not significant when log RT was used as the dependent variable, $F(1, 58)<1$, *ns*. A test of simple effects showed significant switch costs for all blocks except the SS, RS block (see Figure 3.2). This suggests that it is only when there is no overlap whatsoever between tasks that children find switching task easier. The influence of stimulus and response overlap on switch costs was the same for both age groups of children, $F(1, 58)=1.44$, *ns*.

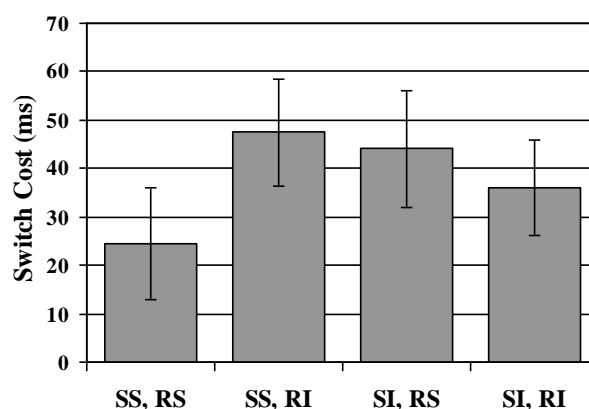


Figure 3.2: Mean switch cost (SE) in each of the four conditions.

As shown in Figure 3.3, the children were faster on congruent trials ($M=1044$, $SD=275$), where both tasks required a response on the same side of the screen, than on incongruent trials ($M=1058$, $SD=275$), where the two tasks required responses on different sides of the screen, $F(1, 58)=9.18$, $p<.01$, $\eta^2=.137$. Congruence interacted with Trialtype, $F(1, 58)=6.60$, $p<.05$, $\eta^2=.102$, such that there was a larger difference between congruent and incongruent trials for switch trials (congruent: $M=1056$, $SD=283$; incongruent; $M=1083$, $SD=293$) than for non-switch trials (congruent: $M=1031$, $SD=269$; incongruent; $M=1034$, $SD=259$ 1034). Congruence did not interact with Age Group, $F(1, 58)<1$, ns , in contrast to Experiment 1.

The results suggested that a congruence effect was only present in the high response overlap condition, as shown by a trend towards an interaction between Response Overlap and Congruence, $F(1, 58)=3.24$, $p<.077$, $\eta^2=.053$. This shows that separating the responses reduced the interference between the two tasks. Reducing response overlap affected the congruence effect in both age groups equally, $F(1, 58)<1$, ns .

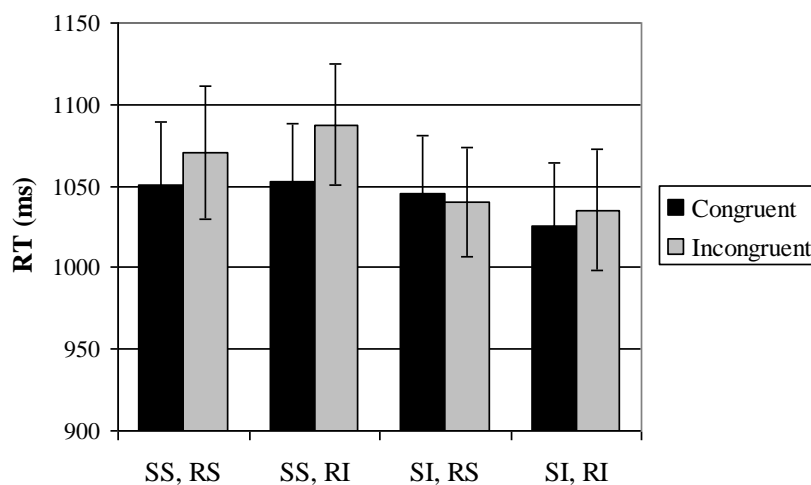


Figure 3.3: Mean RT (SE) showing congruence effects in the four conditions

An interaction was also found between Stimulus Overlap and Congruence, $F(1, 58)=6.89$, $p<.05$, $\eta^2=.106$. This was due to a congruence effect in the SS condition but not in the SI condition. This result is surprising given that we expected separating the stimulus dimensions would reduce conflict, not increase it. This suggests that our manipulation of stimulus conflict had not worked in the way we had intended. A three-way interaction between Stimulus Overlap, Congruence and Age Group showed that this effect was only present in the younger children, $F(1, 58)=7.16$, $p=.01$, $\eta^2=.110$. Furthermore, a marginally significant three-way interaction between Trialtype, Congruence and Stimulus Overlap, $F(1, 58)=4.38$, $p<.05$, $\eta^2=.070$, showed that separating the stimuli slowed both congruent and incongruent non-switch trials but only slowed incongruent switch trials.

This first set of analyses suggested that reducing stimulus and response overlap had a combined effect on switch costs, while congruence effects seemed to be driven by response conflict. Contrary to prediction, these effects were not modulated by age, suggesting that stimulus and response overlap have a similar effect on task-switching performance throughout mid-childhood. Surprisingly, separating the stimulus dimensions increased, rather than reduced the congruence effect in the younger children, suggesting that our manipulation of stimulus conflict had not worked in the way we intended.

Given that using colour and shape tasks showed asymmetric switch costs in Experiment 1 as well as in other studies in the literature (Ellefson et al., 2006), we decided to examine the effect of stimulus and response overlap for each task separately. This revealed that the influence of stimulus and response overlap was task specific. Furthermore, while order had not interacted with any factors other than overall speed when the tasks were combined, when the tasks were analysed

separately order was found to be an important mediator in the influence of stimulus and response overlap. The new analyses also helped to elucidate the unexpected effects separating the stimulus dimensions had on children's performance. Below we report the effects of stimulus and response overlap for each task separately. Means for all conditions can be found in Appendix II.

The influence of task and order

We first carried out a two-way repeated-measures ANOVA with Trialtype (switch, non-switch) and Task (colour, shape) as factors to check whether switch costs in the two tasks differed. Responses were faster for the colour task ($M=1024$, $SD=267$) than the shape task ($M=1094$, $SD=293$), $F(1, 59)=63.6$, $p<.001$, $\eta^2=.519$, suggesting that the children found the colour task easier. The interaction between Trialtype and Task approached significance, $F(1, 59)=3.84$, $p=.055$, $\eta^2=.061$, demonstrating a larger switch cost in the colour task (49ms) than the shape task (30ms). This is consistent with the results in Experiment 1 and Ellefson et al. (2006) in showing asymmetric switch costs between colour and shape tasks. As a result of this we decided to examine the influence of stimulus and response overlap on switch costs and congruence effects for each task separately using a six-way mixed-measures ANOVA with Age Group (5- to 7-year-olds, 9- to 11-year-olds) and Order (one, two) as between-subjects factors and Trialtype (switch, non-switch), Congruence (congruent, incongruent), Response Overlap (RI, RS) and Stimulus Conflict (SI, SS) as within-subject factors.

For both the colour and shape task, there were significant main effects of Age Group (colour: $F(1, 56)=63.2$, $p<.001$, $\eta^2=.530$; shape: $F(1, 56)=63.0$, $p<.001$, $\eta^2=.529$), Trialtype (colour: $F(1, 56)=37.5$, $p<.001$, $\eta^2=.401$; shape: $F(1, 56)=21.4$, $p<.001$, $\eta^2=.276$) and also an interaction between Trialtype and Age Group (colour:

$F(1, 56)=8.72, p<.01, \eta^2=.135$; shape: $F(1, 56)=9.11, p<.01, \eta^2=.140$), confirming that switch costs for both tasks decreased with age.

Overall speed on both tasks was influenced by stimulus and response overlap. For the shape task only, there was a significant Response Overlap x Stimulus Overlap x Age Group interaction, $F(1, 56)=4.36, p<.05, \eta^2=.072$, reflecting the slightly different patterns of response times across the four blocks reported earlier. Responses on the shape task were also slower in the SS conditions ($M=1118, SD=314$) than in the SI conditions ($M=1069, SD=287$) as shown by a main effect of Stimulus Overlap, $F(1, 56)=8.79, p<.01, \eta^2=.136$.

The order in which the blocks were completed mediated the effects of stimulus and response overlap on overall speed in both tasks (Figure 3.4). Order interacted with Stimulus Overlap for both the colour task, $F(1, 56)=11.6, p<.001, \eta^2=.171$, and the shape task, $F(1, 56)=9.58, p<.01, \eta^2=.146$, such that for those who did Session A first there was no significant difference in speed between SI and SS conditions, while those who did Session B first were slower in the SS condition. This suggests that overall speed on the SS condition was only slower if separated stimuli were encountered in the first rather than the second session. Order also interacted with Response Overlap for both the colour task ($F(1, 56)=20.6, p<.001, \eta^2=.269$) and shape task ($F(1, 56)=13.3, p<.001, \eta^2=.192$) but with slightly different results in each task. For the shape task, the children were slowest in the response overlap condition they encountered in the first block. In the colour task there was a trend towards an interaction between Order, Response Overlap and Age Group, $F(1, 56)=3.93, p=.052, \eta^2=.066$, which showed that the 5- to 7-year-olds were also slower in the response overlap condition they encountered first for the colour task. For the 9- to 11-year-olds this was only true for the children who did a high response overlap

condition first. This is generally consistent with the finding from the previous analysis that suggested slower performance in the response condition first encountered, but it shows that this is partly dependent on the task that is being performed.

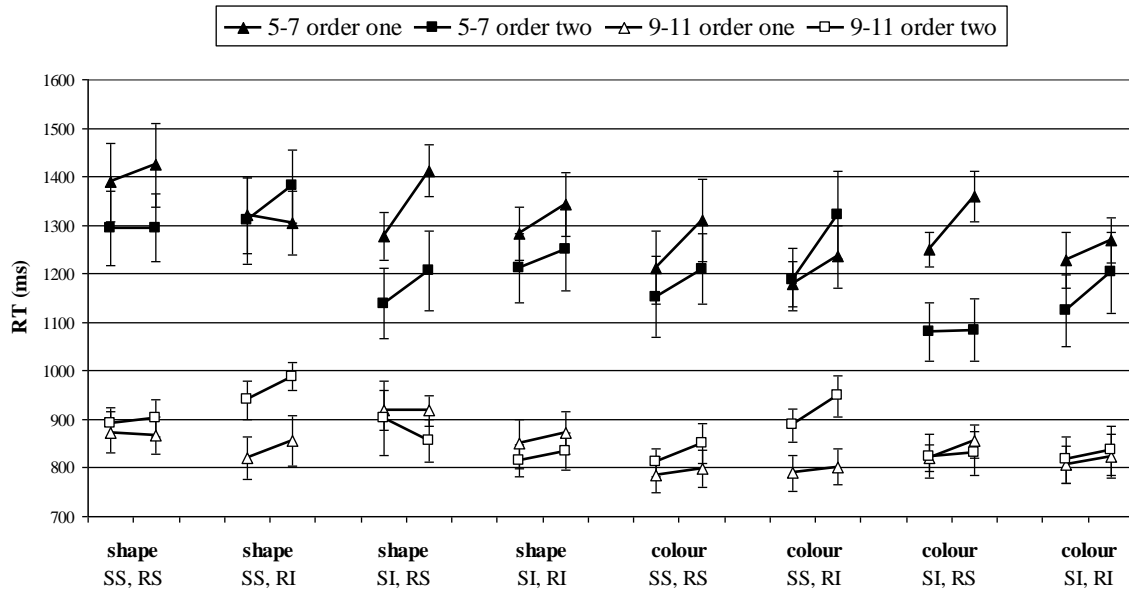


Figure 3.4: Mean RT (SE) for switch and non-switch trials in each condition as a function of age group and order. Within each pair, non-switch RT is on the left and switch RT on the right

The first analyses showed a trend towards a reduction in switch costs when both response and stimulus overlap were reduced. However, examining the results for the two tasks separately showed that the influence of stimulus and response overlap on switch costs was mainly seen on the shape task, with different effects for the two age groups. While reducing *stimulus* overlap on the shape task lowered switch costs in the younger children, $F(1, 56)=3.95$, $p=.052$, $\eta^2=.066$, reducing *response* overlap lowered switch costs in the older children, $F(1, 56)=6.46$, $p<.05$, $\eta^2=.099$. This could suggest that the older children were more influenced by response overlap on the shape task whereas the younger children were more influenced by stimulus overlap. However, as shown in Figure 3.4, separating

stimulus dimensions resulted in increased RTs on non-switch as well as switch trials for the younger children, giving the appearance of smaller switch costs.

The interaction between Response Overlap and Congruence found in the previous analysis seemed to be driven by the colour task only, $F(1, 56)=16.8$, $p<.001$, $\eta^2=.231$. Congruent trials ($M=1008$, $SD=261$) were generally faster than incongruent trials ($M=1039$, $SD=276$), and separating the responses reduced the congruence effect, $F(1, 56)=7.53$, $p<.01$, $\eta^2=.119$, however this did not interact with age, $F(1, 56)=2.17$, *ns*.

Despite there being no main effect of congruence on the shape task, $F(1, 56)<1$, *ns*, the Stimulus Overlap x Congruence interaction seen in the first analyses was present in the shape task only, $F(1, 56)=8.28$, $p<.01$, $\eta^2=.129$. This was due to the fact that responses were particularly slow on incongruent shape trials when the stimulus dimensions were separated (congruent: $M=1107$, $SD=314$; incongruent, $M=1129$, $SD=319$) but not when the stimulus dimensions were integrated (congruent: $M=1078$, $SD=300$; incongruent, $M=1061$, $SD=278$). Thus the congruence effect increased rather than decreased when colour was separated from shape. This shows that our manipulation of stimulus conflict did not work as we intended it to. In contrast to the first analyses, the Stimulus Overlap x Congruence interaction was not modified by either Age Group, $F(1, 56)=1.65$, *ns*, or Trialtype, $F(1, 56)=1.71$, *ns*.

Discussion

This experiment set out to systematically examine the effects of stimulus and response conflict on children's ability to switch between tasks. We reduced response conflict by separating the response locations for the colour and shape tasks. At a stimulus level we attempted to reduce conflict by making shape a property of the

foreground and colour a property of the background, following Diamond et al. (2005). However, far from reducing stimulus conflict, in certain situations this manipulation actually seemed to increase conflict, particularly on the shape task. In addition to this unexpected effect, we were also surprised to find that both the task and the order in which stimulus and response conflict were manipulated had such an impact. The children appeared to find the colour task easier than the shape task, and the presence of asymmetric switch costs also suggested that colour was the stronger task. As a result, there was much more interference from the colour task on the shape task than the other way round, particularly at the stimulus level. This made it very difficult to draw general conclusions about the influence of stimulus and response conflict on task-switching. Nonetheless, it is interesting to examine the complex interplay of factors that affect children's ability to switch task.

At a basic level, stimulus and response overlap were found to have a significant effect on overall speed, although this largely depended on the order in which the blocks were performed. The children who experienced the separated stimuli in the first session were slower in these conditions than when the stimuli were integrated. This may be because the children found the tasks more difficult with separated stimuli, so that if they did this condition first, then they found the subsequent joint condition easier. In contrast, practising the joint condition first made the separate condition less difficult. Responses were generally slower on the response overlap condition encountered in the first block, which may be indicative of practice effects. This was particularly evident in the younger children, however in the colour task, order had no effect on the responses separate condition in the older children. This may be because the older children found this condition relatively easy. The influence of order shows the importance of considering what are often

assumed to be unimportant factors. Further work using a more sophisticated manipulation of order would determine if these effects are driven by practice or if it is how the tasks are first encountered that determines the influence that separating the task dimensions will have.

Our initial prediction was that stimulus and response conflict would have independent but additive effects on switch costs. The first analyses did not show independent effects but a weak interaction pointed to reduced switch costs when stimulus and response dimensions were jointly separated. Further analyses revealed a more complicated pattern of results whereby reducing stimulus and response overlap seemed to have independent effects on switch costs. However, this depended on the relevant task and also the order in which the blocks were performed. Overall, separating the overlap of the tasks at a response level reduced the switch cost, and this had a greater effect if it was not done in the first block, suggesting it was most effective after practice with the tasks.

Switch costs were smaller in the older children, demonstrating that the ability to switch task improves during development. Further developmental differences were seen in the shape task where the two age groups showed different patterns of switch costs. The 9- to 11-year-olds showed a reduction in switch costs when the responses were univalent, whereas the 5- to 7-year-olds showed equivalent switch costs both when the responses were separated and integrated, suggesting that they still experienced interference from the colour task even when the responses were separated. This finding is interesting given that separating response locations has been shown to influence switch costs in adults (Brass et al., 2003; Meiran, 2000; but see Mayr, 2001) but not in preschoolers (Rennie et al., 2004; Towse et al., 2000). While this may be due to the paradigm used, or because response conflict has a greater

effect on RT than accuracy, it may indicate that as children get older, their ability to use univalent response mappings to separate task sets at a conceptual level improves.

While separating responses on the shape task did not reduce switch costs in the younger children, separating the stimulus dimensions did. This seems to conflict with another finding, that separating the stimuli increased the congruence effect on the shape task, which the first analyses indicated was particularly true for the younger children. It appears that separating the stimulus dimensions and putting colour as a property of the background made it more salient, increasing conflict between the tasks and creating interference on incongruent trials. The switch cost and congruence results can be reconciled by considering the fact that switch costs were only reduced when the stimulus dimensions were separated because non-switch trials were also slower. Therefore, this suggests that the younger children experienced interference from the colour task on all incongruent trials, whether a switch was required or not. Interestingly, the first analyses indicated that separating the stimulus dimensions also slowed congruent non-switch trials. Rubin and Meiran (2005) argued that activation from the competing task at a stimulus level interferes with a task decision process that takes place on every trial, including non-switch trials. However Mayr (2001) proposed that only older adults need to select a relevant task set on both switch and non-switch trials whereas young adults only do this on switch trials. A similar pattern seems to emerge in the shape task between younger and older children. While the younger children were slowed on both non-switch and switch trials when there was more task interference (in this case when the stimulus dimensions were separated), the older children only seemed to be slowed on switch trials, evidenced by the fact that their switch costs were not reduced.

Our prediction that separating the response locations would reduce the difference in RT between congruent and incongruent trials was supported. However this was only true for the colour task, showing that interference from the response mappings for the shape task was reduced when the responses were separated. In the shape task increased conflict from the colour task at the stimulus level may have counteracted the reduction in conflict caused by separating the response mappings. While manipulations of stimulus and response overlap did not appear to have additive or interactive effects, it is interesting to note that interference from the colour task on the shape task when the stimulus dimensions were separated was greater when the tasks also had incongruent response mappings, therefore there does seem to be some interaction between stimulus and response conflict.

Our results quite clearly showed a discrepancy in the interference between the two tasks. Interference from the colour task on the shape task was much larger than interference from the shape task on the colour task, and this mediated the influence of stimulus and response overlap on the two tasks. These results are very similar to those found by Ridderinkhof et al. (1997). Although they did not investigate switching, Ridderinkhof et al. found different patterns of interference on a colour task and an orientation task. There were larger interference and congruence effects on the colour task when the irrelevant dimension (orientation) was part of the same stimulus (vertical or tilted bar). However, consistent with our findings, interference from the colour task on the orientation task was greater when colour was a property of a square contour surrounding the bar. Together these findings show that two dimensions do not have to be part of the same object for conflict to occur. As colour is a particularly salient dimension which is likely to capture attention, separating it

from the relevant dimension may draw attention away from the target, slowing processing of the relevant task even more than if colour was part of the same object.

Given these findings, it is interesting that there are no task differences in the DCCS, where performance is equivalent for colour and shape, even when the stimuli were separated, as in our experiment. This may be because performance is measured by accuracy rather than RT. Another possible explanation is that in the DCCS only one task is performed per block, rather than continuous switching between tasks. It may be that the asymmetry in task interference only affects switch costs when it is necessary to keep both task sets actively maintained. It may be possible to test asymmetry in the DCCS however. Brooks et al. (2003) showed that irrelevant changes in colour can influence decisions about the shape of an object in the DCCS. If irrelevant changes in shape did not interfere with performance on the colour task, this would suggest that there was some asymmetry in conflict between the two tasks.

Different patterns of development were apparent for the colour and shape tasks. On the colour task, the manipulations of stimulus and response overlap were largely the same for both age groups. However, on the shape task the younger children seemed to experience more conflict from the irrelevant colour task, shown by increased interference from colour when it surrounded the shape, and the fact that separating the response dimensions did not reduce interference from the irrelevant mappings and make it easier to switch tasks. This suggests that while all children were able to overcome the interference from the shape task on the easier colour task, the younger children struggled when there was more irrelevant interference from the stronger colour task. Therefore the ability to overcome interference from previous S-R mappings improves during development. In contrast to Experiment 1 there was no

developmental change in the congruence effect itself. Arguably, this may have been masked by the stimulus and response overlap manipulations.

As a result of task differences, and the fact that by separating the stimulus dimensions we actually increased stimulus conflict rather than reduced it, addressing our initial hypotheses about the relative contribution of stimulus and response conflict was difficult. A better way to examine the effects of stimulus conflict may be to vary the perceptual similarity of the irrelevant feature, compared to a prototype used as the target feature, for example by using a paler shade of the same colour (Liston et al., 2006) or to use univalent stimuli.

Reducing the overlap between the tasks at a stimulus and response level did affect switch costs. This is in contrast to some findings from the adult literature (Mayr, 2001; Mayr & Bryck, 2007; Rubin & Meiran, 2005) which suggested that manipulating stimulus conflict had a greater effect on mixing costs than on switch costs. Mixing costs could not be examined in this experiment as all blocks contained a mixture of trials. However, given that stimulus overlap also affected non-switch trials on the shape task in the younger children, this would be an interesting avenue to pursue.

In conclusion, this experiment demonstrated that a number of different factors contribute to children's performance on the task-switching paradigm, affecting not only the ability to switch task but also to resist interference from the irrelevant task, both of which appear to improve with age. The results showed that the bottom-up interference and priming effects in the task-switching paradigm are largely dependent on the specific tasks that are used, making it difficult to generalise to other situations. Interference from colour was particularly high, even when it was separated from the relevant object. Thus while conflict at the level of the stimulus

and the response does play an important role in this paradigm, even more basic factors, such as the tasks used and the order in which conditions are completed, should not be overlooked.

Chapter 4: Self-ordered pointing as a test of working memory in typically developing children

In this experiment, typically developing children (5 to 11 years) and young adults performed two versions of the self-ordered pointing test (SOPT; Petrides & Milner, 1982), a measure of non-spatial executive working memory requiring the ability to generate and monitor a sequence of responses. One version of the task used pictures of familiar objects and the other hard-to-verbalise abstract designs. Performance improved with age but the children did not reach adult levels of performance. Participants of all ages found the object condition easier than the abstract condition suggesting that verbal processes are utilised by the SOPT. However, performance on the task was largely independent from both verbal and nonverbal cognitive ability.

As reviewed in Chapter 1, executive function is multi-dimensional, and includes a number of separable components. Chapters 2 and 3 concentrated on shifting, however in this chapter the focus changes to explore the development of executive working memory, investigated using the self-ordered pointing test (SOPT).

The SOPT was developed by Petrides and Milner (1982) as a test of working memory for patients with frontal lobe lesions. The task takes the form of a set of pictures of familiar objects or abstract designs, arranged in a grid. These are presented in a different spatial arrangement on each trial and the participant is required to point to a different picture every time. The test requires executive abilities in order to organise and carry out a sequence of responses as well as to retain and constantly monitor the responses made.

Given its reputation as an executive task, the SOPT has been used as a test of working memory with childhood clinical populations that demonstrate an executive deficit, such as children with phenylketonuria (Diamond, Briand, Fossella, & Gehlbach, 2004; Smith, Klim, & Hanley, 2000), attention deficit hyperactivity disorder (Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004; Scheres et al., 2004), oppositional-defiant disorder (van Goozen et al., 2004), and autism (Geurts et al., 2004; Joseph, Steele, Meyer, & Tager-Flusberg, 2005). The majority of these studies have administered the SOPT as part of a battery of executive tasks in order to determine which executive components are deficient in the population being studied. However, there are few developmental data available to interpret these results against the level of performance for typically developing children in different age groups.

Normative developmental data are available for a spatial version of the self-ordered pointing task, which relies on the same underlying principles as the SOPT but requires remembering a sequence of locations instead of a sequence of pictures. This is more widely available as a test of executive working memory in children (DeLuca et al., 2003; Hughes, Plumet, & Leboyer, 1999; Luciana & Nelson, 1998; 2002; Rhodes, Coghill, & Matthews, 2004) due to its inclusion in the Cambridge Neuropsychological Testing Automated Battery (CANTAB), a widely used measure of neuropsychological function. Normative data for the CANTAB were provided by Luciana and Nelson (2002) who showed that the executive working memory skills tapped by the spatial SOPT are not fully developed by 12 years of age. While the normative data from the spatial self-ordered task give us some information on the developmental trajectory of executive working memory skills, the non-spatial version may not follow the same pattern (Conklin, Luciana, Hooper, & Yarger, 2007). Although the tasks may share domain-general processes involved in

generating and organising the sequence of responses, there may be domain-specific processes involved concerning the aspect of the stimuli to be remembered (location vs. identity) which may develop at different rates. The non-spatial version of the task is also useful to use alongside the spatial version with clinical populations to determine if there is a general underlying deficit in monitoring and manipulation information in working memory, or a domain-specific problem dependent on the type of stimuli used.

Studies using the non-spatial SOPT in typically developing preschoolers (Hongwanishkul, Happaney, Lee, & Zelazo, 2005) and school-age children (Archibald & Kerns, 1999) have indicated that performance on the task improves with age. However, as these studies included the SOPT as part of a battery of tests, a detailed assessment of developmental changes is not provided.

Most researchers using this task with children have administered the task following Petrides and Milner (1982), presenting the stimuli on paper with three repetitions of the set sizes 6, 8, 10 and 12. However, the error score is often summed or averaged across set sizes and as a result, changes in performance as a function of task difficulty have not been addressed. The present study aimed to examine the effect of set size by including it as a factor in the analyses. Previous studies have also collapsed the results across the three repetitions. Unfortunately however, this may result in practice or interference effects being missed. We specifically examined the effect of task repetitions, labelled ‘games’, to determine if repeating the task had a beneficial or detrimental effect on performance. The reliability of performance across task repetitions was also investigated.

One aspect of the standard administration of the non-spatial SOPT which may be problematic when used with children is that when the pictures are arranged in a

grid, a high score can be obtained simply by repeatedly choosing the same location. This is prevented in adults using a verbal warning if the strategy is adopted, however this may be confusing to young children. To avoid this scenario, we presented the pictures in random locations which changed each time a response was required. This meant that it was not possible to consistently choose the same location.

Another factor that may influence task performance is the availability of verbal encoding and verbal rehearsal strategies. To explore this, our task compared performance in an object condition (where pictures were easy to name) and an abstract condition where pictures were very hard to label. Performance should be better in the object version of the task if children use verbal encoding to help remember the objects.

The level of verbal ability required by a task is an important factor to take into consideration when studying developmental populations who may have concomitant or comorbid language problems in addition to other deficits. Joseph, Steele, Meyer and Tager-Flusberg (2005) used the SOPT to test the hypothesis that children with autism are impaired in using verbal encoding and rehearsal strategies to aid working memory. Their results showed that the typically developing group (aged 5;10-13;10 years) found a condition with line drawings of objects significantly easier than an abstract condition, suggesting that verbal encoding was being used to help remember the objects. Furthermore, it appears that language ability is correlated with performance on the object condition of the SOPT, such that children with better language skills are more successful. Joseph et al. (2005) found that language level, measured by the Expressive Vocabulary Test (Williams, 1997) and the Peabody Picture Vocabulary Test (Dunn & Dunn, 1997) was significantly correlated with performance on the object condition, but not the abstract condition of the SOPT,

once age had been controlled for. The same relationship was shown by Hongwanishkul et al. (2005) in preschoolers and we predicted a similar pattern of results in our own experiment.

The role of language abilities in task performance may become more important with age as children become more reliant on verbal strategies such as rehearsal. We predicted that the older children in our experiment would benefit more from using verbal strategies in the object condition of the SOPT than the younger children, and therefore that we would find a greater difference in performance between the object and abstract conditions in the older children. This is supported by evidence that verbal rehearsal strategies are not used to aid memory for pictorial stimuli until after the age of 8 years (Halliday, Hitch, Lennon, & Pettipher, 1990; Hitch & Halliday, 1983).

In summary, the present study aimed to provide a more detailed analysis of SOPT performance in typically developing children. Prior to testing the children we tested a sample of adults to ensure that our modified task produced the expected pattern of results. This sample also acted as a comparison group to help determine the age at which children reach adult levels of performance. As well as examining changes over development, the effects of set size and task repetition manipulations were specifically examined. We predicted that performance would be better in the object condition than the abstract condition, due to the use of verbal labelling. Furthermore, we hypothesised that if the use of verbal strategies increases with age then the difference in performance between object and abstract conditions would also increase. On the basis of previous research (Hongwanishkul et al., 2005; Joseph et al., 2005) we predicted that language ability would correlate with performance on the object, but not abstract condition of the task.

Method

Participants

Ninety children and 15 young adults participated in this study. Data were collected from 15 children in each of the following British school year groups: Year 1 (5-6yrs); Year 2 (6-7yrs); Year 3 (7-8yrs); Year 4 (8-9yrs); Year 5 (9-10yrs) and Year 6 (10-11yrs). All of the children attended state primary schools and were selected at random by class teachers. Informed parental consent was received for all children that participated. Bilingual children and those with a statement of Special Educational Needs were excluded from the study. The young adults who participated were all students at Oxford University, some of whom received course credits for taking part. Background information for all participants is presented in Table 4.1.

Table 4.1: Participant characteristics

<u>Age Group¹</u>	<u>Gender</u>	<u>Age (yrs)</u>		<u>WASI</u>		<u>WASI</u>	
				<u>Matrices*</u>		<u>Vocabulary*</u>	
	Male:Female	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Year 1	7:8	6.01	.33	53.7	10.7	50.0	8.04
Year 2	7:8	6.81	.25	56.3	11.0	50.6	7.99
Year 3	8:7	8.13	.28	52.1	12.5	52.5	13.3
Year 4	9:6	9.15	.24	52.2	9.10	52.1	10.6
Year 5	7:8	10.1	.32	49.9	7.68	59.4	8.68
Year 6	7:8	11.0	.24	48.2	8.14	55.2	11.7
Adults	5:10	19.4	1.35	58.6	5.82	---	---

Note. ¹*n*=15 for all groups. *T scores: *M*=50, *SD*=10.

The Matrices and Vocabulary subtests of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) were completed by all children. As shown in Table 4.1, performance was close to average for all groups of children suggesting that the sample was representative of typically developing children. The adults completed only the Matrices subtest and as a group, they achieved scores in the high-average range.

Materials and Procedure

The experimental task was created and controlled using E-Prime software and run on a Dell laptop computer. The participants responded using an ELO touchscreen placed approximately 270mm from the edge of the table with an ergonomic mouse mat centred in front of it which acted as a hand-rest. The experiment was carried out in a quiet area in the school or university. The participants sat within comfortable reaching distance of the touchscreen and were asked to begin by placing their dominant hand on the hand-rest.

Participants were shown a set of pictures and were required to touch a different picture on each trial, until all of the pictures had been touched once. There were two versions of this task, one using line drawings of objects, and one using black and white abstract patterns. The line drawings were pictures of objects taken from the online database of the International Picture-Naming Project, Center for Research in Language, University of California, San Diego (Szekely et al., 2004). The objects were high frequency words with an early age of acquisition. The abstract pictures were kindly donated by Dr Louise Phillips at Aberdeen University following her use of the SOPT with older adults (Philips, MacPherson, & Della Sala, 2002). They were chosen as they were hard to verbalise. Examples of both sets of stimuli are shown in Figure 4.1.

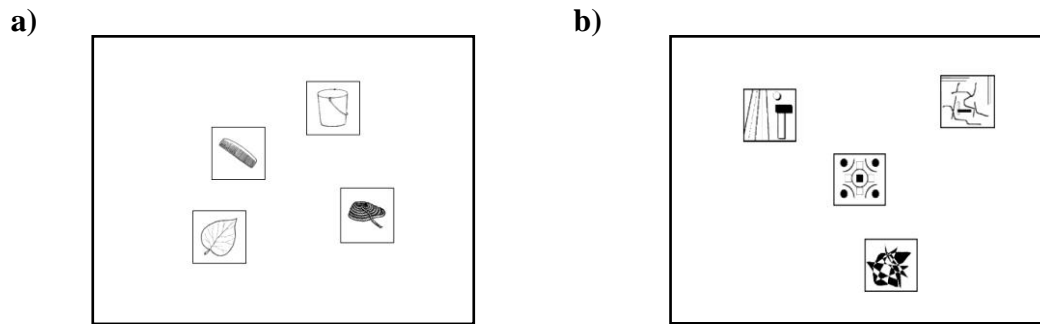


Figure 4.1: Examples of a) the object and b) the abstract stimuli used

Each picture measured 43 by 43 mm and was presented on a blue background. Set sizes of 4, 6, 8 and 10 pictures were used with a unique set of pictures for each set-size. The task was repeated three times at each set-size level to create three ‘games’, which differed only in the location of the pictures on the screen. To distinguish between these, each game began with a brightly coloured screen, displayed for 2000ms to tell the participant whether it was Game 1, 2 or 3 and another screen displayed ‘game over’ for 1000ms when they had touched the required number of pictures.

The children completed all conditions of the task in a fixed order. The participants were first shown a demonstration using four pictures of objects. They were then asked to perform the task themselves using first 4, then 6, 8 and 10 pictures of objects. This was then repeated for the abstract pictures but without the demonstration. Set size 4 was used as a practice and was therefore excluded from data analysis. No feedback was given to the participant at any stage of the task except to remind participants that they should not touch a picture which they had already touched. There were no time restrictions yet all children completed the task in approximately ten minutes.

Results

Performance on this task was assessed in two different ways. First, the number of errors was calculated, defined as touching a picture already selected. Second, following Joseph et al. (2005) span was also measured, defined as the number of consecutive novel responses prior to the first error. A one-way ANOVA showed that there was no effect of gender on the total error score ($F < 1$) for either children or adults. Therefore, gender was not included as a factor in further analyses. The Greenhouse-Geisser correction was used in all ANOVAs and the Games-Howell test was used for post-hoc comparisons. Means for all conditions can be found in Appendix III.

Reliability

To examine the consistency between the object and abstract conditions of the task, correlation and regression analyses were performed. The error rates for the two conditions correlated reasonably highly, $r(104) = .74$, $p < .001$. Once age was controlled, the number of errors on the abstract condition accounted for 24% additional variance in the object condition ($F(1,102) = 62.0$, $p < .001$) and the number of errors in the object condition accounted for a similar amount of unique variance in the abstract condition ($R^2 = .26$, $F(1,102) = 62.0$, $p < .001$). This suggests that the two conditions are tapping into some of the same processes. To assess internal reliability, Cronbach's alpha was computed for the error scores in Games 1, 2 and 3, collapsed across conditions. The reliability was acceptable with a value of $\alpha = .88$. This indicates that performance in the three games was consistent across individuals.

Adult data

To assess SOPT performance in adults a three-way repeated-measures ANOVA was run with either errors or span as the dependent variable. The within-subject factors were Condition (object, abstract), Set Size (6, 8, 10) and Game (1, 2, 3). The results are presented in Figure 4.2. Unsurprisingly, a significant main effect of Set Size (errors: $F(1.90, 26.6)=30.2$, $p<.001$, $\eta^2=.683$; span: $F(1.90,26.6)=50.9$, $p<.001$, $\eta^2=.784$) showed that even though span length increased with set size, more errors were made as more pictures were added. Fewer errors and longer spans were observed in the object condition (errors: $M=.47$, $SD=.26$; span: $M=7.14$, $SD=.50$) than in the abstract condition (errors: $M=1.15$, $SD=.46$; span: $M=5.70$, $SD=1.02$), as shown by a significant main effect of Condition (errors: $F(1,14)=39.6$, $p<.001$, $\eta^2=.739$; span: $F(1,14)=26.7$, $p<.001$, $\eta^2=.656$).

The main effect of Game was not significant in the adults; however there was a Condition x Game interaction (errors: $F(1.64, 22.9)=5.29$, $p<.05$, $\eta^2=.274$; span: $F(1.73,24.3)=4.11$, $p<.05$, $\eta^2=.227$). This was due to more errors and shorter spans in Game 1 than in Games 2 and 3 for the abstract condition, but no difference between games for the object condition. There was also a Set Size x Game interaction for the errors ($F(3.30, 46.2)=3.34$, $p<.05$, $\eta^2=.193$), however this was not significant when span was used as the dependent variable ($F(2.99, 41.9)=1.64$, *ns*).

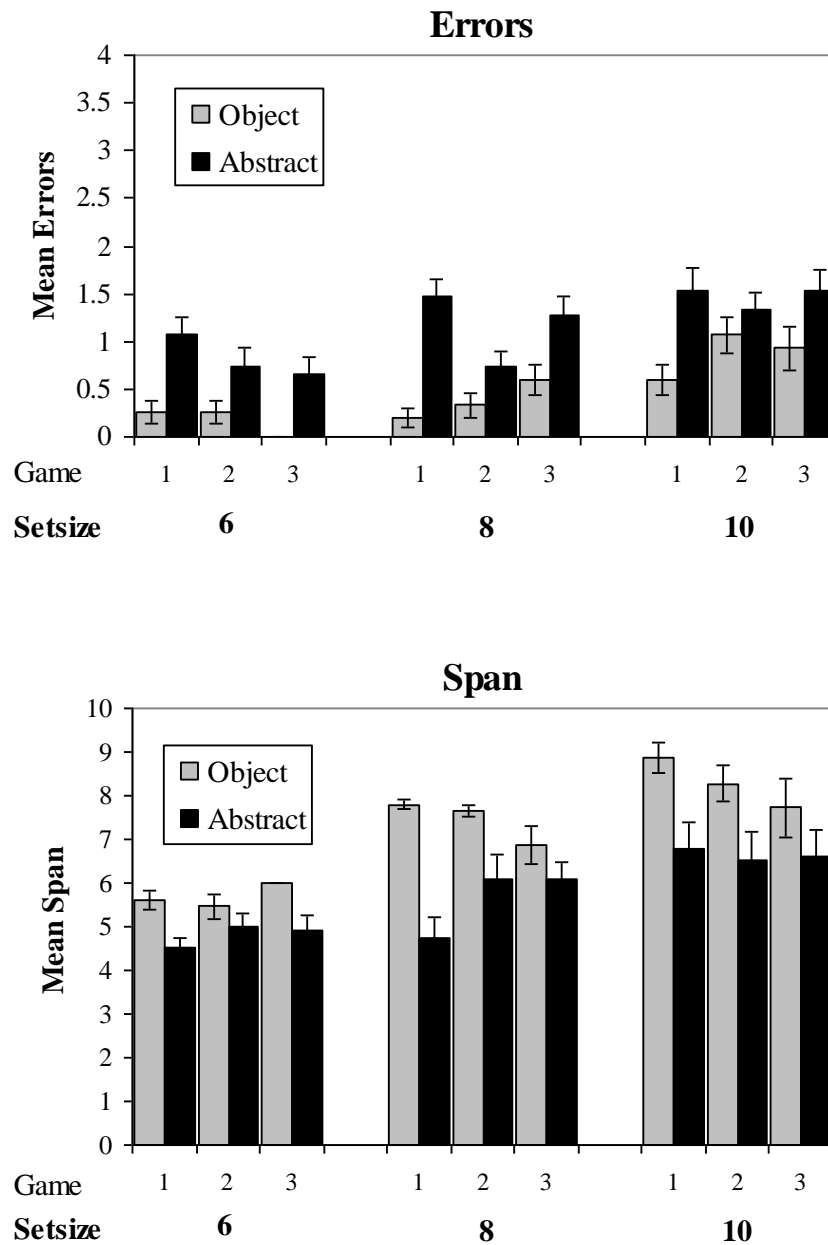


Figure 4.2: Mean (*SE*) errors and span for adult participants

In summary, these results show that as expected, adults made more errors as set size increased and found the object condition easier than the abstract condition. Performance across the three games differed according to the condition, with no difference between games when the pictures were of objects, but a higher error score and shorter span in the first game than in the following two for abstract pictures. These results replicate those of the original study by Petrides and Milner (1982) and

as such provide a good background against which to consider the data from the children.

Child Data

A four-way mixed-measures ANOVA was used to analyse the children's data with the within-subject factors Condition (object, abstract), Set Size (6, 8, 10) and Game (1, 2, 3), and Year Group (Year 1, Year 2, Year 3, Year 4, Year 5, Year 6) as the between-subjects factor. Comparing the error rates of the six groups of children showed that performance on the SOPT improved with age resulting in a significant main effect of Year Group, (errors: $F(5,84)=5.64$, $p<.001$, $\eta^2=.251$; span: $F(5,84)=5.18$, $p<.001$, $\eta^2=.236$). Post-hoc tests revealed that Year 2 children made significantly more errors than the children in Years 4 to 6 and that Year 1 and Year 2 children had significantly shorter spans than children in Years 4 to 6.

This demonstrated that the younger children differed from the older children but that there were no differences within these groups. As a result of this the children were split into two groups: younger children (Years 1 to 3) and older children (Years 4 to 6) and the results reanalysed with Age Group (younger children, older children) replacing Year Group as the between-subjects factor. Reducing the data in this way allowed for greater clarity when interpreting the results.

A four-way mixed measures ANOVA was performed with Age Group as the between-subjects factor and Condition (object, abstract), Set Size (6, 8, 10) and Game (1, 2, 3) as the within-subject factors. The results are illustrated in Figure 4.3. The older children ($M=1.46$, $SD=0.43$) made significantly fewer errors than the younger children ($M=1.93$, $SD=0.50$) and had significantly longer spans ($5.27(0.78)$ vs. $4.53(0.82)$) as shown by a significant main effect of Age Group (errors: $F(1,88)=21.9$, $p<.001$, $\eta^2=.199$; span: $F(1,88)=19.5$, $p<.001$, $\eta^2=.182$). As in adults,

both span and the number of errors increased as the set got larger, shown by a main effect of Set Size (errors: $F(1.92, 169)=294, p<.001, \eta^2=.770$; span: $F(1.93,170)=44.3, p<.001, \eta^2=.335$). A significant Set Size x Age Group interaction was found for errors ($F(1.92,169)=4.36, p<.05, \eta^2=.047$) due to the fact that the difference in error rate between the younger and older children increased as the set size got larger. However, this was not significant for span ($F(1.93,170)=1.17, ns$).

The children performed differently depending on the stimuli used, as shown by a significant main effect of Condition (errors: $F(1,88)=212, p<.001, \eta^2=.707$; span: $F(1,88)=168, p<.001, \eta^2=.657$), with fewer errors and longer spans in the object condition (errors: $M=1.34, SD=0.52$; span: $M=5.52, SD=1.02$) than the abstract condition (errors: $M=2.05, SD=0.62$; span: $M=4.28, SD=0.96$). The interaction between Age Group and Condition was not significant, showing that performance improved with age to the same extent in both conditions. A significant interaction occurred between Condition and Set Size (errors: $F(1.85, 163)=7.52, p<.001, \eta^2=.079$; span: $F(1.78,156)=5.81, p<.01, \eta^2=.62$) as there was a greater difference between conditions as the set size increased.

There was also a significant main effect of Game, (errors: $F(2.00, 176)=23.7, p<.001, \eta^2=.213$; span: $F(1.99,175)=15.1, p<.001, \eta^2=.147$) which a test of simple effects showed was due to significantly fewer errors being made in Game 1 ($M=1.48, SD=.56$) than Games 2 ($M=1.80, SD=.58$) and 3 ($M=1.80, SD=.66$), which did not differ in error score. An identical pattern was found for span length with longer spans in Game 1 ($M=5.24, SD=1.04$) than in Games 2 ($M=4.75, SD=1.05$) and 3 ($M=4.71, SD=1.08$). There was an interaction between Set Size and Game for errors ($F(3.60, 317)=3.58, p<.01, \eta^2=.039$) but not span length ($F(3.44, 303)<1, ns$), due to

a greater difference in error rate between Game 1 and the other two games as the set size increased.

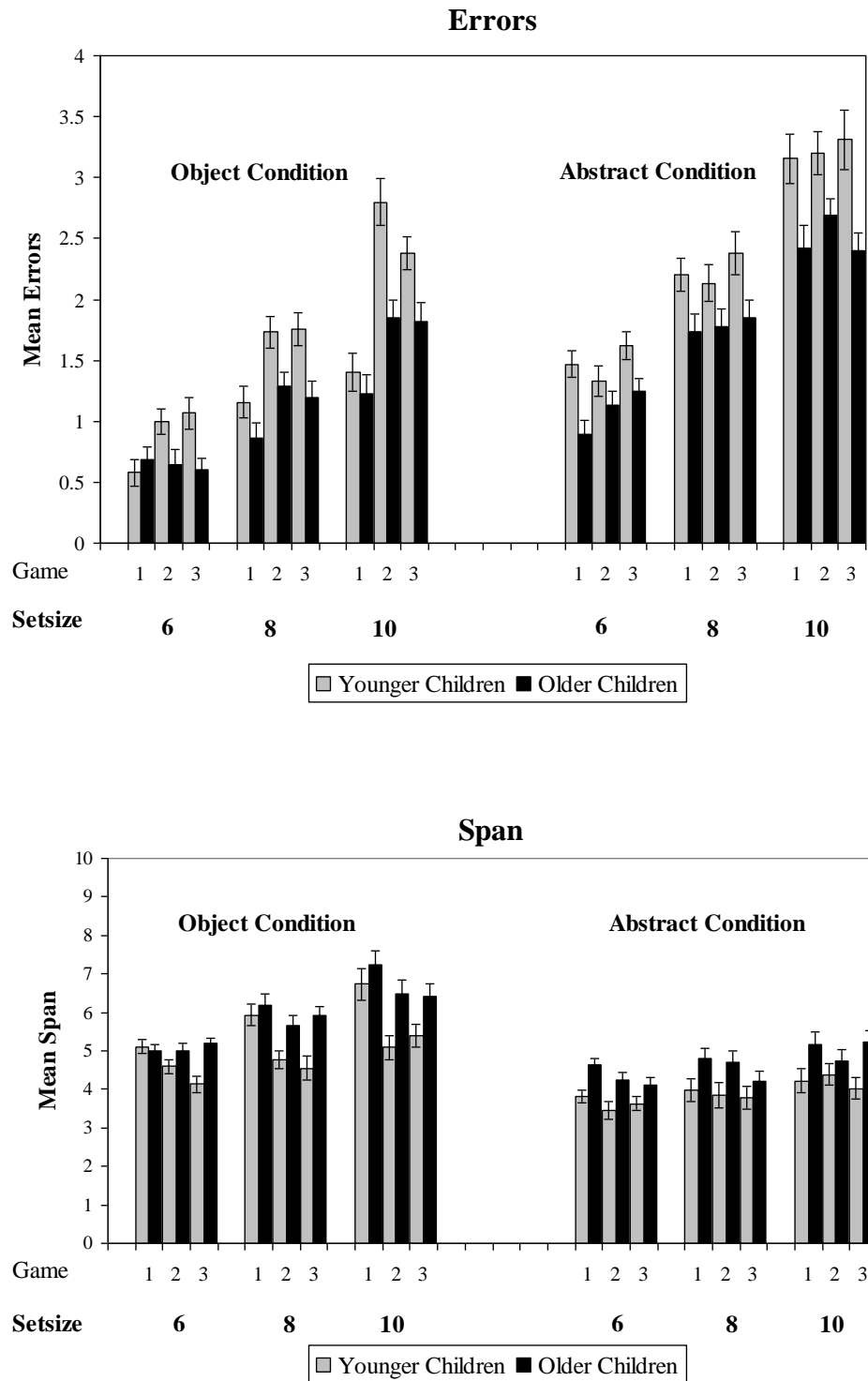


Figure 4.3: Mean (*SE*) errors and span for child participants

Performance across the three games varied depending on the condition, as shown by an interaction between Condition and Game, (errors: $F(1.81, 160)=15.2$, $p<.001$, $\eta^2=.147$; span: $F(1.95, 172)=5.94$, $p<.01$, $\eta^2=.063$). In the object condition participants showed longer spans and made fewer errors in Game 1 than in Games 2 or 3 for pictures of objects, whereas in the abstract condition performance was similar across the three games. A significant Age Group x Condition x Game interaction, (errors: $F(1.81,160)=7.31$, $p<.001$, $\eta^2=.077$; span: $F(1.95, 172)=5.24$, $p<.01$, $\eta^2=.056$) showed that this effect was larger in the younger children. This pattern of results was further illustrated by a significant Condition x Game x Set Size interaction for error rate, $F(3.79, 334)=3.02$, $p<.05$, $\eta^2=.033$. In the object condition fewer errors were made in Game 1 than Games 2 and 3, and this difference grew larger as set size increased, whereas for abstract pictures performance across games was similar for all three set sizes.

In summary, the children's performance was similar to the adults in that they made more errors and showed shorter spans in the abstract condition than in the object condition. They also made more errors as set size increased. However, a series of one-way ANOVAs comparing younger children, older children and adults showed that the children had not reached adults levels of performance on either the object condition (errors: $F(2,102)=31.7$, $p<.001$; span: $F(2,102)=28.6$, $p<.001$) or the abstract condition (errors: $F(2,102)=27.2$, $p<.001$; span: $F(2,102)=23.1$, $p<.001$). Post-hoc analyses showed significant differences in both errors and span between all three age groups (younger children, older children, adults) in both conditions.

The children and adults differed in terms of performance across the three games as shown by a significant Age Group x Condition x Game interaction, $F(3.59, 183.3)=3.87$, $p<.01$, $\eta^2=.071$. Whereas the adults made more errors in Game 1 in the

abstract condition but showed no difference between games in the object condition, the children showed no difference between games in the abstract condition but made fewer errors in Game 1 of the object condition. This effect was larger for the younger children.

The Effects of Verbal and Nonverbal Ability in the SOPT

A significant main effect of condition suggests that verbal factors are playing a role in SOPT performance, with verbal labelling improving performance in the object condition. To assess this further, individual differences in the children's verbal and nonverbal abilities were compared to performance on the SOPT. If verbal skills are important in the task then we would expect that children with a high verbal ability will perform well in the object condition of the SOPT. Correlations between the different measures were calculated and are presented in Table 4.2. The error and span measures correlated highly, suggesting that both were measuring the ability to maintain and monitor items in working memory. Vocabulary and Matrices, measuring verbal and nonverbal abilities respectively, correlated significantly with both error and span measures for both conditions. Once chronological age was controlled for however, the only relationship which remained significant was between Matrices and the object condition of the SOPT.

Table 4.2: Correlations for the different measures: above the diagonal are Pearson correlation coefficients, below the diagonal are partial correlations controlling for chronological age

	Errors- Object	Errors- Abstract	Span- Object	Span- Abstract	WASI Vocabulary	WASI Matrices
Errors-Object		.677**	-.868**	-.623**	-.368**	-.427**
Errors-Abstract	.627**		-.640**	-.845**	-.378**	-.340**
Span-Object	-.846**	-.581**		.581**	.346**	.461**
Span-Abstract	-.563**	-.820**	.510**		.363**	.286*
Vocabulary	-.145	-.162	.081	.127		.562**
Matrices	-.286*	-.172	.318*	.096	.239°	

Note. ** $p < .001$. * $p < .01$. ° $p < .05$.

Two series of hierarchical multiple regressions were performed for each condition separately. Both the total error score and the total span score for each condition, summed across all games and set sizes, were used to enable comparisons with previous studies. The predictor variable chronological age (CA) was always entered in the first block, followed by raw scores on either WASI Vocabulary or Matrices in the second block. These showed that age was a significant predictor of SOPT performance, accounting for 13.4% of variance in error score in both the object condition ($F(1,88)=13.6$, $p < .001$) and the abstract condition ($F(1,88)=13.6$, $p < .001$). Age accounted for a similar amount of variance in span length (object condition: $R^2=.15$, $F(1,88)=15.6$, $p < .001$; abstract condition: $R^2=.14$, $F(1,88)=14.4$, $p < .001$). Once age had been accounted for, Vocabulary did not account for significant extra variance in either condition for either errors or span. Nonverbal abilities, as indexed by Matrices, accounted for additional variance in the object condition over and above age-related improvements (errors: $R^2=.071$, $F(1,87)=7.74$,

$p < .01$; span: $R^2 = .086$, $F(1,87) = 9.75$, $p < .01$. However, Matrices accounted for no additional variance in the abstract condition once the contribution of age had been accounted for.

Overall, these analyses show that the contribution of age is the same in both the object and abstract condition. Interestingly, nonverbal skills seemed to play a greater role in the object condition than the abstract condition while verbal abilities did not account for variance in either condition. Thus neither verbal nor nonverbal abilities are good predictors of performance on this working memory task.

Discussion

This study provides a detailed investigation of developmental changes in performance on the SOPT and how these are affected by various task manipulations, as well as the role of verbal skills in task performance. The results demonstrate that the SOPT is an appropriate task to use with a wide age-range of children. Randomising the spatial location of the pictures reduced the complexity of the instructions without changing the demands of the task and the choice of set sizes was of an appropriate difficulty level for the age range tested. The reliability of the SOPT was acceptable, with a Cronbach's alpha value above the recommended value of .8 (Coolican, 2004).

Performance on the SOPT improved with development with the older children making significantly fewer errors and creating longer spans than the younger children. The greatest difference between the age groups was found at larger set sizes when the task demands were higher. This was the first time children and adults have been directly compared on the non-spatial SOPT. While the findings should be treated with caution as the adult sample were students rather than from the general population, the results were consistent with Luciana and Nelson's (2002)

comparison of 12-year-olds and adults on a spatial version of the self-ordered pointing task in showing that the older children did not reach adult levels of performance.

Despite developmental improvement, age only accounted for a relatively small portion of variance in our study, similar to the findings of Archibald and Kerns (1999). A large amount of unexplained variance remained which was not accounted for by either verbal or nonverbal abilities. This suggests that there are other within-group differences, namely in working memory ability, that are more important factors in predicting successful task performance. Comparisons with other complex working memory tasks should be carried out to confirm this.

An interesting difference in performance between the children and the adults was shown by comparing the task repetitions at each set-size. Repeating the task had a detrimental effect on children's performance in the object condition. While the adults showed no difference in performance across games, the children made fewer errors and longer spans in Game 1 compared to the following two games, which did not differ. This could be because the children lost interest in the task as the games progressed, although if this were the case it would be expected that performance would be worse in the third game than the second. Good internal reliability between the games also suggests that the children were not losing interest in the task.

An alternative explanation is that the memory trace from the first game interfered in performance in the subsequent games. This only occurred in the object condition, possibly because there is more information about the stimuli to help encode them, and therefore a stronger memory trace. The difference between games also interacted with set size, implying that the interference had a larger effect when other task demands were high. The younger children showed the largest difference

between games, suggesting that there was more interference from previous items in this age group than in the older children. In contrast, the adults showed no interference effects suggesting that the ability to inhibit the interference of memory traces from previous games develops with age.

An opposite pattern of results was found in the abstract condition. While there was no difference between games for the children, repeating the task led to improved performance in Games 2 and 3 for adults. This could be due to the fact that the adults were aware that abstract pictures are less memorable than objects and therefore consciously attempted to encode them. This would lead to a benefit in performance in the second game once the pictures have been encoded. If this is the case, it suggests an important development in meta-memory or strategy use.

As predicted, performance was better in the object condition than the abstract condition as the availability of verbal labels for objects made them easier to remember. Contrary to our prediction, it was surprising that the relationship found in previous studies (Hongwanishkul et al., 2005; Joseph et al., 2005) between verbal ability and performance on the object condition of the SOPT was not demonstrated in this study. This result is puzzling, especially since the difference in performance between object and abstract conditions suggests that verbal labelling is being used. The reason why no relationship was found is unclear, however we offer two possible explanations. The first relates to the vocabulary tests used to measure verbal ability in the different studies. Both Hongwanishkul et al. (2005) and Joseph et al. (2005) used the Peabody Picture Vocabulary Test (Dunn & Dunn, 1997), a measure of receptive vocabulary which uses pictorial stimuli and does not require a verbal response. The expressive vocabulary test used by Joseph et al. required the generation of verbal labels, whereas the expressive vocabulary measure used in this

experiment entailed giving a definition. Arguably, the measures used by Hongwanishkul et al. and Joseph et al. are more similar to the skills involved in the SOPT, nevertheless, it is surprising that we found no relationship between verbal ability and SOPT performance. If it is indeed the case that general language ability is important in this task then we should expect to see a relationship between the two using any reliable measure of language ability.

An alternative explanation for the lack of association between verbal ability and the object condition is that we used pictures of objects which have an early age of acquisition. Therefore, all of the children should have found it very easy to name the stimuli. If more demanding vocabulary had been used in the object condition, we may have seen a relationship between SOPT performance in the object condition and vocabulary, as assessed by the WASI. Vocabulary difficulty has been shown to influence the recall of words from short-term memory in both children (Nation, Adams, Bowyer-Crane, & Snowling, 1999) and adults (Walker & Hulme, 1999).

Based on evidence that children under the age of 8-years-old do not use verbal rehearsal strategies to aid memory performance (Hitch & Halliday, 1983), we predicted that there would be a greater difference between the two conditions in the older children than the younger children. Our results did not support this conclusion, with a similar difference between the two conditions in all children. One possible explanation for these findings is that none of the children were using verbal rehearsal strategies because the task did not rely on a verbal output (cf. Hitch & Halliday, 1983). This is supported by Joseph et al. (2005) who found that a measure of verbal span was not associated with performance on the object condition of the SOPT. The two tasks differed in that the stimuli in the span task were presented auditorily, and as such were in a suitable format for verbal rehearsal. In contrast, in the SOPT the

children needed to spontaneously adopt the strategy of recoding the picture stimuli into verbal form before they could verbally rehearse. Alternatively, it may be that the executive demands of the task prevented verbal rehearsal. Hitch and Halliday (1983) suggested that there may be a lack of rehearsal in young children because naming pictures taxes the central executive of working memory, leaving insufficient capacity for rehearsal. However, it may be that it is not naming the pictures, but having to continuously generate and monitor responses that taxes the central executive and prevents a verbal rehearsal strategy from being adopted.

In conclusion, the results of this study show that the SOPT is an appropriate measure of working memory for use with children across a wide age-range. Performance on this task showed improvement between the ages of 5 and 11 years, but had not reached adult levels by the end of this period. With increasing age, the children were able to remember a greater number of pictures and the ability to resist interference from previous memory traces also improved. Despite a difference between the two conditions suggesting use of verbal encoding, our predictions concerning the increasing use of verbal rehearsal strategies with age were not supported. Further study into the role of verbal factors in the SOPT in both adults and children, using techniques such as concurrent articulation and explicit questioning about strategy use may reveal if, and to what extent, verbal strategies are used in this task at different stages of development.

Chapter 5: Go or no-go? Developmental improvements in the efficiency of response inhibition in mid-childhood

This experiment used a modified go/no-go paradigm to investigate the processes by which response inhibition becomes more efficient during mid-childhood. The novel task, which measured trials on which a response was initiated but not completed, was sensitive to developmental changes in response inhibition. The effect of inducing time pressure by narrowing allowable response time was also examined. While increasing time pressure did not reduce the inhibitory demands of the task for either age group, older children (aged 9 to 11 years) were able to inhibit their responses at an earlier stage of movement than younger children (aged 5 to 7 years). This shows that as children get older they become more efficient at controlling their behaviour which drives developmental improvements in response inhibition.

Now that the development of shifting and working memory have been considered, this chapter changes focus once more, turning to inhibition, the final executive component explored in this thesis. Response inhibition is one of the purest forms of inhibition, involving only a choice between an action or a non-action (Rubia et al., 2001). The go/no-go task reflects this and simply requires a response to be made to a frequently occurring 'go' stimulus but withheld when a less frequent 'no-go' stimulus is presented. The relative frequency of go trials compared to no-go trials creates a tendency to respond on every trial (prepotent response) which then has to be inhibited in order to suppress the action. Response inhibition is indexed by the number of no-go trials on which a response is made, which indicates a failure to actively inhibit the response.

Previous studies investigating the development of response inhibition using the go/no-go task have shown mixed results. While some have shown that performance on no-go trials improves with age during childhood (Archibald & Kerns, 1999; Becker, Isaac, & Hynd, 1987; Brocki & Bohlin, 2004; Dowsett & Livesey, 2000; Levin et al., 1991; Levy, 1980; Livesey & Morgan, 1991; Luria, 1959) this has not always been found (Johnstone et al., 2007; Jonkman, 2006). In other cases, developmental change is only seen under certain conditions. Espy (1997) showed an improvement with age only when an efficiency score took response speed into account, but not on accuracy alone. Furthermore, Levin et al. (1991) found that a developmental improvement in response inhibition was no longer significant once the number of trials completed by each age group was taken into account. Even for those studies that found a developmental improvement, the age at which response inhibition matures is not clear: Some studies suggest that mature go/no-go performance is achieved around 8 years of age (Becker, Isaac, & Hynd, 1987), whereas others comparing children up to the age of 12 with adults suggest that response inhibition is still not fully developed in these older children (Booth et al., 2003; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey et al., 1997).

These discrepant findings are difficult to interpret, especially as methodological differences such as the relative frequency of no-go trials (Berwid et al., 2005), the number of go trials preceding a no-go trial (Durstun, Thomas, Worden, Yang, & Casey, 2002) and time pressure (Simpson & Riggs, 2006) can have a large impact on the pattern of results observed. In addition, differences between age groups are often small. Thus, lack of developmental change may be a consequence of task insensitivity rather than a true reflection of no difference between children of a different age.

While there is at least some evidence that the ability to inhibit a response improves during childhood, the exact process by which this occurs is not clear. Although the standard go/no-go task involves a simple choice between an action and a non-action (Rubia et al., 2001), this does not mean that inhibiting that action is also an all-or-none process. A response to a no-go trial may be initiated but not completed for example. One simple hypothesis is that as children get older, they are able to inhibit their actions at an earlier stage in the execution of the motor response, thereby becoming more efficient at controlling their behaviour. On this view, young children have slow inhibitory processes and therefore are unable to inhibit a response quickly enough to prevent an error being made. As older children have faster inhibitory processes, they are able to inhibit a response before it is completed, thereby avoiding an error. This improves until a response can be inhibited at the planning stage, prior to its initiation.

The go/no-go task has not been thought of in these terms before. However, another measure of response inhibition, the stop-signal task, is based on a similar principle. Here, participants are presented with stimuli that require a speeded motor response. On some trials a signal occurs at a variable delay after the stimulus, telling the participant to withhold that response. If the stop-signal occurs at a sufficiently short delay the response can be prevented but at longer delays, the stop-signal arrives too late to prevent the response from being executed. Logan and colleagues' horse-race model (Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984) proposes a race between two independent processes: selecting and executing a response to the first stimulus, and inhibiting all motor responses. Whichever process is completed first determines whether a response is made. Therefore, the speed of each set of processes is critical. Although not directly observable, inhibition speed can be

estimated from other parameters in the task. This is labelled the stop-signal reaction time (SSRT) and quantifies the efficiency of inhibition.

Developmental studies using the stop-signal task provide mixed findings concerning age-related improvement on the task. While some studies have found a significant decrease in SSRT with age (Bedard et al., 2002; Ridderinkhof, Band, & Logan, 1999; Williams, Ponesse, Schachar, Logan, & Tannock, 1999) others have not (Band, van der Molen, Overtoom, & Verbaten, 2000; Jennings, van der Molen, Pelham, Debski, & Hoza, 1997; Schachar & Logan, 1990). However, it has been argued that the null results are largely due to a lack of power, suggesting that inhibition processes do in fact become more efficient with age (Band, van der Molen, & Logan, 2003; Ridderinkhof et al., 1999; Williams et al., 1999). We predict that this is also the case for the go/no-go task: As inhibition processes become faster, responses should be inhibited at an earlier stage of the movement. By modifying the standard go/no-go paradigm, we assessed this hypothesis in this experiment.

In addition to the speed of inhibitory processes affecting performance, response speed may also influence go/no-go performance. Simpson and Riggs (2006) argued that if the amount of time given to respond is short, young children may not have enough time to respond, removing the opportunity for inhibitory failure on no-go trials. They suggested that only when accuracy is higher on go trials than on no-go trials can the task be considered to have inhibitory demands as this shows that children understand the task and so do not make errors on go trials, but have particular difficulty inhibiting responses on no-go trials. With a presentation time of 2s and a high frequency of go trials this criteria was met, showing that inhibitory demands were high. In contrast, when the presentation time was too short (1s), there was not enough time for the children (aged 3 years) to respond and therefore, no

inhibition was observed. Similarly, when presentation time was too long (3s), inhibitory demands were reduced as time pressure was insufficient to make button-pressing prepotent.

To determine whether a restriction on response time affects older children in a similar manner, we manipulated the inter-stimulus interval (ISI). Additionally, by comparing two age-groups of children, we examined whether shortening the response window is more detrimental to younger vs. older children. As children get faster at responding with age, we predicted that reducing the length of the ISI would have a greater effect on the younger children who, given their slower response times, may not have enough time to respond at a shorter ISI.

In summary, this experiment aimed to reveal factors that underpin go/no-go performance. We modified the standard go/no-go paradigm in order to assess the hypothesis that as children get older, they are able to inhibit their responses at an earlier stage during the movement. We also manipulated response time (ISI) to investigate the effects of time pressure across different stages of development.

Method

Participants

Ninety children from primary schools in England participated. Two groups of children were recruited: 5- to 7-year-olds and 9- to 11-year-olds, allowing us to examine maximal changes in response inhibition development during mid-childhood. One 5- to 7-year-old was excluded due to an excessive number of anticipatory responses, and a 9- to 11-year-old was excluded due to experimenter error, leaving forty four 5- to 7-year-olds ($M=6.55$ years, $SD=0.58$, 21 male) and forty four 9- to 11-year-olds ($M=10.57$ years, $SD=0.61$, 22 male). The Matrices and Vocabulary

subtests of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) were completed by all children and the Swanson, Nolan and Pelham (SNAP) rating scale, which includes items from the DSM-IV criteria for ADHD and the Conners Index Questionnaire, was completed for each child by their class teacher.

Materials

A background scene consisting of grass, sky and a football goal was constantly present on the screen (see Figure 5.1). On each trial either a football (go stimulus) or a rugby ball (no-go stimulus) was presented centrally near the bottom of the screen. Rather than simply pressing a key in response to go stimuli and withholding this response for no-go stimuli, participants held down a home key with their index finger between trials and responded to targets using an adjacent key. The ‘left-click’ mouse button on a laptop was the home key and the ‘right-click’ mouse button was the target key. A red star sticker was placed on the home key to indicate where to press. If the key was released between trials then a reminder “Press the star!” appeared at the top of the screen. The correct response to a go stimulus was to release the home key and press the adjacent target key with the same finger as fast as possible, whereas the correct response to a no-go stimulus was to continue pressing the home key. This manipulation allowed for a more sensitive measure of task performance, as trials where the participant released the home key but did not press the target key were treated as partial inhibitions that were initiated but successfully inhibited before completion.

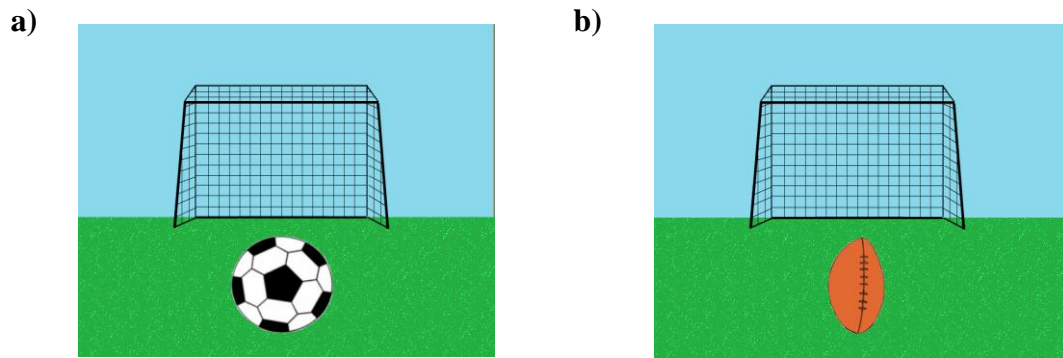


Figure 5.1: Examples of a) the go trial stimulus and b) the no-go trial stimulus

Procedure

To encourage the development of a prepotent response, children first completed two blocks of 30 go trials. Following instruction and 10 practice trials, the first block was presented. The appearance of the target was contingent on the home key being pressed down, after which the football appeared for 200ms. A variable ISI ensured that the appearance of the target could not be predicted therefore discouraging anticipatory responses. The average length of the ISI was also manipulated with an ISI of 2600-3400ms in the first block and 1600-2400ms in the second block. Feedback (number of correct responses) was presented after each block.

Following two blocks of go trials, two blocks including no-go stimuli were presented. The children were told that they were going to play a new game that was very similar to the first, but that this time they would sometimes see a rugby ball. It was explained that they should not kick the rugby ball but should keep their finger pressed down on the star button when one appeared. The children completed eight practice trials (including two no-go trials) followed by two blocks of 52 trials. Thirteen trials (25%) of each block were no-go trials. Both go and no-go stimuli

were presented for 200ms. To encourage a regular pattern of responding, stimulus presentation was not contingent on the home key being pressed and the targets appeared at fixed regular intervals with an ISI of 3000ms in the first block and 2000ms in the second block. Feedback (number of correct responses to go trials) was provided at the end of each block.

Results

Any trial with an RT less than 200ms or where the first response was not the release of the home key was classed as an anticipatory trial (7.2% of trials). To determine if the number of anticipatory responses differed between the two age groups a two-way mixed-measures ANOVA with Age (5-7, 9-11) as a between-subjects factor and Trialtype (go, no-go) as a within-subjects factor was performed. The only significant result was a main effect of Age $F(1, 86)=9.59$, $p<.01$, $\eta^2=.100$, which showed that the younger children ($M=8.06$, $SD=8.51$) made more anticipatory responses than the older children ($M=3.55$, $SD=4.53$) on both go and no-go trials. As anticipatory responses did not relate to our hypotheses concerning response inhibition they were not considered further.

Responses to go trials were coded as either *hits* (the home key was lifted and the target key was pressed) or *misses* (the home remained pressed or the home key was lifted but the response key not pressed). Responses to no-go trials were coded as either *successful inhibitions* (the home remained pressed), *partial inhibitions* (the home key was lifted but the response key not pressed) or *failed inhibitions* (the home key was lifted and the target key was pressed). Each response type was calculated as a percentage of the total number of go or no-go trials within a block. We present three sets of analyses on these responses. Our first analysis classed partial inhibitions on no-go trials as correct. This is similar to standard go/no-go paradigms

in which any no-go trial on which a response is not completed is treated as correct. In our second set of analyses, partial inhibitions to no-go stimuli were re-classified as incorrect. Finally, we examined the number of each type of response for no-go trials. For the RT analyses, RTs greater than 2.5 *SDs* above the participant's mean for each measure (release time: stimulus-release; movement time: release-press) were excluded (release time: 0.02% excluded; movement time: 1.18% excluded). The Greenhouse-Geisser correction was used in all analyses. Means for all conditions can be found in Appendix IV.

Standard analyses

For go trials hits were treated as correct and misses treated as incorrect. Successful and partial inhibitions were treated as correct for no-go trials, whereas failed inhibitions were treated as incorrect. The number of correct responses were calculated as a percentage of the overall number of go or no-go trials for each ISI and entered into a three-way ANOVA with Age (5-7, 9-11) as a between-subjects factor, and ISI (2000ms, 3000ms) and Trialtype (go, no-go) as within-subject factors. There was a main effect of Trialtype, $F(1, 86)=38.4$, $p<.001$, $\eta^2=.308$, reflecting more correct responses for go trials ($M=85.2$, $SD=10.2$) than for no-go trials ($M=74.4$, $SD=20.2$) showing that the task created inhibitory demands. Consistent with the findings of Simpson and Riggs (2006) there were more correct responses when the ISI was longer (3000ms: $M=81.5$, $SD=13.9$; 2000ms: $M=78.2$, $SD=15.4$) as shown by a main effect of ISI, $F(1,86)=9.66$, $p<.01$, $\eta^2=.101$. Overall, 9- to 11-year-olds ($M=82.7$, $SD=13.8$) made more correct responses than 5- to 7-year-olds ($M=76.9$, $SD=13.3$) as shown by a main effect of Age, $F(1, 58)=3.97$, $p=.05$, $\eta^2=.044$. There was no Age x Trialtype interaction showing that performance on both go and no-go trials improved with age.

RT analyses were performed for hits on go trials only. RTs for partial inhibitions are analysed in the next section while RTs for failed inhibitions could not be analysed due to the small number of these responses at each ISI. Two 2-way ANOVAs were used, one with release time as the dependent variable and the other with movement time as the dependent variable. In both analyses, ISI (2000ms, 3000ms) was a within-subject factor and Age (5-7-, 9-11) a between-subjects factor. Overall 9- to 11-year-olds were faster to respond than 5- to 7-year-olds as shown by a main effect of Age for both release time ($F(1, 86)=57.4, p<.001, \eta^2=.040$; 5- to 7-year-olds: $M=450, SD=89.2$; 9- to 11-year-olds: $M=330, SD=57.0$) and movement time: ($F(1, 86)=31.1, p<.001, \eta^2=.265$; 5- to 7-year-olds: $M=187, SD=68.0$; 9- to 11-year-olds: $M=125, SD=30.3$). The home key was released more quickly in the 2000ms ISI condition ($F(1, 86)=5.72, p<.05, \eta^2=.062$; 2000ms: $M=386, SD=97.8$; 3000ms: $M=394, SD=97.0$) but there was no effect of ISI on movement time ($F(1, 86)<1, ns$). There was no Age x ISI interaction for either measure (release time; $F(1, 86)<1, ns$; movement time: $F(1, 86)=2.09, ns$) showing that manipulating the amount of time to respond on go trials affected both age groups in the same way.

In summary, accuracy was higher on go trials than no-go trials, and when the ISI was longer. All children were slower to release the home key with a longer ISI, suggestive of a speed-accuracy trade-off. 9- to 11-year-olds were faster than 5- to 7-year-olds on go trials and more accurate on both go and no-go trials.

Analysis including partial inhibitions

Hits were treated as correct and misses treated as incorrect for go trials. Only successful inhibitions were treated as correct for no-go trials, whereas failed inhibitions and partial inhibitions were treated as incorrect. Thus, some no-go trials which were classed as correct in the previous analyses (i.e. if the home key had been

released but the target key was not pressed) were now classed as partial inhibitions and scored as incorrect.

A three-way ANOVA was performed on the percentage of correct responses, with Age (5-7, 9-11) as a between-subjects factor, and ISI (2000ms, 3000ms) and Trialtype (go, no-go) as within-subject factors. There was a main effect of Trialtype, $F(1, 86)=569, p<.001, \eta^2=.869$, reflecting more correct responses for go ($M=85.0, SD=10.7$) than for no-go trials ($M=36.7, SD=22.9$). While there was no main effect of ISI ($F(1, 86)<1, ns$) there was an interaction between ISI and Trialtype, $F(1,86)=18.2, p<.001, \eta^2=.175$. Accuracy improved on no-go trials when the ISI was shorter (3000ms: $M=34.3, SD=23.1$; 2000ms: $M=39.1, SD=25.8$), but decreased on go trials (3000ms: $M=87.2, SD=10.6$; 2000ms: $M=82.8, SD=14.2$), suggesting that there was not enough time for the children to respond on go trials when the ISI was reduced. A marginally significant interaction between Age and ISI, $F(1,86)=3.82, p=.054, \eta^2=.043$, indicated that the younger children were particularly affected by this increase in time pressure (3000ms: $M=56.8, SD=13.8$; 2000ms: $M=54.3, SD=16.2$). In contrast, the older children were more accurate with a shorter ISI (3000ms: $M=64.7, SD=14.3$; 2000ms: $M=67.6, SD=16.9$). Overall, older children ($M=66.2, SD=14.8$) were more accurate than younger children ($M=55.5, SD=13.7$), $F(1, 86)=10.8, p=.001, \eta^2=.111$. Again, there was no Age x Trialtype interaction ($F(1, 86)=1.75, ns$) indicating that younger children made fewer correct responses on go as well as no-go trials. A significant correlation between correct go trials and correct no-go trials, controlling for age, showed that children who made more correct go responses were also more likely to inhibit responses on no-go trials, $r(87) = .506, p<.001$.

As there were relatively few partial inhibitions made in each condition, RT data were only analysed for the 16 younger and 13 older children who made at least five partial inhibitions in each ISI condition so that a reliable RT measure was obtained. Before describing the results of this analysis, it is important to determine whether the two groups of children (those who made at least five partial inhibitions and those that did not) differed on key variables such as age, IQ and aspects of task performance, such as speed, RT variability and number of anticipation trials. Relevant data are presented in Table 5.1. We analysed group differences for the two age groups separately as we hypothesised that there would be different reasons for older and younger children making partial inhibitions. For younger children, partial inhibitions may be seen in children with more mature performance, reflecting a move away from failed inhibitions. In contrast, the older children who make more partial responses may be those with more impulsive performance. Overall, we found no differences between the younger children who made more or less than five partial inhibitions. However, the older children who made more than five partial responses were faster to release the home key on go trials, suggesting they may be more impulsive. This tentative finding should be investigated further in future experiments.

Table 5.1: Means (*SD*) and *F* values for one-way ANOVAs comparing children who did or did not make more than 5 partial inhibitions on no-go trials for each ISI condition

	More than 5 partial inhibitions in each ISI condition	Less than 5 partial inhibitions in each ISI condition	<i>F</i> value
<u>5- to 7-year-olds</u>	<i>n</i> =16	<i>n</i> =28	
Age (years)	6.66 (0.67)	6.49 (0.52)	<1
WASI vocabulary	23.2 (6.32)	21.9 (6.97)	<1
WASI matrices	12.0 (6.55)	10.7 (6.85)	<1
SNAP ¹ inattention score	0.19 (0.28)	0.35 (0.47)	1.49
Anticipation trials	6.69 (8.15)	8.84 (8.76)	<1
Go release RT	444.9 (54.8)	453.5 (105)	<1
Go release RT variability	129.4 (42.9)	130.8 (44.7)	<1
PI release RT	415.5 (52.4)	420.8 (110)	<1
<u>9- to 11-year-olds</u>	<i>n</i> =13	<i>n</i> =31	
Age (years)	10.7 (0.64)	10.5 (0.60)	<1
WASI vocabulary	38.5 (6.65)	38.7 (8.77)	<1
WASI matrices	17.5 (5.74)	18.8 (5.11)	<1
SNAP ¹ inattention score	0.64 (0.77)	0.35 (0.52)	2.14
Anticipation trials	3.65 (4.04)	3.52 (4.78)	<1
Go release RT	301.2 (26.3)	341.3 (62.4)	4.96*
Go release RT variability	67.7 (11.3)	85.8 (45.0)	2.02
PI release RT	286.1 (31.1)	309.3 (50.5)	2.31

Note. * = $p < .01$. ¹Swanson, Nolan and Pelham (SNAP) rating scale. This includes items from the DSM-IV criteria for ADHD and the Conners Index Questionnaire.

PI = partial inhibition

Release time RTs were entered into a three-way ANOVA with Age (5-7, 9-11) as a between-subjects factor, and ISI (2000ms, 3000ms) and Response (hit, partial inhibition) as within-subject factors. The means are presented in Appendix IV. There was a main effect of Age, $F(1, 27)=75.0$, $p<.001$, $\eta^2=.735$, as overall 9- to 11-year-olds were faster than 5- to 7-year-olds ($M=294$, $SD=26.7$ vs. $M=430$, $SD=51.4$). There was also a main effect of ISI, $F(1, 27)=8.02$, $p=.01$, $\eta^2=.229$ as responses were faster when the ISI was shorter (3000ms: $M=378$, $SD=83.4$; 2000ms: $M=360$, $SD=80.9$). The home key was released more quickly on partial inhibition trials ($M=357$, $SD=78.6$) than on correct hits on go trials ($M=380$, $SD=84.8$) as shown by a main effect of Trialtype, $F(1, 27)=19.5$, $p<.001$, $\eta^2=.419$. This suggests that faster responses were less likely to be inhibited. There was no Age x Trialtype interaction, $F(1, 27)=1.99$, *ns*, suggesting that the greater number of partial inhibitions in younger children was not simply due to the fact that they were responding more quickly on these trials.

While the results including partial inhibitions mirror those seen in the standard analyses, it is interesting to note that considering partial inhibitions reduced the number of correct responses on no-go trials from 72% to 43% in the 9- to 11-year-olds, and from 77% to 31% in the 5- to 7-year-olds. This demonstrates that all children often inhibited their response after the movement had been initiated but before its completion. For those children making more than five partial inhibitions in each ISI condition, these partial inhibitions were faster than hits on go trials, consistent with the idea that fast responses are initiated before inhibitory processes are completed.

Responses to no-go trials

If response inhibition becomes more efficient with age, younger children should make more partial inhibitions on no-go trials than older children, who should be more likely to fully inhibit their response. To test this hypothesis, we compared the number of each type of response (successful inhibition, partial inhibition, failed inhibition) made by each age group on no-go trials (Figure 5.2).

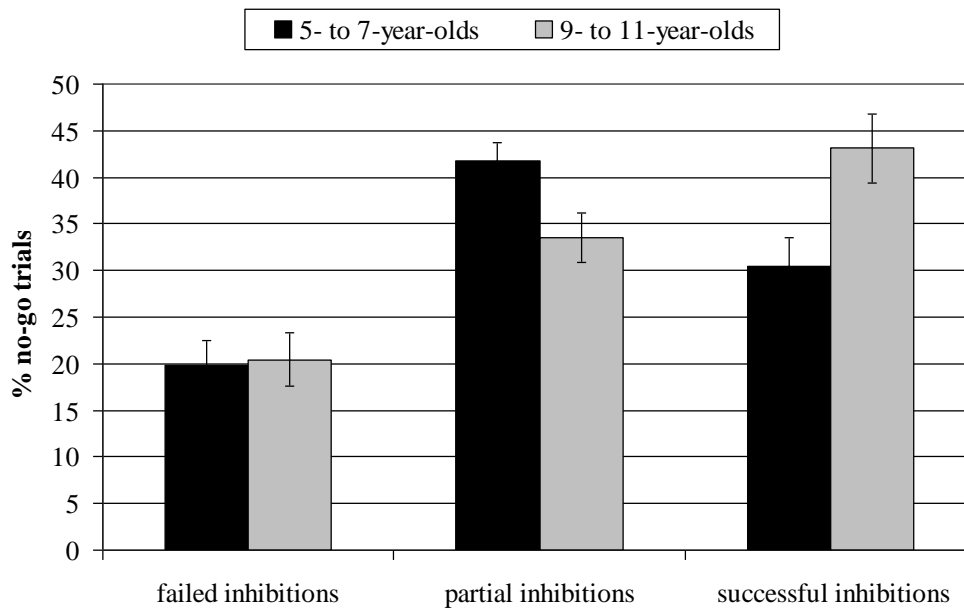


Figure 5.2: Mean (*SE*) percentage of each response type made on no-go trials by 5- to 7-year-olds and 9- to 11-year-olds

A three-way mixed measures ANOVA was performed with Age (5-7, 9-11) as a between-subjects factor, and ISI (2000ms, 3000ms) and Response (successful inhibition, partial inhibition, failed inhibition) as within-subject factors. Main effects of Age, $F(1, 86)=10.6$, $p<.01$, $\eta^2=.110$, and Response, $F(1.81, 156)=16.4$, $p<.001$, $\eta^2=.160$ were qualified by a Response x Age interaction, $F(1.81, 156)=4.63$, $p<.05$, $\eta^2=.051$. This showed that the younger children ($M=41.8$, $SD=13.3$) made more partial inhibitions than the older children ($M=33.5$, $SD=17.6$), whereas the older children made more successful inhibitions than the younger children (5- to 7-year-

olds: $M=30.5$, $SD=19.6$; 9- to 11-year-olds: $M=43.1$, $SD=24.4$), confirming our predictions. In contrast to some previous findings (Archibald & Kerns, 1999; Brocki & Bohlin, 2004) there was no difference in the number of failed inhibitions made by the two age groups (5- to 7-year-olds: $M=19.8$, $SD=17.4$; 9- to 11-year-olds: $M=20.5$, $SD=19.0$). A main effect of ISI, $F(1, 86)=12.1$, $p=.001$, $\eta^2=.123$, was qualified by an interaction between ISI and Response, $F(1.89, 162)=7.75$, $p=.001$, $\eta^2=.083$, which showed that the ISI manipulation affected the response types in different ways. There was no effect of ISI on the number of failed inhibitions. Importantly however, partial inhibitions were not caused by insufficient time to complete the response as there were more successful inhibitions with a shorter ISI (3000ms: $M=34.5$, $SD=23.0$; 2000ms: $M=39.1$, $SD=25.9$) and more partial inhibitions with an ISI of 3000ms ($M=41.4$, $SD=18.3$ vs. $M=33.8$, $SD=18.8$).

Adding further support to our hypothesis that response inhibition becomes more efficient as children get older, the number of partial inhibitions made decreased with increasing age $r(87)= -.240$, $p<.05$, whereas the number of successful inhibitions increased with age, $r(87) = .295$, $p<.01$.

Discussion

This experiment compared the performance of two age groups of children on a version of the go/no-go paradigm modified to capture the stage at which a movement is inhibited. This allowed us to investigate how changes in the efficiency of response inhibition underlie developmental improvement on the go/no-go task. As expected, our standard analyses showed that accuracy was higher on go trials than on no-go trials, confirming that the task is tapping into inhibitory processes. The children understood what they were supposed to do and tended to respond correctly to go stimuli but had greater difficulty inhibiting responses to no-go stimuli. There

was an overall improvement with age demonstrating developments in response activation processes on go trials as well as response inhibition on no-go trials.

Further analyses investigated the nature of this developmental change in response inhibition. Taking partial inhibitions into account revealed the same pattern of results as standard analyses. Importantly however, this more sensitive response measure demonstrated that successful inhibition on no-go trials occurred on only 43% and 31% of trials for 9- to 11-year-olds and 5- to 7-year-olds respectively, compared to the inflated figures of 72% and 77% suggested by the standard analyses. This shows that many responses by both age groups were partial inhibitions, classed as successful inhibitions in the standard paradigm. Thus, our modified task demonstrates that on many trials children were inhibiting responses after they had been initiated but before they were completed.

Although we showed a developmental improvement in accuracy on no-go trials, further analyses showed no difference in the number of failed inhibitions made by the two age groups. While this is in contrast to some developmental studies which have shown a reduction in failed inhibitions in a similar age group (Archibald & Kerns, 1999; Brocki & Bohlin, 2004), it is consistent with others in showing that failed inhibitions are not a sensitive measure of the development of response inhibition (Johnstone et al., 2007; Jonkman, 2006). Go/no-go performance is heavily influenced by task parameters such as the relative frequency of no-go trials (Berwid et al., 2005) the number of go trials preceding a no-go trial (Durstun et al., 2002) and time pressure (Simpson & Riggs, 2006) and therefore differences in the stimuli, response demands, or even the type of analyses used, may have contributed to discrepancies between studies.

In contrast, our new partial inhibition measure was sensitive to developmental change. It revealed that 5- to 7-year-olds made more partial inhibitions on no-go trials than 9- to 11-year-olds, who in turn inhibited more no-go responses before any movement was made. Although both age groups were able to halt some responses before completion, the older children were more likely to inhibit responses at an earlier stage in the movement, before it had been initiated, whereas more of the younger children were inhibiting their responses at a later stage, after it had been initiated. In line with our prediction, the efficiency of response inhibition improves during mid-childhood. This complements findings from the stop-signal paradigm where developmental improvements in the speed of inhibition have also been found (Bedard et al., 2002; Ridderinkhof et al., 1999; Williams et al., 1999). Together, these results strengthen the argument that as children get older they are able to inhibit a response at an earlier stage in its execution.

For those children who made more than five partial inhibitions in each ISI condition, release times for partial inhibitions on no-go trials were generally faster than hits on go trials. This may reflect the fact that these faster responses are initiated before inhibitory processes are completed, consistent with Logan and Cowan's (1984) horse-race model. A further prediction following from this is that failed inhibitions would be faster still than partial inhibitions. We were unable to test this however, due to the small number of failed inhibitions.

It is important to note that older children were more accurate than younger children on go trials as well as no-go trials, consistent with earlier studies (Archibald & Kerns, 1999; Berwid et al., 2005; Brocki & Bohlin, 2004; Levin et al., 1991). This demonstrates developmental change in other factors, as well as response inhibition. Potentially, misses on go trials may reflect a lapse in monitoring processes or

sustained attention (Berwid et al., 2005). While there may be different processes underlying errors on go and no-go trials, a significant correlation between performance on go and no-go trials suggests that there are some factors, such as stimulus recognition, which contribute to successful performance on both types of trial.

Performance on go trials may also have been affected by the amount of time given to respond on each trial. Consistent with this suggestion, Simpson and Riggs (2006) found that manipulating the time to respond affected the balance of errors on go versus no-go trials in pre-schoolers, and therefore whether or not the task could be considered to have inhibitory demands. Manipulating the ISI allowed us to investigate the influence of availability of response time in our experiment. The partial response analyses showed that there were more correct responses on no-go trials when the ISI was shorter, but more correct responses on go trials with a longer ISI. This suggests that decreasing the ISI may have negatively affected go trials, which required a speeded response, but made it easier to keep the home key pressed down on no-go trials. Alternatively the improvement in performance on no-go trials may have been due to practice effects, as the block with the shorter ISI was always performed second. The children were also faster to release the home key when the ISI was shorter, possibly due to the fact that it forced some of the participants to respond at a faster rate than normal. However, this could also be explained by practice effects. Further experiments balancing the ISI between blocks would be needed to distinguish between these two explanations.

We anticipated that a shorter response time would have a greater effect on the younger children, as they would be slower to respond and therefore a shorter response window would result in greater time pressure in this age group. There was

a trend towards a decrease in the younger children's performance in the 2000ms condition, compared to a slight increase in performance in the older children. However, this did not affect the balance of go and no-go errors in the two groups. Overall the pattern of results for both age groups with an ISI of either 2000ms or 3000ms was very similar; accuracy was higher on go trials than on no-go trials in both conditions, showing that the task was posing inhibitory demands for all children at both ISIs. This contrasts with Simpson and Riggs' (2006) finding that reducing the presentation time by 1s resulted in lower accuracy on go trials than on no-go trials in pre-schoolers. This suggests that while manipulations of time pressure may affect preschooler's performance on the no-go task, small changes in ISI do not affect patterns of accuracy in school-age children. However, it may be that shorter ISIs than those used in this study would have a more detrimental effect on school-aged children's performance.

In conclusion, this study used a novel version of the go/no-go paradigm to test the hypothesis that children's performance on the task improves as they become more efficient at inhibiting their responses. The younger children were found to inhibit their movements at a later stage in response execution than the older children, supporting this hypothesis. Further research is needed in order to conduct a more fine-grained analysis of these developmental changes.

Chapter 6: Neural correlates of successful and partial inhibitions in children:

An ERP study

This experiment used event-related potentials (ERPs) to investigate the neural processes underlying response inhibition, using the modified version of the go/no-go paradigm developed in Chapter 5. N2 and P3 ERP components on correct go trials and partial and successful inhibitions were compared in 7- and 9-year-old children. Despite a lack of significant behavioural differences, there were differences between the age groups and trial types in the ERP components. Age-related changes were reflected in a reduction in N2 latency with age, suggesting an improvement in the efficiency of response inhibition. The N2 amplitude correlated positively with behavioural performance in the 7-year-olds, suggesting that this component is related to better response inhibition, yet this relationship was not found in the 9-year-olds. The no-go P3 was not enhanced on no-go trials in either age group, while age differences were apparent in the go P3 component. Successful and partial inhibitions did not differ in N2 amplitude but a longer N2 latency on partial inhibitions reflected slower inhibitory processes on these trials. In addition, a larger no-go P3 amplitude for successful inhibitions indicated that there may be differences in processing between successful and partial inhibitions rather than a simple difference in the timing of the inhibition.

The experiment described in Chapter 5 used a modified version of the go/no-go paradigm to test the hypothesis that the efficiency of response inhibition improves during mid-childhood. This was done by measuring trials on which a response was inhibited after it had been initiated, but before completion. It was found that older

children were more likely to inhibit their responses before any movement had been made, whereas younger children were more likely to inhibit a response part-way through the movement, demonstrating that response inhibition becomes more efficient with age. These results suggest that there are differences in the inhibitory processes taking place when a response is inhibited either prior to initiation or during the movement. These differences cannot be investigated behaviourally as there is no response to measure on trials inhibited prior to movement initiation. However, one way in which successful and partial inhibitions on no-go trials can be compared is to use event-related potentials (ERPs) which allow brain activity to be recorded in the absence of a behavioural response.

ERP studies of the go/no-go paradigm in adults have shown that the brain responds differently to correct go trials and successfully inhibited no-go trials. This is seen in a larger negative peak on no-go trials than go trials between 200 and 400 ms at fronto-central electrodes. This component, labelled the N2, is widely believed to be an index of response inhibition (Bokura, Yamaguchi, & Kobayashi, 2001; Falkenstein, Hoormann, & Hohnsbein, 1999; Jackson, Jackson, & Roberts, 1999; Jodo & Kayama, 1992; Kopp, Mattler, Goertz, & Rist, 1996). Others however, have suggested that the N2 component may reflect the detection of response conflict (Donkers & van Boxtel, 2004; Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003).

A further component often enhanced on no-go trials is the no-go P3, a positive deflection at fronto-central electrodes between 300 and 500 ms after the stimulus (Bokura et al., 2001; Kiefer, Marzinzik, Weisbrod, Scherg, & Spitzer, 1998; Pfefferbaum, Ford, Weller, & Kopell, 1985). This component is later and has a more frontal topography than the P300 typically elicited by go stimuli. The P3

components for go and no-go stimuli are believed to reflect different underlying processes (Eimer, 1993; Pfefferbaum et al., 1985; Tekok-Kilic, Shucard, & Shucard, 2001). The go P300 is enhanced on go trials at parietal electrode sites and has been linked to processing the information content of the stimulus event or identifying the target (Stige, Fjell, Smith, Lindgren, & Walhovd, 2007; Tekok-Kilic et al., 2001). In contrast, the no-go P3 has been linked to response inhibition (Bokura et al., 2001; Donkers & van Boxtel, 2004; Kiefer et al., 1998). However, unlike the N2 the no-go P3 is not modulated by performance differences (Falkenstein et al., 1999) or response priming (Kopp et al., 1996), suggesting that it is not an index of inhibition itself. Lavric, Pizzagalli and Forstmeier (2004) suggested that the no-go P3 may reflect differences in stimulus frequency or 'relative novelty' as they found no difference in amplitude between go and no-go trials when there were matched for frequency. It has also been argued that the no-go P3 simply reflects a lack of a movement-related negativity on no-go trials (Kopp et al., 1996). However, Pfefferbaum, Ford, Weller and Kopell (1985) demonstrated that a no-go P3 occurred even when participants were required to silently count the go stimuli rather than make an overt response, suggesting that the difference between go and no-go trials is due to more than just a difference in the amount of movement required.

The current experiment marks the first time successful and partial inhibitions on the go/no-go task have been compared using ERPs. Partial inhibitions are responses that are started but then inhibited before completion. Comparing these to successful inhibitions using ERPs investigates whether the same inhibitory processes are in place on both type of trial or if there is a difference in the processes underlying partial and successful inhibitions. While previous studies using the go/no-go task with ERPs have recorded partial responses using a force transducer, (Donkers & van

Boxtel, 2004) these responses were not compared to successful inhibitions. The two response types have been compared within the stop-signal paradigm however (van Boxtel, van der Molen, Jennings, & Brunia, 2001). In this task a speeded choice reaction time task is performed and occasionally a signal is presented that instructs participants to withhold their response to the stimulus. Van Boxtel, van der Molen, Jennings and Brunia (2001) used a force transducer and designated a response at a force level above 2% of the maximum force but below the criterion for a complete response (15%) as a partial response. They found that the N2 component was enhanced on partial response trials compared to fully-inhibited trials but that there was no difference in the latency of its onset. Van Boxtel et al. argued that this reflects the assumption from Logan and Cowan's horse race model (Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984) that the duration of the stopping process is constant. However, Kok, Ramautar, de Ruiter, Band and Ridderinkhof (2004) showed that the stop-signal P3 peaked later on unsuccessful than on successful stop trials, suggesting that the stopping process is not constant.

Developmental changes on the go/no-go task

As reviewed in Chapter 5, behavioural studies using the go/no-go task with children have shown evidence of a developmental improvement in response inhibition (Archibald & Kerns, 1999; Becker, Isaac, & Hynd, 1987; Berwid et al., 2005; Brocki & Bohlin, 2004; Dowsett & Livesey, 2000; Levin et al., 1991; Levy, 1980; Livesey & Morgan, 1991; Luria, 1959). Developmental changes in task performance within mid-childhood can often be quite small, although this may be due to insensitive measures rather than a lack of developmental change. It may also be the case that while the response processes in the go/no-go task do not show much development during this period, there are still changes relating to stimulus processing

or inhibitory processes that cannot be captured by the behavioural response. Using ERPs allows the examination of developmental changes in the neural processes underlying the development of response inhibition that are not constrained by behavioural performance.

A number of researchers have used ERPs to explore the development of the neural processes underlying response inhibition in the go/no-go paradigm. Many of these have used the continuous performance test (CPT) in which the target involves a particular sequence of stimuli, rather than a more standard go/no-go task, however the findings for the two tasks are similar. As in adults, children show an enhanced N2 component on no-go trials compared to go trials (Ciesielski, Harris, & Cofer, 2004; Johnstone, Pleffer, Barry, Clarke, & Smith, 2005; Jonkman, 2006; Jonkman, Lansbergen, & Stauder, 2003; Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006) suggesting that the N2 reflects inhibition or conflict processes. One exception to this finding is Davis, Bruce, Snyder and Nelson (2003) who did not find this pattern in either children or adults. They attribute this to the propagation of the P3 reducing the ability to detect the N2, however it may also be due to the fact that no-go trials were only presented in the second half of a block of 84 trials at 50% probability, and therefore the inhibitory demands may have been small.

It has consistently been found that the amplitude of the N2 component decreases with age (Ciesielski et al., 2004; Davis et al., 2003; Johnstone et al., 2007; Johnstone et al., 2005; Jonkman, 2006; Jonkman et al., 2003; Lewis et al., 2006; Okazaki et al., 2004). If it is the case that the reduction in N2 with age reflects an improvement in the efficiency of inhibitory processing, rather than other incidental age-related changes, such as increased skull density and thickness or cortical folding (Lamm, Zelazo, & Lewis, 2006) then it would be expected that the N2 in response to

no-go trials would change with age, whereas the N2 on go trials would not. While this pattern of results has been found in some studies (Johnstone et al., 2005; Jonkman, 2006) this is not always the case (Jonkman et al., 2003; Lewis et al., 2006).

The developmental changes in the N2 component have not always been found to tie-in with a behavioural improvement in inhibition. Johnstone et al. (2007) found that while the N2 component at centro-parietal electrodes decreased with age, it was the N2 at frontal electrodes that correlated with behavioural performance on the task, suggesting it was indexing inhibitory processes. Furthermore, the N2 was larger in those children with better behavioural performance. Therefore age-related changes did not appear to be linked to an improvement in inhibition. They did find that the latency of the frontal N2 showed developmental changes, with a shorter latency on no-go trials in the older children which is consistent with previous findings (Ciesielski et al., 2004; Davis et al., 2003; Johnstone et al., 2005; Lamm et al., 2006). Johnstone et al. argued that this was related to an increase in the efficiency of inhibitory processing with age.

A study by Lamm, Zelazo and Lewis (2005) also suggested that the amplitude of the N2 is related to cognitive control rather than to developmental change. They did not investigate the relationship between performance on the go/no-go task and the amplitude of the N2, but found that performance on two other executive tasks, the Stroop Colour-Word Task and the Iowa Gambling Task predicted the amplitude of the N2 better than age, with better performance resulting in a smaller N2. This is in contrast to the findings of Johnstone et al. (2007), however the reduction in N2 may reflect a more general improvement in attention as it relates to performance on two very different tasks-the Stroop and Gambling tasks, rather than to a more specific measure of inhibition. In some cases, a relationship

between behavioural performance and the amplitude of the N2 has not been found. Ciesielski, Harris and Cofer (2004) found that the N2 in children was influenced by stimulus probability rather than the inhibitory load of the task as it was in adults, however this N2 was largest at parietal rather than frontal electrodes.

In summary, there are mixed findings concerning the development of the N2 components. Overall, the N2 decreases with age. However as this occurs on go as well as no-go trials this change may not specifically be linked to developments in inhibition. Indeed, there is some evidence for a *larger* N2 on no-go trials in children with better inhibitory control (Johnstone et al., 2007). However, it has also been shown that better performance on other executive tasks is reflected in a smaller N2 (Lamm et al., 2005) while a relationship between the N2 and behavioural performance has not always been found.

While a robust N2 component is present throughout development, the no-go P3 component is not always enhanced on no-go trials in children. Indeed, Jonkman, Lansbergen and Stauder (2003) found that the no-go P3 component was larger for go compared to no-go trials in children aged 9 to 10 years. Johnstone, Pleffer, Barry, Clarke and Smith (2005) found a similar pattern in children although this was non-significant. This effect was not due to the type of paradigm used as standard no-go P3 effects were found with adults. It has been proposed that the enhanced no-go P3 begins to develop around the age of 10-years-old (Jonkman, 2006; Okazaki et al., 2004). As in adults, it is not clear what the no-go P3 in children represents. Jonkman (2006) suggested that the no-go P3 reflects response inhibition processes as it follows a similar pattern of development to behavioural performance on her task, with no improvement between 6 to 7 years and 9 to 10 years but a large difference between children and adults. However, it is obvious that this component cannot be

an index of whether response inhibition occurs or not as children's behavioural performance on the go/no-go task is typically high even in the absence of the no-go P3.

Davis et al. (2003) did find an enhanced no-go P3 component in children but suggested that the difference in the no-go P3 between children and adults may reflect the fact that they are processing the task in different ways. They found that adults showed a larger P3 component on no-go trials, even at parietal sites, while children showed an enhanced P3 component on both go trials and no-go trials in a mixed block compared to a block of pure go trials. From this they argued that in children, the no-go P3 could index withholding an automatic response in order to evaluate the stimuli, whereas in adults it may be related to a later control process involved in inhibiting incorrect responses on no-go trials. Lewis, Lamm, Segalowitz, Stieben and Zelazo (2006) also found that children showed larger no-go P3 components on no-go trials compared to go trials. One similarity between these studies is that they identified the peak amplitude of the component in a large and late time window: 475-1090ms (Davis et al., 2003) and 250-1000ms (Lewis et al., 2006). Thus it may just be that the enhanced no-go P3 component is delayed as opposed to absent in children.

This experiment aimed to examine the neural processes underlying the development of response inhibition by comparing successful and partial inhibitions on a go/no-go task. The experiment formed part of a larger study examining cognitive development between the ages of 7 and 9. Given that behavioural developments on the go/no-go task in this age group are often small (Johnstone et al., 2007; Jonkman, 2006) it was not expected that there would be a large difference in the behavioural performance of these two age groups. However, we predicted that

they would show the same pattern of results as found in Chapter 5, with the 9-year-olds making more full inhibitions and the 7-year-olds more partial responses. In addition, even in the absence of behavioural differences we expected that significant neurophysiological changes would take place. It was predicted that developmental improvements in the efficiency of response inhibition would be reflected in a shorter N2 latency, however given the mixed findings in the literature, no predictions were made concerning N2 amplitude. Consistent with previous findings (Johnstone et al., 2005; Jonkman et al., 2003) we did not expect to find an enhanced no-go P3 component in this age group.

Method

Participants

Forty-four 7-year-olds and forty-one 9-year-olds recruited from primary schools in Perth, Western Australia took part in this experiment as part of a larger project addressing the cognitive changes that take place between these ages. Children who didn't meet the criteria of more than 50% accuracy on go trials (five 7-year-olds and seven 9-year-olds) or for whom there were not more than five trials contributing to the average in each condition (twelve 7-year-olds and four 9-year-olds) were excluded. The children excluded on these grounds did not differ from the rest of the sample in terms of age ($F(1, 83)=1.29, ns$) or full-scale IQ ($F(1, 83)<1, ns$). In addition two participants were excluded because of a technical problem with recording. One further 7-year-old was excluded because the recording from the Fz channel was bad. This left a sample of twenty-six 7-year-olds (13 male; $M=7.51$ years, $SD=.23$) and thirty 9-year-olds (10 male; $M=9.26$ years, $SD=.50$).

Behavioural task and procedure

This experiment formed part of Project K.I.D.S. a scheme run during the school holidays at the University of Western Australia which children attended for two days, completing a variety of psychological tasks. Electrophysiological data were collected in the same session as other ERP paradigms with the go/no-go data collected in the last 10 minutes of a 40 minute recording session.

The go/no-go task used was virtually identical to that reported in Chapter 5 but without the ISI manipulation. Two children performed the task at the same time. They were told that they were part of a football team and that the aim of the game was to score lots of penalties by pressing the target key whenever a football appeared. The task was explained using a series of instruction screens and the response was demonstrated by an experimenter. First, two blocks consisting of 30 go trials were performed, in which a football was presented for 200ms on a background screen consisting of grass, sky and a football goal. The children were required to keep their index finger pressed down on a home key ('left-click' button on a mouse) during the inter-stimulus interval (1500-2500ms) and respond to the footballs by releasing the home key and pressing the adjacent target key ('right-click' mouse button) with the same finger as fast as possible. A red star sticker was placed on the home key to indicate where to press, and as a result it was referred to as the 'star button'. If the key was released between trials then a reminder "Press the star!" appeared at the top of the screen. These blocks of go trials allowed the children to become familiar with the task, and also encouraged a prepotent response to respond to the stimuli on every trial. Feedback consisting of the current score (always a draw) was presented after each block to encourage the children to continue and 'win' the match.

Following the blocks of go trials, two blocks of the go/no-go task were presented, with 100 trials in each block. The no-go stimulus was a rugby ball presented on 25% of trials. Again, the home key was to remain pressed during the inter-stimulus interval (2000ms) and it was explained that when the rugby ball appeared they should keep their index finger pressed down on the home key so as not to kick the ball. After the final block a feedback screen announced that they had won the football match.

Electrophysiological recording

The electroencephalogram (EEG) was recorded from electrodes positioned according to the EC40 standardised montage at 35 sites (FP1, FP2, F7, F3, FZ, F4, F8, FT9, FC5, FC1, FCZ, FC2, FC6, FT10, T7, C3, CZ, C4, T8, TP9, CP5, CP1, CP2, CP6, TP10, P7, P3, PZ, P4, P8, O1, O2, PO9, IZ, PO10). The vertical electro-oculogram (EOG) was measured with electrodes placed above and below one eye. The electrodes were referenced to linked mastoids and the ground electrode was AFz. Prior to recording impedances for the scalp electrodes were reduced below 5 k Ω . The signal was sampled at 250 Hz filtered online at DC to 70 Hz. The EEG was recorded using a Nuamps 40 channel amplifier and Scan 4.3 software.

The ERP epoch was defined as 100ms pre-stimulus to 1000ms post-stimulus and baseline-corrected to the 100ms prior to stimulus onset. Trials contaminated by eye movements were corrected using the EOG correction algorithm of Semlitsch (1986). The data were filtered offline using a bandpass filter with a high frequency cut-off at 0.01 Hz (6dB/oct roll-off) and a low frequency cut-off at 30 Hz (24dB/oct roll-off). Automatic artefact rejection was applied offline to exclude all epochs with voltage exceeding $\pm 150 \mu\text{V}$.

Data Analysis

Separate grand averages (Figure 6.1) were calculated for correct go trials (hits) and partial and successful inhibitions on no-go trials. An average of 91.3 (27.8), 12.9 (4.67) and 16.4 (7.87) trials contributed to each condition respectively. A problem we faced in analysing this data was that not all participants showed N2 or P3 peaks in all conditions. Because of this both peak and mean amplitudes were used in the analyses. All time windows were selected by examining both grand-average and individual waveforms. Scalp topographies for these time windows are presented in Appendix V. Peak identification for the N2 component was defined as the largest baseline-to-peak negative deflection in the region of 260-400ms, at electrodes Fz, FCz and Cz. If no peak was identified then the data point was set to missing. Three 7-year-olds and nine 9-year-olds could not be included in the N2 peak analysis as they did not demonstrate a peak in one of the conditions for at least one electrode. The analyses were also performed using the mean N2 amplitude between 260 and 400ms, to include all participants. N2 latency was only measured in the partial and successful inhibition conditions as the majority of participants not included in the peak analysis lacked a peak in the go condition. The N2 latency was measured from stimulus-onset to peak at Fz. For this analysis one 7-year-old could not be included as they had no peak in the successful inhibition condition at Fz. For the no-go P3 component, no peak was evident in the grand average of the partial inhibition in the 7-year-olds. Therefore mean amplitudes between 400 and 500ms were used at electrodes Fz, FCz and Cz for the no-go P3 component. For the go P3 component the mean amplitude between 240 and 400ms at Pz was used.

Results

Anticipatory trials (defined as $RT < 200\text{ms}$, or when the first response was not the release of the home key) were discarded (15.4%). Responses to go trials were coded as either *hits* (the home key was lifted and the target key pressed) or *misses* (the home key remained pressed or the home key was lifted but the response key not pressed). Responses to no-go trials were coded as either a *successful inhibition* (the home key remained pressed), *partial inhibition* (the home key was lifted but the response key not pressed) or *failed inhibition* (the home key was lifted and the target key pressed). For the RT analyses, RTs greater than $2.5SD$ above the participant's mean for each response measure (release time, movement time) were excluded (release time: 3.06%; movement time: 1.00%) and the mean RT was then calculated for each condition.

Behavioural results

A two-way repeated measures ANOVA with Age (7, 9) as a between-subjects factor and Response (failed inhibition, partial inhibition, successful inhibition) as a within-subjects factor showed that the children made more partial inhibitions ($M=31.6$, $SD=10.2$) than failed inhibitions ($M=16.6$, $SD=10.7$) and more successful inhibitions ($M=39.9$, $SD=17.3$) than both other response types. Although the pattern of responses on no-go trials mirrored those found in the previous chapter, with more successful inhibitions in the 9-year-olds (7-year-olds: $M=36.3$, $SD=16.8$; 9-year-olds: $M=43.1$, $SD=17.4$) and more partial inhibitions in the 7-year-olds (7-year-olds: $M=33.2$, $SD=11.0$; 9-year-olds: $M=30.3$, $SD=9.50$), there was no significant difference in the number of each response type made by the two age groups ($F(1.69, 91.2)=1.41$, *ns*).

RTs were compared for the time taken to release the home key. A two-way ANOVA with Age (7, 9) as a between-subjects factor and Trialtype (hits, partial inhibitions) as a within-subjects factor main effect of Trialtype ($F(1, 54)=9.67$, $p<.01$, $\eta^2=.152$) demonstrating that all children were faster to release the home key on partial inhibition trials ($M=368.6$, $SD=111$) than on go trials ($M=392.6$, $SD=81.2$). This is consistent with Logan and Cowan's horse-race model (Logan & Cowan, 1984; Logan et al., 1984), suggesting that these faster responses are initiated before inhibitory processes are completed. Overall the RTs for the two age groups did not differ, $F(1, 54)=2.21$, *ns*. To compare the RTs for hits and partial inhibitions with failed inhibitions only the sixteen 7-year-olds and twenty-two 9-year-olds who made more than five failed inhibitions were included². Again there was no difference in RT between age groups ($F(1, 36)<1$, *ns*), and this time no effect of Trialtype ($F(1.41, 50.8)=2.03$, *ns*). The movement time between releasing the home key and pressing the target key was also compared for hits and failed inhibitions, however there was no difference either between trialtypes ($F(1, 36)<1$, *ns*), or age groups ($F(1, 36)<1$, *ns*).

ERP results

N2 component

A three-way repeated measures ANOVA was performed with Age (7, 9) as a between-subjects factor and Trialtype (hits, partial inhibitions, successful inhibitions) and Electrode (Fz, FCz, Cz) as within-subject factors for both peak and mean

² The children not included in this analyses did not differ from those who were included in terms of age, IQ or go RT (all $F(1, 54)<1$, *ns*), but did make fewer anticipation errors suggesting they made fewer failed inhibitions because they were more on-task ($F(1, 54)=5.39$, $p<.05$).

amplitude. Means and standard deviations are presented in Table 6.1 for the mean amplitude and Table 6.2 for the peak amplitude. As Mauchly's test of sphericity was violated the greenhouse-geisser correction was used. A main effect of Trialtype was found (peak: $F(1.91, 80.1)=41.0, p<.001, \eta^2=.494$; mean: $F(1.93, 104)=27.6, p<.001, \eta^2=.339$) as the N2 was more negative on both partial and successful inhibition no-go trials than on hits on go trials. There was also a main effect of Electrode, (peak: $F(1.31, 54.9)=43.4, p<.001, \eta^2=.508$; mean: $F(1.33, 71.7)=66.9, p<.001, \eta^2=.554$) as the N2 was more negative at Fz and FCz than it was at Cz. This was qualified by a Trialtype x Electrode interaction, (peak: $F(3.03, 127)=4.45, p<.01, \eta^2=.096$; mean: $F(2.76, 149)=2.73, p=.051, \eta^2=.048$) as the N2 for go trials was more distributed across electrodes than the N2 for both types of no-go trials which were larger at frontal electrodes. There was also an Electrode x Age interaction (peak: $F(1.31, 54.9)=5.32, p<.05, \eta^2=.112$; mean: $F(1.33, 71.7)=6.41, p<.01, \eta^2=.106$) as there was a greater difference between the two frontal electrodes and Cz for the 9-year-olds than there was for the 7-year-olds. The three-way interaction between Electrode, Age and Trialtype approached significance for mean amplitude ($F(2.76, 149)=2.30, p=.085, \eta^2=.041$) but not peak amplitude ($F(3.03, 127)<1, ns$). As this may have been due to a lack of power, additional three-way ANOVAs were carried out for partial response and no response trials separately.

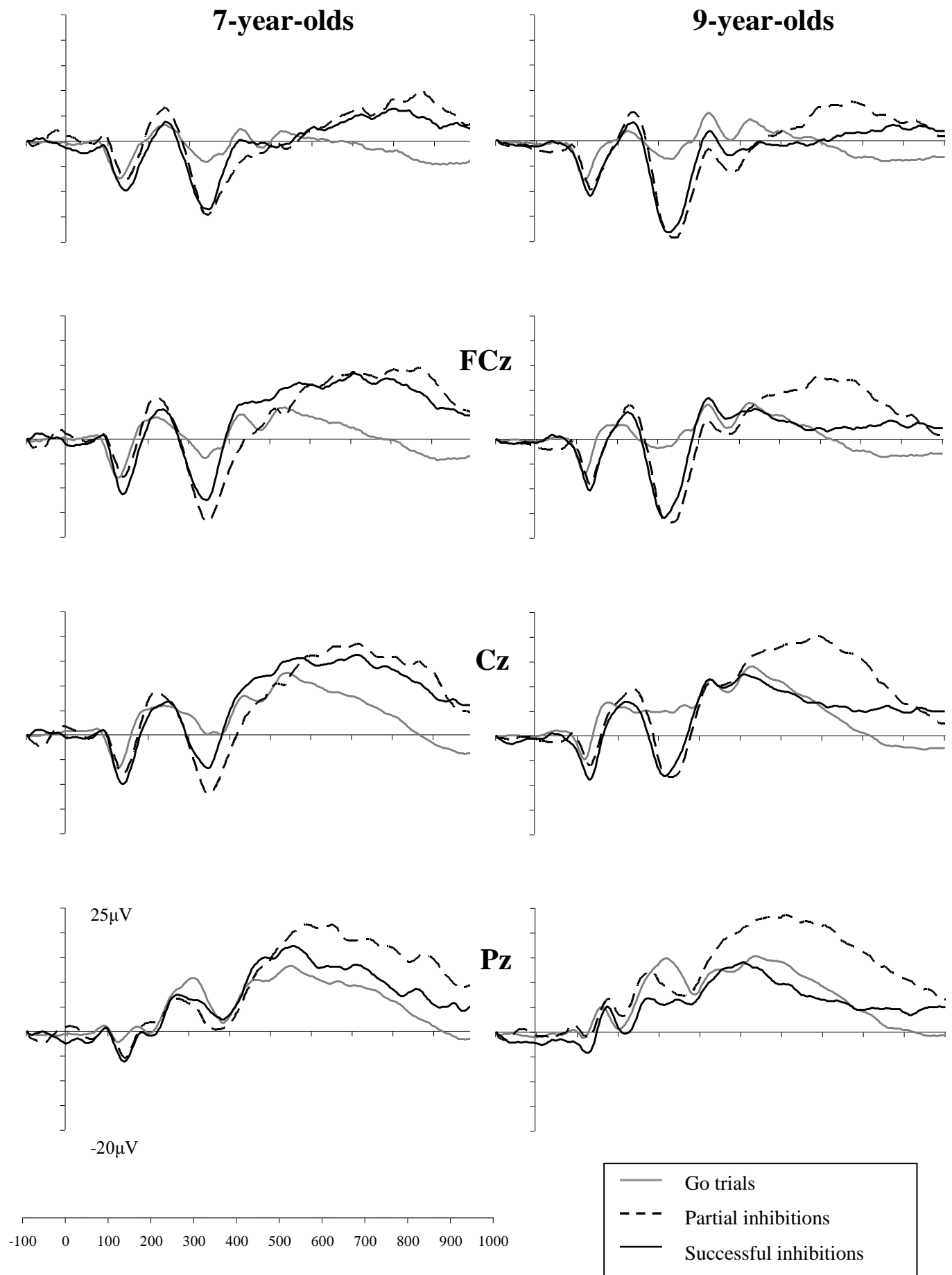


Figure 6.1: Grand averages for go trials and partial and successful inhibitions in 7- and 9-year-olds

Table 6.1: Mean (*SD*) N2 mean amplitude (μ V)

	Fz	FCz	Cz
7-year-olds			
Hits	-1.86 (6.40)	-1.13 (8.46)	2.34 (8.92)
Partial Inhibitions	-7.94 (10.5)	-9.27 (9.44)	-5.24 (8.88)
Successful Inhibitions	-7.49 (9.54)	-5.66 (10.7)	-1.21 (9.47)
9-year-olds			
Hits	-1.63 (3.94)	-0.05 (5.05)	5.38 (5.85)
Partial Inhibitions	-12.3 (9.8)	-10.1 (10.8)	-2.51 (11.4)
Successful Inhibitions	-11.3 (8.74)	-8.12 (9.36)	-2.10 (9.51)

The ANOVA for partial inhibitions was performed with Age (7, 9) as a between-subjects factor and Trialtype (hits, partial inhibitions) and Electrode (Fz, FCz, Cz) as within-subject factors. There were main effects of Trialtype (peak: $F(1, 43)=65.6$, $p<.001$, $\eta^2=.604$; mean: $F(1, 54)=45.5$, $p<.001$, $\eta^2=.457$) and Electrode (peak: $F(1.30, 55.7)=30.6$, $p<.001$, $\eta^2=.416$; mean: $F(1.32, 71.1)=51.8$, $p<.001$, $\eta^2=.490$) and an Electrode x Age interaction (peak: $F(1.30, 55.7)=6.21$, $p<.01$, $\eta^2=.126$; mean: $F(1.32, 71.1)=7.69$, $p<.01$, $\eta^2=.125$). The Trialtype x Electrode interaction, suggesting a more frontal N2 for partial inhibitions than for hits, was significant for the peak ($F(1.84, 79.2)=3.78$, $p<.05$, $\eta^2=.081$) but not the mean analysis ($F(1.56, 84.2)=1.20$, ns). While the interaction between Trialtype and Age was not significant for either the set of analyses (peak: $F(1, 43)<1$, ns ; mean: $F(1, 54)<1$, ns), there was a marginal Trialtype x Electrode x Age Group interaction for the mean ($F(1.56, 84.2)=3.04$, $p=.065$, $\eta^2=.053$) but not the peak analysis ($F(1.84,$

79.2)=1.07, *ns*. This was due to a larger difference in N2 amplitude between hits and partial inhibitions at Fz in 9-year-olds than in 7-year-olds.

Table 6.2: Mean (*SD*) N2 peak amplitude (μ V) and latency (ms)

	Fz	FCz	Cz	Latency (Fz)
7-year-olds				
Hits	-7.96 (7.61)	-7.95 (8.64)	-5.48 (8.05)	--
Partial Inhibitions	-19.5 (12.0)	-21.1 (9.74)	-16.1 (10.1)	353 (29.1)
Successful Inhibitions	-18.7 (12.0)	-17.8 (13.1)	-12.1 (11.7)	341 (26.8)
9-year-olds				
Hits	-8.89 (4.95)	-7.82 (6.14)	-1.95 (8.05)	--
Partial Inhibitions	-24.8 (11.4)	-23.6 (12.2)	-14.4 (11.3)	332 (24.2)
Successful Inhibitions	-25.8 (9.6)	-24.5 (9.08)	-15.6 (9.54)	325 (25.3)

The ANOVA for successful inhibitions (Age (7, 9) as a between-subjects factor and Trialtype (go trials, successful inhibitions) and Electrode (Fz, FCz, Cz) as within-subject factors) also showed main effects of Trialtype (peak: $F(1, 42)=71.5$, $p<.001$, $\eta^2=.630$; mean: $F(1, 54)=37.1$, $p<.001$, $\eta^2=.407$) and Electrode (peak: $F(1.45, 60.9)=44.9$, $p<.001$, $\eta^2=.517$; mean: $F(1.45, 78.5)=71.3$, $p<.001$, $\eta^2=.569$) as well as an Age x Electrode interaction (peak: $F(1.45, 60.9)=4.01$, $p<.05$, $\eta^2=.087$; mean: $F(1.45, 78.5)=3.08$, $p=.067$, $\eta^2=.054$). In addition there was a Trialtype x Electrode interaction as the difference between trialtypes was greatest at Fz (peak: $F(1.28, 53.7)=9.23$, $p<.01$, $\eta^2=.180$; mean: $F(1.33, 71.8)=5.32$, $p<.05$, $\eta^2=.090$). There was a Trialtype x Age interaction (peak: $F(1, 42)=5.20$, $p<.05$, $\eta^2=.110$; mean:

$F(1, 54)=3.22$, $p=.078$, $\eta^2=.056$) as there was a greater difference between N2 amplitude on hits and successful inhibitions for 9-year-olds than for 7-year-olds. The Trialtype x Electrode x Age interaction was not significant (peak: $F(1.28, 53.7)<1$, *ns*; mean: $F(1.33, 71.8)<1$, *ns*).

The latency of the N2 was measured at Fz as this is where it was largest. The participants who did not show clear N2 peaks ($n=12$) were not included in this analysis. A two-way ANOVA was performed with Age (7, 9) as a between-subjects factor and Trialtype (partial inhibitions, successful inhibitions) as a within-subject factor. There was a significant effect of Age ($F(1, 53)=9.38$, $p<.01$, $\eta^2=.150$) as the latency was slightly shorter for the 9-year-olds than the 7-year-olds (see Table 6.2). There was also a main effect of Trialtype, $F(1, 53)=5.87$, $p<.05$, $\eta^2=.100$, due to the fact that the latency on partial inhibitions was slightly later than the latency for successful inhibitions. The Trialtype x Age interaction was not significant ($F(1, 53)<1$, *ns*) demonstrating that both age groups showed shorter latencies on partial inhibitions compared to successful inhibitions.

In summary, the results for the N2 component were similar for both mean and peak analyses. There was a significant N2 effect in both age groups, with a larger N2 on both types of no-go trials (partial and successful inhibitions) than on go trials. The amplitude of the N2 component did not decrease with age. In fact the 9-year-olds showed a larger N2 effect on successful inhibitions than the 7-year-olds at all three electrode sites. This was less apparent for the partial inhibitions, although there was some evidence that the 9-year-olds showed a greater difference between partial inhibitions and hits than the 7-year-olds at Fz. Generally the N2 was larger at Fz and FCz than at Cz. This pattern was more exaggerated in the 9-year-olds than the 7-year-olds, suggesting that the N2 may become more focussed at frontal electrodes

with age. Consistent with our predictions, the N2 was earlier in the 9-year-olds than the 7-year-olds and for both age groups the N2 was earlier on successful than on partial inhibitions, suggesting that as well as due to faster response processes, partial inhibitions were also affected by slower inhibitory processes on these trials.

No-go P3 component

To assess the no-go P3 component a three-way ANOVA was carried out with Age (7, 9) as a between-subjects factor and Trialtype (hits, partial inhibitions, successful inhibitions) and Electrode (Fz, FCz, Cz) as within-subject factors. Means and standard deviations are presented in Table 6.3. There was a main effect of Trialtype, $F(1.82, 98.0)=3.99, p<.05, \eta^2=.069$, as overall the no-go P3 was smaller on partial inhibitions than on hits or successful inhibitions. There was also a main effect of Electrode, $F(1.32, 71.4)=76.3, p<.001, \eta^2=.586$.

Table 6.3: Mean (SD) no-go P3 amplitude (μ V)

	Fz	FCz	Cz
7-year-olds			
Hits	0.37 (8.36)	3.24 (8.18)	6.90 (8.04)
Partial Inhibitions	-3.41 (13.5)	0.01 (12.7)	4.00 (12.8)
Successful Inhibitions	-0.55 (10.1)	6.84 (11.0)	9.99 (10.4)
9-year-olds			
Hits	2.57 (5.47)	4.52 (6.74)	9.96 (7.76)
Partial Inhibitions	-4.43 (10.1)	1.95 (12.3)	10.3 (16.0)
Successful Inhibitions	-0.87 (8.95)	5.84 (9.82)	10.5 (9.55)

The main effects were qualified by a Trialtype x Electrode interaction, $F(2.61, 141)=8.32, p<.001, \eta^2=.134$, as at Fz both partial and successful inhibitions were more negative than hits, whereas at FCz there was no difference between the no-go P3 for hits and successful inhibitions, but the partial inhibition no-go P3 was still smaller. This pattern continued at Cz for the 7-year-olds, however the 9-year-olds showed an equivalent response for all trialtypes at Cz. This was confirmed by a significant three-way interaction between Trialtype, Electrode and Age, $F(2.61, 141)=3.63, p<.05, \eta^2=.063$.

Go P3 component

One 9-year-old could not be included in the analysis for the Go P3 component as the Pz electrode was a bad channel. A two-way mixed-measures ANOVA was performed with Age (7, 9) as a between-subjects factor and Trialtype (hits, partial inhibitions, successful inhibitions) as a within-subject factor. There was a main effect of Trialtype, $F(1.95, 103)=4.32, p<.05, \eta^2=.075$, which post-hoc tests revealed was due to a significant difference between hits ($M=9.05, SD=6.67$) and successful inhibitions ($M=5.52, SD=9.57$). The amplitude for partial inhibitions was in-between ($M=6.54, SD=9.28$) and did not significantly differ from either of the other two trialtypes. There was also a main effect of Age, $F(1, 53)=4.20, p<.05, \eta^2=.073$ as overall the Go P3 was larger in 9-year-olds ($M=8.77, SD=6.11$) than in 7-year-olds ($M=5.10, SD=7.15$). There was a trend towards a Trialtype x Age interaction, $F(1.95, 103)=2.50, p=.089, \eta^2=.045$, due to the fact that the 9-year-olds showed a larger go P3 than the 7-year-olds on hits and partial inhibitions but not on successful inhibitions.

Relationship with behavioural performance

Correlations between the ERP components and behavioural performance, indexed by the percentage of successful inhibitions, were performed for 7 and 9-year-olds separately. The N2 amplitude in the 7-year-olds was related to behavioural performance, such that those with more accurate performance showed a larger N2 at FCz on both partial inhibitions (peak: $r(26) = .452, p < .05$; mean: $r(26) = .429, p < .05$) and successful inhibitions (peak: $r(26) = .427, p < .05$; mean: $r(26) = .309, ns$), and also at Fz for successful inhibitions (peak: $r(26) = .471, p < .05$; mean: $r(26) = .534, p < .01$). With regards to latency, within the group of 7-year-olds, latency on go trials ($r(26) = -.414, p < .05$) and partial inhibition trials ($r(26) = -.389, p < .05$) showed a negative correlation with age, with a shorter latency in the older children within this age group.

In the 9-year-olds the peak N2 did not correlate with behavioural performance and a negative relationship with partial inhibitions was seen at Fz when the mean N2 amplitude was used ($r(30) = -.369, p < .05$). However, those 9-year-olds who were more accurate on the task showed a trend towards a larger no-go P3 on successful inhibitions at FCz ($r(30) = .351, p = .057$).

Discussion

This experiment investigated the neural changes underlying improvements in the efficiency of response inhibition during childhood. This was done through a comparison of the electrophysiological responses to successful and partial inhibitions in 7- and 9-year-old children. The developmental changes and differences between successful and partial inhibitions are discussed separately.

Developmental changes

The behavioural data did not show a significant developmental improvement in response inhibition, although the pattern of results supported our previous experiment, reported in Chapter 5, with more successful inhibitions and fewer partial inhibitions in the older children. With more power these differences may become significant.

Despite the lack of significant differences in behaviour, there were developmental differences in the ERPs. Consistent with Johnstone et al. (2007) there was a decrease in the latency of the N2 component with age, supporting the results presented in Chapter 5 showing that the efficiency of response inhibition improves during childhood. Not only was there a difference between the two age groups, there was also developmental change within the 7-year-olds as the latency of the N2 on partial inhibition trials decreased with age. This shows that improvement in the efficiency of response inhibition is a continuous development.

The results concerning the N2 amplitude were intriguing. The N2 was larger in 9-year-olds than 7-year-olds on successful inhibition trials. While this seems at odds with the existing developmental literature showing a reduction in N2 amplitude with age (Ciesielski et al., 2004; Davis et al., 2003; Johnstone et al., 2007; Johnstone et al., 2005; Jonkman, 2006; Jonkman et al., 2003; Lewis et al., 2006; Okazaki et al., 2004) it may be because of the small age range in this experiment. There is also little evidence that age related changes in the N2 actually reflect an improvement in response inhibition. The reduction in N2 amplitude with age found in other studies may simply be due to incidental age-related changes such as increased skull density and thickness.

In this experiment the 7-year-olds with more accurate behavioural performance showed a larger N2. This is consistent with previous studies (Falkenstein et al., 1999; Johnstone et al., 2007) and suggests that the N2 reflects inhibitory processes. This finding supports Johnstone et al. (2007) in showing a positive correlation between the size of the N2 and performance, however these results are inconsistent with the findings of Lamm et al. (2005) who found that children who had better cognitive control showed a smaller N2. This may be because Lamm et al. correlated the N2 with performance on the Stroop and Iowa gambling tasks rather than performance on the no-go task itself. The enhanced N2 on successful inhibitions in 9-year-olds may reflect greater inhibition on successfully inhibited trials in the older children. Interestingly however, behavioural performance did not correlate with N2 amplitude in the 9-year-olds, whose performance seemed to be related to the no-go P3 component instead. This result is difficult to explain and warrants further investigation.

Developmental changes were apparent in the pattern of the N2 component across electrodes. The N2 was more distributed across electrodes in 7-year-olds than in 9-year-olds, who showed a more frontal N2 component. While this cannot be taken to reflect different localisation of the components within the brain, it does show that age-related changes are occurring and is consistent with the idea that developmental changes in patterns of brain activity involve a shift from diffuse to more focal activation (Casey, Giedd, & Thomas, 2000; Durston & Casey, 2006).

This experiment replicated the finding that the no-go P3 component is not enhanced compared to go trials in children (Johnstone et al., 2005; Jonkman, 2006; Jonkman et al., 2003). There were no significant developmental differences in this component, with a similar pattern across frontal electrodes in both age groups. This

is in contrast to the results of Jonkman (2006) who found an enhanced no-go P3 in 9- and 10-year-olds compared to 6- and 7-year-olds. One explanation for this is that it was only the 10-year-olds in Jonkman's study who were showing more mature performance and therefore creating a difference between groups.

Developmental differences were apparent in the go P3, believed to be related to processing the information content of the stimulus (Tekok-Kilic et al., 2001) at parietal electrodes. The 9-year-olds showed an enhanced go P3 compared to 7-year-olds, particularly on go trials and partial inhibitions. Inspection of the grand averages suggests that the go P3 on partial inhibitions was more similar to successful inhibitions in the 7-year-olds but more similar to hits in the 9-year-olds. It also appears that the P3 on partial inhibition trials returned to baseline more quickly than the P3 for go trials in the older age group. There is no clear explanation for these results, however the differences in the go P3 between the 7 and 9-year-olds may reflect the fact that the two groups are processing partial inhibition trials in different ways. The enhanced P3 on go trials presumably indicates that the stimulus has been identified as the target. Thus the enhanced go P3 on partial inhibition trials in 9-year-olds may occur because they mistakenly treated the no-go stimulus as a target on these trials and started to respond. The earlier return to baseline may reflect either the realisation that the stimulus actually requires no response, or the start of inhibitory processes. In contrast, the 7-year-olds may have realised that they should not respond on these trials but were unable to stop themselves from initiating the movement. This explanation for these developmental differences is a tentative suggestion which requires further investigation.

Partial vs. Successful Inhibitions

This was the first time that fully inhibited responses, and those on which a response is started but then inhibited part-way through have been compared using ERPs in the go/no-go paradigm. Differences were apparent in the latency of the N2 component and the amplitude of the no-go P3 component. The N2 component was later on partial inhibition trials than on successful inhibition trials, suggesting that in addition to partial inhibitions resulting from faster responses, inhibition also occurs slightly later on these trials. This also supports Kok et al.'s (2004) suggestion that the speed of inhibition is not constant. There was no difference in the amplitude of the N2 on the successful and partial inhibition trials. These results are in contrast to the findings of van Boxtel et al. (2001) who found a larger N2 on partial inhibition trials than on successful inhibition trials, but no difference in latency. This may be due to the different tasks used in the two studies. Van Boxtel et al. used a stop-signal task that included go/no-go trials and found similar results on no-go trials and successful stop-signal trials. From this they suggested that the ERP components for the two tasks are comparable. This may not be the case in children however. Johnstone et al. (2007) compared ERPs to separate go/no-go and stop-signal tasks in children and found very few similarities between the two tasks, suggesting that the ERP components for the two tasks are not comparable in children. It should also be noted that the response in this experiment differed from the response used by van Boxtel et al. While they defined a partial inhibition as one which did not reach the required level of force, in our experiment a partial inhibition could be thought of as one half of a two-part response.

Although the amplitude of the N2 did not differ between partial and successful inhibitions, the amplitude of the no-go P3 did. The difference between the

two trial types was most apparent at FCz, where the amplitude was smaller on partial inhibitions than on hits and successful inhibitions. It is not entirely clear what this difference between partial and successful inhibitions represents. However, it suggests that there may be differences in processing between successful and partial inhibitions, possibly related to greater inhibition on successfully inhibited trials, rather than simply that inhibition occurs at an earlier stage during the movement on successfully inhibited trials. It is difficult to draw firm conclusions from these differences in the no-go P3 component given that the children did not show the enhancement on no-go trials seen in adults. It would be useful to replicate this experiment in adults to see if the difference between successful and partial inhibitions in the no-go P3 component is still present.

Conclusion

In conclusion, using ERPs with this modified version of the go/no-go task showed developmental changes and differences between successful and partial inhibitions that were not apparent through the use of behavioural measures. The shorter latency of the N2 component in older children supported the idea that response inhibition becomes more efficient with age. The results were partly consistent with the notion that the amplitude of the N2 is linked to better response inhibition (Johnstone et al., 2007) as 7-year-olds with more accurate performance showed a larger N2. However, despite the fact that 9-year-olds showed a larger N2 than 7-year-olds on successful inhibitions, the N2 was not related to behavioural performance in this age group, a difficult finding to explain. Consistent with previous studies (Johnstone et al., 2005; Jonkman et al., 2003), the no-go P3 was not enhanced on no-go trials in either age group. Developmental changes were apparent

in the go P3, perhaps indicating different explanations for partial inhibitions in the two age groups.

The N2 latency was shorter for successful inhibitions than partial inhibitions suggesting that inhibition is not constant (Kok et al., 2004) and that partial inhibitions may be due to slower inhibitory processes as well as faster responses. The larger no-go P3 component for successful inhibitions may indicate additional processing on these trials in addition to a simple difference in the timing of inhibition. However, this finding does need replicating. Further investigation of these processes in a wider age range of participants, including a comparison between children and adults, would help to determine exactly what these differences represent and how they develop.

Chapter 7: The bigger picture: Relationships and trajectories in executive function

In this chapter we took a broader approach and investigated the relationships between shifting, inhibition and working memory during development. The first step involved validating our new executive tasks against existing standardised tests to ensure they were indexing the constructs they were designed to measure. Once this was ascertained we proceeded to investigate the relationships between these executive skills, particularly the roles of inhibition and working memory in switching ability. These processes appeared to be relatively independent from each other, and also from general intelligence. Despite this independence, shifting and working memory showed a strikingly similar pattern of development between the ages of 5 and 11 years. While overall these improved with age, there seemed to be a small decrement in performance both before and after a relatively steep linear improvement between the ages of 7 and 10 years. In contrast to switching and working memory, response inhibition did not show as much improvement during this period and reached a stable level of performance at an earlier age.

The main aim of this experiment was to investigate the relationships between the executive skills of shifting (shifting back and forth between multiple tasks, operations or mental sets), inhibition (the deliberate, controlled suppression of prepotent responses) and working memory (the activation and manipulation of task-relevant information in memory). We also sought to determine if these skills show a similar pattern of development during mid-childhood. As stated in Chapter 1, there is evidence from both children and adults that executive function can be fractionated

(Brocki & Bohlin, 2004; Fassbender et al., 2004; Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000; Pennington, 1998; Stuss et al., 2002; Stuss & Benson, 1986). Yet even though executive skills can be dissociated, they are still closely related. Some theories suggest that working memory and inhibition are particularly tightly linked and that there is an interactive relationship between the two (Bjorklund & Harnishfeger, 1990; Miller & Cohen, 2001; Munakata, 2001; Roberts & Pennington, 1996). However, the relative importance of these processes is debated. It has been suggested that inhibition is primary, such that good inhibitory skills stop irrelevant information from entering working memory (Bjorklund & Harnishfeger, 1990). Others have argued that working memory is more important and that activation of relevant information in working memory results in the concomitant suppression of irrelevant information (Roberts & Pennington, 1996). If there is such a close link between these processes, then performance on tasks of working memory and inhibition should be correlated. This has been demonstrated in some studies (Archibald & Kerns, 1999; Davidson, Amso, Anderson, & Diamond, 2006) but others have not found a strong relationship between the two skills (Beveridge, Jarrold, & Pettit, 2002; Huizinga et al., 2006).

Inhibition and working memory are also related to the process of shifting. In Chapter 1 we raised the point that shifting in children is often explained in terms of inhibition and/or working memory demands (Davidson et al., 2006; Kirkham, Cruess, & Diamond, 2003; Morton & Munakata, 2002; Muller, Dick, Gela, Overton, & Zelazo, 2006; Munakata & Yerys, 2001), even though factor analyses produce a separate factor for switching tasks (V. Anderson, Levin, & Jacobs, 2002; Huizinga et al., 2006; Pennington, 1998). If shifting tasks are simply situations with high working memory and inhibition demands, these skills should explain much of the

variability in switching performance. However, if shifting is an independent executive skill, inhibition and working memory should not be good predictors of performance on shifting tasks. Cepeda, Kramer and Gonzalez de Sather (2001) investigated the role of working memory in a task-switching paradigm and found that it predicted a small amount of variance in switch trial RT in 7- to 24-year-olds. However, Huizinga, Dolan & van der Molen (2006) found that working memory and shifting were related in adults but not in children, suggesting that the relationship found by Cepeda et al. may have been driven by the older participants within the group. In contrast, Huizinga et al. found that shifting did appear to be related to inhibition, with a significant correlation between shifting and the stop-signal task in 7-year-olds and between shifting and the Eriksen flanker task in 11-, 15-, and 21-year-olds. This suggests that in children, shifting may involve some form of inhibition, but not necessarily working memory skills.

Several existing studies have examined the developmental trajectories of executive skills by administering the same tasks to different age groups of children (Brocki & Bohlin, 2004; Huizinga et al., 2006; Levin et al., 1991; Luciana, 2003; Luciana & Nelson, 2002; Welsh, Pennington, & Groisser, 1991). These suggest that response inhibition develops relatively early, with switching and working memory skills showing a more protracted development into adolescence. Our current knowledge of the development of these executive skills has mainly been determined by ascertaining at what age children no longer differ from adults or older children on particular tasks. Very few studies have looked at continuous development with age or even fine-grained developmental changes within a few years, let alone longitudinal development within one sample. Furthermore, the developmental trajectories of different EFs have never been directly compared. We compared the

developmental trajectories of shifting, working memory and inhibition in children aged between 5 and 11 years using trend analysis to look at the overall pattern of development during this age-range. We compared the developmental paths where possible. Based on the existing literature, we expected that shifting, inhibition and working memory would show different patterns of development, with response inhibition showing less development during mid-childhood than shifting and working memory.

To compare the constructs of shifting, inhibition and working memory we used the data from the Football task-switching paradigm (Chapter 2; Experiment 1; session 1) as a test of shifting ability, and the self-ordered pointing test (SOPT; Chapter 4) to measure working memory. While the same go/no-go task was used as in Chapters 5 and 6 as a measure of inhibition, the data used were mainly from the same group of children who participated in the task-switching and working memory experiments, and have not previously been reported in the thesis.

Before using these tasks to investigate the relationships between different EFs, we wanted to investigate whether these new tasks tap into the constructs that they were designed to measure. To do this we compared our tasks to a number of standardised tests also thought to tap into these constructs. We predicted that if our tests were valid measures then they would correlate with these standardised tests.

In addition to examining the relationships between different EFs, we also took the opportunity to investigate the role of general intelligence in executive skills. Duncan (2005; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan, Johnson, Swales, & Freer, 1997) argued that executive function and general intelligence (*g*) are largely synonymous such that the key function in both is constructing an effective task plan by activation of appropriate goals or action

requirements. This theory has only been applied to adults; however the development of EF has also been linked to general intelligence. Mike Anderson (2001), proposed that there are two dimensions to *g*: one related to individual differences between people of the same age and based on differences in speed of processing, and the other related to developmental changes based on the development of processing modules, some of which constitute the basis of executive functions. He suggested that Duncan's conception of a *g* that it is underpinned by frontal functions is only correct for the developmental dimension of general intelligence.

If general intelligence and executive function are highly related, then even if executive skills do not correlate highly with each other then they should all relate to general intelligence (c.f. Duncan et al., 1997). Evidence for this in children is limited, as many studies do not find a relationship between EF tasks and intelligence tests (Huizinga et al., 2006; Welsh et al., 1991) while for those that do, the magnitude of the relationship is often small (Luciana & Nelson, 2002). Some studies have found that intelligence is related to some, but not all, aspects of executive function. Pennington (1998) found that IQ tests loaded onto the same factor as shifting measures in a factor analysis, while remaining unrelated to inhibition and working memory skills, and Archibald and Kerns (1999) found a relationship between performance IQ and the SOPT but no other executive tests. This suggests that general intelligence may be a better predictor of some executive skills than others.

In summary, this experiment used the measures of shifting, inhibition and working memory developed for previous chapters to explore four issues: (i) validation of the new measures against existing standardised tests; (ii) the link between executive function and general intelligence; (iii) the relationships between

shifting, inhibition and working memory; and (iv) the developmental trajectories of these three executive processes in 5- to 11-year-old children.

Method

In total 100 children between the ages of 5 and 11 years took part in this experiment. Seventy of the children ($M=8.06$, $SD=1.51$) completed all of the measures across two time-points, one year apart. An additional fifteen 10- to 11-year-olds ($M=10.97$, $SD=0.24$) completed the tasks administered at Time 1. Fifteen 5- to 6-year-olds ($M=5.96$, $SD=0.29$) completed the tasks administered at Time 2.

The test battery consisted of a mixture of experimental and standardised tests designed to tap into shifting, inhibition and working memory skills. These are described in more detail below. The standardised tests were taken from the Test of Everyday Attention for Children (TEA-Ch; (Manly, Robertson, Anderson, & Nimmo-Smith, 1999), the Behavioural Assessment of the Dysexecutive Syndrome for Children (BADS-C; (Emslie, Wilson, Burden, Nimmo-Smith, & Wilson, 2003), and the British Ability Scales: Second Edition (BASII; Elliott, Smith, & McCullough, 1983). In addition to these tests, all children completed the Vocabulary and Matrices subtests of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) to measure verbal and performance IQ respectively.

Shifting

Task-switching paradigm (Time 1). Footballers in coloured, patterned shirts were presented on the computer screen and the child had to decide either whether the shirt was pink or yellow (colour task) or if it was spotty or stripy (pattern task). They responded by touching the appropriate location on a touchscreen. To begin with, pure blocks of either the colour or shape task were presented. In the final blocks the

task changed randomly on a trial-by-trial basis. The dependent variable used was the switch cost (the RT on trials where the task stayed the same, subtracted from the RT on trials where the task switched) from the first session of Experiment 1. Better performance was shown by smaller switch costs. For more information about the task see Chapter 2; Experiment 1.

Creature Counting subtest of the TEA-Ch (Time 2). This task involved counting aliens in their burrows, shifting between counting upwards and counting downwards. The burrows formed a path across the page with occasional arrows telling the child to change the direction in which they were counting. There were two practice trials and seven test trials. The number of correct trials and total number of correct switches were scored, in addition to a timing score calculated by dividing the total time taken on the test by the total number of correct switches. Better performance was shown by greater accuracy and more switches, but a lower timing score.

Playing Cards subtest of the BADS-C (Time 2). Pictures of playing cards were presented in a small flip chart, one card per page. First of all the child had to say yes to a red card and no to a black card as quickly as possible as the experimenter turned the pages. This was then repeated but now the child had to say yes if the card was the same as the previous card, and no if the card was different from the previous card. The number of errors and time taken to complete this were recorded. A timing score was taken from the difference in completion time between the two tasks. The children made few actual errors on this task so self-corrections were included as errors for the purposes of this experiment. Better performance was shown by fewer errors and a lower timing score.

Inhibition

Go/no-go (Time 2). The child was asked to keep their finger pressed down on one of the mouse buttons throughout this task. When a football appeared on the screen (go trial) they had to release this key and press an adjacent response button as fast as possible. When a rugby ball appeared (no-go trial) they had to inhibit this response. The variable used was the number of partial inhibitions (no-go trials on which the home key was released but the response key not pressed) which has been shown to be sensitive to developmental change (Chapter 5). Better performance was indicated by a lower score. More details about the task can be found in Chapters 5 and 6.

Opposite Worlds subtest of the TEA-Ch (Time 2). This consisted of two types of trials: Same World and Opposite World. In the Same World the child followed a path across the page, naming the digits 1 and 2 that were scattered along it. In the Opposite World they did the same except that now they had to say ‘one’ when they saw a 2 and ‘two’ when they saw a 1. The critical variable was the time taken to complete the Opposite World condition, with a lower score indicating better performance. The data from one 6-year-old had to be discarded for this test due to exceptionally slow performance.

Working memory

SOPT (Time 1). A set of pictures were presented on the computer screen in a different spatial arrangement on each trial. The child had to point to a different picture every time. The pictures were either line drawings of familiar objects or abstract designs. After a practice with four pictures, the set-size increased to six, eight, and then ten pictures. There were three repetitions at set-size. For each repetition the number of errors and number of consecutive correct responses before

an error (span) were recorded. The variables used in this experiment were the mean errors and span across the whole task. Better performance was indicated by fewer errors and a higher span. More information about the task can be found in Chapter 4.

Forward digit span from the BASII (Time 2). The experimenter said a list of digits which the child then had to repeat. The task started with a span of two digits and increased up to a possible nine. There were two trials at each span length and the task was terminated when the child failed both of these trials. The span length was calculated as the highest span length where both trials were correct, plus 0.5 if they got one trial at the following span length correct. A higher score indicated better performance.

Backward digit span from the BASII (Time 2). This was the same as forward digit span except that the child had to repeat the digits in reverse order.

Results

Two sets of analyses were performed: The first focussed on the similarity between the experimental and standardised measures as well as the role of IQ in executive skills. The relationships between the experimental measures of shifting, inhibition and working memory were also examined. Only those children who had completed all of the measures ($n=70$) were included in this first set of analyses. Descriptive statistics for these analyses are presented in Appendix VI. The second set of analyses investigated the extent to which shifting, inhibition and working memory follow similar developmental trajectories.

(i) Validation against existing standardised tests

Shifting. One Year 2 child was removed from these analyses due to an extreme value on the Creature Counting timing score. As shown in Table 7.1, all

three shifting tasks were relatively well correlated, suggesting that all three are tapping into similar abilities. For the standardised tests, the within-task measures on both the Creature Counting and Playing Cards tests correlated. Errors on the playing cards test did not correlate with the Creature Counting test but those children who were faster on the Playing Cards were also better on the Creature Counting test. Unsurprisingly, the timing scores for the two tests correlated particularly highly.

The experimental task-switching paradigm correlated with all measures of the Creature Counting test, such that those children with smaller switch costs made more correct switches and successfully completed more trials on the Creature Counting test, as well as being faster to switch on this measure. Those children who were faster to switch on the task-switching paradigm were also faster on the Playing Cards test, but there was no relationship between the task-switching paradigm and number of errors on the Playing Cards test. These relationships are impressive given that the experimental paradigm and standardised measures were administered a year apart.

Table 7.1: Correlations between measures of shifting ability. Above the diagonal are Pearson correlation coefficients, below the diagonal are partial correlations controlling for chronological age

	PC	PC	CC	CC	CC	TS
	Errors	Time	Accuracy	Switches	Time	Switch Cost
PC-Errors		.356**	-.062	-.031	.234	.216
PC-Time	.285°		-.246*	-.265*	.744**	.241*
CC-Accuracy	-.123	-.210		.985**	-.276*	-.363**
CC-Switches	-.078	-.234	.978**		-.286*	-.312**
CC-Time	.113	.654**	-.192	-.207		.323**
TS-Switch Cost	.166	.093	-.322*	-.251°	.119	

Note. PC = Playing Cards subtest of the BADS-C. CC = Creature Counting subtest of the TEA-Ch. TS = task-switching paradigm. ** = $p < .001$. * = $p < .01$. ° = $p < .05$.

The correlations were also performed controlling for age, shown below the diagonal in Table 7.1. Once age was accounted for, the task-switching paradigm no longer showed any relationship with the Playing Cards test. Performance on the task-switching paradigm and the Creature Counting test was still related after controlling for age, with significant correlations between the switch costs and the number of switches and trials correct on the Creature Counting test, but not the timing measure. These correlations were also significant when IQ was partialled out (Creature Counting-switches: $r(69) = -.297, p < .05$; Creature Counting-accuracy: $r(69) = -.364, p < .01$) suggesting that they were not simply due to general ability.

Inhibition. There was no relationship between the number of partial inhibitions on the go/no-go task and the time taken to complete the Opposite Worlds test ($r(69) = .055, ns$).

Working Memory. Forward digit span is considered a measure of short-term memory or storage capacity, while backward digit span requires manipulation of the items in memory and is therefore considered a measure of working memory. Because of this, we predicted that the SOPT would be more closely related to backward than to forward digit span. Consistent with this prediction, the span score on the SOPT correlated with backward digit span ($r(70) = .370, p < .01$) but not with forward digit span ($r(70) = .208, ns$). The relationship with backward span was no longer significant once age was controlled ($r(67) = .204, ns$).

(ii) Links between executive function and general intelligence

Correlations between the measures of shifting, inhibition and working memory and verbal and performance IQ, as measured by the Vocabulary and Matrices subtests of the WASI, are shown in Table 7.2. Those children with higher verbal and performance IQ demonstrated smaller switching costs and fewer errors on

the SOPT. However, these relationships were no longer significant once age was taken into account.

Table 7.2: Correlations between the experimental executive measures and verbal and performance IQ. Above the diagonal are Pearson correlation coefficients, below the diagonal are partial correlations controlling for chronological age.

	Switching	Go/no-go	SOPT	Vocabulary	Matrices
Switching		-.084	.166	-.353**	-.349**
Go/no-go	-.184		.103	-.148	-.205
SOPT	-.027	.001		-.415**	-.422**
Vocabulary	-.096	.018	-.085		.496**
Matrices	-.184	-.113	-.224	.171	

Note. ** = $p < .001$.

(iii) Relationships between shifting, inhibition and working memory.

As shown in Table 7.2 there were no significant correlations between the measures of shifting, inhibition and working memory. Therefore, it does not seem as if working memory and inhibition are highly involved in shifting. To check if the lack of correlation was simply due a problem with our tasks, task-switching performance was correlated with backward digit span as a measure of working memory and the Opposite Worlds subtest of the TEA-Ch as a measure of inhibition. There was still no relationship between shifting and working memory ($r(70) = -.166$, *ns*), but there was between shifting and inhibition ($r(69) = .334$, $p < .01$). There was also a significant relationship between backward digit span and the Opposite Worlds subtest of the TEA-Ch ($r(69) = -.398$, $p < .001$). Unfortunately, these results did not remain significant once the effect of age had been controlled (shifting and inhibition: $r(66) = .128$, *ns*; working memory and inhibition: $r(66) = -.186$, *ns*).

(iv) Developmental trajectories

To examine the developmental trajectories of shifting, inhibition and working memory, the scores for partial inhibitions on the no-go paradigm (inhibition), mean errors on the SOPT (working memory) and switch cost on Session 1 of the task-switching paradigm (shifting) were converted into z-scores based on the data from all of the children who completed that task. The 70 children from the previous analyses plus 15 extra 10- and 11-year-olds completed the SOPT and the task-switching paradigm.

Table 7.3: Mean (*SD*) ages for the groups included in the developmental trajectory analysis

	<u>SOPT and Task-switching</u>			<u>Go/no-go</u>		
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>
5.5-6.5	14	6.00	0.33	17	6.02	0.32
6.5-7.5	13	6.83	0.25	12	7.01	0.33
7.5-8.5	14	8.09	0.26	13	7.75	0.20
8.5-9.5	16	9.15	0.28	15	9.08	0.28
9.5-10.5	14	10.14	0.28	15	10.17	0.26
10.5-11.5	14	11.00	0.21	13	11.09	0.23

As shown in Table 7.3 the children were split into six age groups for this analysis. The group of 70 also completed the go/no-go task, but when they were a year older. An extra group of fifteen 5- and 6-year-olds were recruited for the go/no-go task so that the trajectories for all tasks could be examined between 5 and 11 years. Mean ages are presented in Table 7.3. The trajectories for the three tasks are

plotted on the same graph (Figure 7.1) but as some of the children contributed to the go/no-go task at a different age, this task could not be directly compared with the other two tasks.

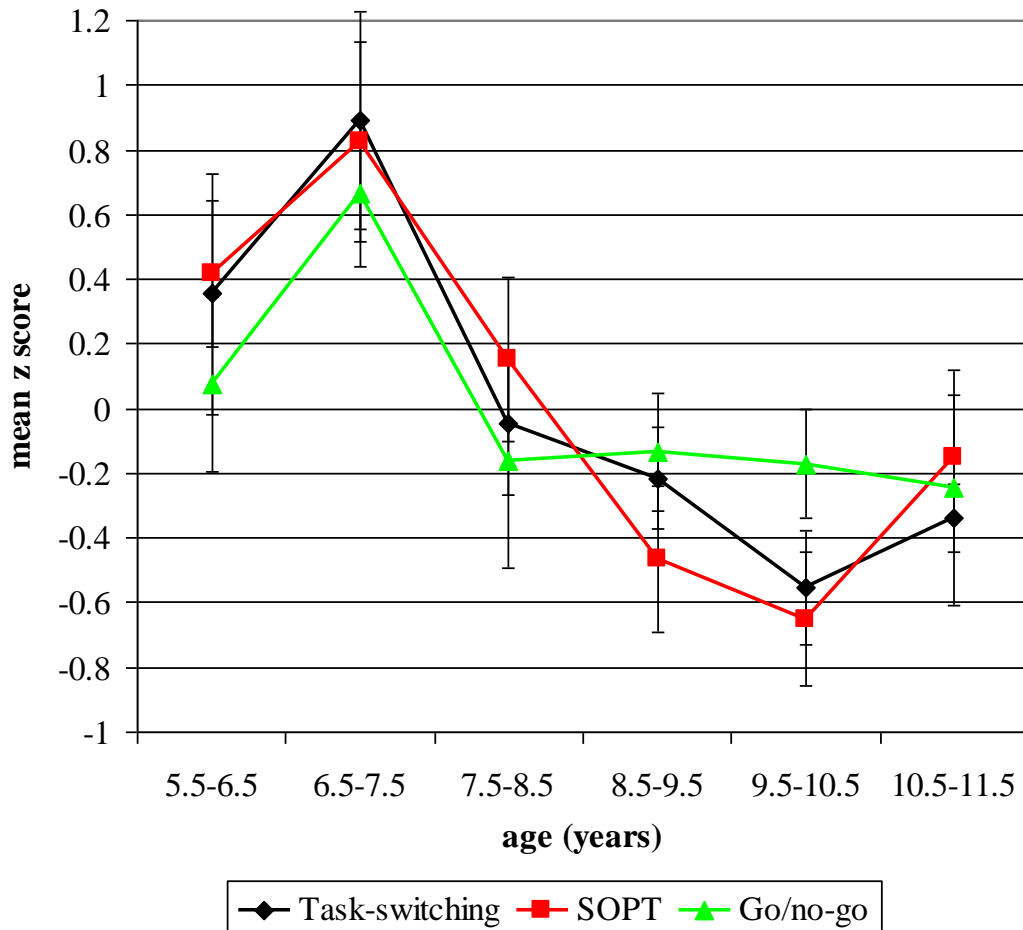


Figure 7.1: Developmental trajectories for shifting, inhibition and working memory in 5- to 11-year-olds. Error bars = *SE*.

Development on the shifting and working memory tasks was compared using a two-way mixed-measures ANOVA with Task (SOPT, task-switching) as a within-subject factor and Age as a between-subject factor. Performance on both tasks improved with age, $F(5, 79)=10.3$, $p<.001$, $\eta^2=.393$, with a reduction in both switch costs and errors on the SOPT. The interaction between Task and Age was not significant, $F(5, 79)<1$, *ns*, showing that the two tasks had a similar pattern of

development. Planned polynomial contrasts showed that the change in task performance with age was explained by both a linear ($t(79) = -5.74, p < .001$) and a cubic ($t(79) = 3.88, p < .001$) trend. Thus although development was generally linear, with a large improvement between roughly 7 and 10 years, a slight decrement in performance both before and after this resulted in a cubic trend.

Development on the go/no-go task was examined using a one-way ANOVA. There was no significant main effect of Age using this measure, $F(5, 79) = 1.48, ns$, and no significant linear trend, $F(1, 79) = 2.90, ns$. This suggests that response inhibition follows a different pattern of development to switching and working memory.

Discussion

This experiment used the data collected for previous experiments to investigate the relationships between shifting, inhibition and working memory and compare their developmental trajectories between 5 and 11 years of age. The relationship between executive skills and intelligence was also examined.

To ensure that the new tasks we developed did tap into the constructs they were designed to measure, we first validated our tasks against existing standardised tests. Our task-switching paradigm correlated well with standardised measures of shifting ability, particularly the Creature Counting subtest of the TEA-Ch. The relationship between these two tests was not accounted for by age or IQ, suggesting that the task-switching paradigm was measuring shifting skills in children. One reason why task-switching correlated better with the Creature Counting test than the Playing Cards subtest of the BADS-C may be because both task-switching and Creature Counting involved multiple switches, whereas the Playing Cards test involved only a single switch.

The SOPT, designed as a measure of executive working memory, correlated with backward digit span, a well-established measure of working memory, but not with forward span. This suggests that the SOPT has the same demands of monitoring and manipulating items in working memory that backward digit span involves. This relationship was no longer significant once age was controlled for however, suggesting that the two tasks may have correlated simply because performance on both improved with age.

Performance on our go/no-go paradigm did not correlate with children's performance on the Opposite Worlds subtest of the TEA-Ch. This could be taken as evidence that our task was not a valid measure of inhibition; however there is an alternative explanation. Many researchers have argued that inhibition can be fractionated into a number of different components (Friedman & Miyake, 2004; Kipp, 2005; Nigg, 2000). One of the main distinctions made is between response inhibition, actively stopping a motor response, and interference suppression: resisting interference from competing stimuli, either at a perceptual or motor level. While the go/no-go task clearly requires response inhibition, the Opposite Worlds test involves interference suppression in order to resolve the conflict created when having to suppress the digit shown in order to say another digit. Therefore, the reason these tasks do not correlate may be because they involve different types of inhibitory skill.

After establishing that the tasks we developed were valid measures of the constructs they were designed to tap into, we proceeded to investigate the relationships between shifting, inhibition and working memory. There were no correlations between our measures of these skills, supporting the fact that EF can be fractionated. However, we did not find the links between these constructs that have been shown in previous studies (Archibald & Kerns, 1999; Davidson et al., 2006;

Miyake et al., 2000). Many theorists have argued for a particularly strong link between inhibition and working memory (e.g. Bjorklund & Harnishfeger, 1990; Roberts & Pennington, 1996) which we did not find using our experimental measures. It could be argued that working memory is more closely related to interference suppression rather than response inhibition and therefore that we did not find a relationship because our inhibition task involved response inhibition rather than interference suppression. Indeed, Roberts and Pennington (1996) suggested that working memory may be relatively specific to “other action alternatives that are relevant for the current and upcoming context” rather than “a more continuous tonic inhibition that might be a product of prefrontal functioning” (p.112) suggesting a stronger link with interference suppression. It does seem more intuitive to think of working memory as involved in activating some representations while interfering ones are suppressed, rather than in actively inhibiting a movement. We found some evidence of a relationship between working memory and interference suppression in a significant correlation between backward digit span and the Opposite Worlds subtest of the TEA-Ch, although this relationship appeared to be mediated by age to some extent. A link between memory and interference suppression, but not response inhibition was also found in a study with preschoolers which showed that children with high short-term memory spans were better at tasks requiring interference suppression but not response inhibition (Espy & Bull, 2005). Nevertheless, Archibald and Kerns (1999) did show a correlation between the SOPT and go/no-go performance indicating a relationship between working memory and response inhibition. However, their go/no-go task may have involved higher working memory demands than our task as their no-go stimulus differed from block to block.

As our measures of shifting, inhibition and working memory did not correlate, it suggested that inhibition and working memory do not play a large role in shifting. In case this was due to some problem with our measures, we investigated this relationship using more established tests, with backward digit span as a measure of working memory and the Opposite Worlds subtest of the TEA-Ch as a measure of inhibition. There was no relationship between shifting and working memory consistent with the findings of Huizinga et al. (2006). We did find a relationship between shifting and the Opposite Worlds test (although this wasn't significant once age was controlled) suggesting that the task-switching paradigm may have involved interference suppression rather than response inhibition skills. Similarly, Huizinga et al. found a significant correlation between shifting and the Eriksen flanker task, a well-established measure of interference suppression, in participants aged 11 and above. However, the results for the youngest age group in their study are difficult to reconcile with our findings. Although 7-year-olds showed a large correlation between shifting and the flanker task, it was not significant, whereas shifting did correlate with the stop-signal task, a measure of response inhibition, in this age group only. The fact that inhibition and working memory were not good predictors of shifting in our experiment suggests that shifting is a separate executive skill that is independent from inhibition and working memory.

This experiment did not find much evidence to support the idea that general intelligence and EF are highly related. Consistent with Archibald and Kerns (1999) and Pennington (1998) we found that intelligence correlated with some but not all executive skills, as there was no relationship between performance on measures of intelligence and the go/no-go task. Furthermore, the correlations between intelligence and our measures of shifting and working memory were no longer

significant once age was controlled, suggesting that age may mediate the relationship between intelligence and executive function. While this does not rule out Anderson's theory (2001) concerning the role of EF in the development of intelligence, it does not support it either, as obviously these correlations cannot tell us whether a developmental improvement in executive function leads to an improvement in intelligence.

The developmental trajectories for the shifting, inhibition and working memory tasks were very interesting, particularly considering that correlations between the different tasks were non-existent. As the same group of children performed both the task-switching paradigm and SOPT in the same test battery, we were able to directly compare the developmental trajectories for these tasks. In contrast to our prediction, performance on the task-switching paradigm and SOPT showed a strikingly similar pattern of development, even though individual participants' performance on the tasks was not highly correlated. Unfortunately, as the go/no-go task was performed a year later it could not be directly compared with the other two tasks. There was definitely less of a developmental change on the go/no-go task however, and consistent with previous findings, performance on this task did appear to reach a stable level of performance at an earlier age than the task-switching paradigm or SOPT.

The most interesting aspect of the developmental trajectories was that there was not a strictly linear progression with age. Development on the SOPT and task-switching paradigm was explained by both a linear and cubic function. While overall there was an improvement in performance with age, with a large linear improvement between roughly the ages of 7 and 10, there was a small decrement in performance just before and just after this spurt. Thus executive function does

improve during mid-childhood but this development is not straightforward. This finding is in need of replication as this pattern of development may be restricted to this relatively small sample of children. The results are also limited by the fact that we used a cross-sectional design with only a single task to measure each executive skill. Ideally, a longitudinal design where the same children were given multiple measures of shifting, inhibition and working memory at different ages would give a more accurate picture of the development of these executive skills.

In conclusion, this experiment supported the idea that different aspects of executive function can be fractionated, evidenced by a lack of correlation between measures of shifting, inhibition and working memory. There was less of a development in response inhibition during mid-childhood than in shifting and working memory, which showed a strikingly similar pattern of development. This development was not strictly linear, however there appeared to be a significant improvement in these skills between 7 and 10 years of age.

Chapter 8: General discussion

This chapter begins with an overview of the experiments presented in this thesis. It then moves on to discuss how this work has addressed major issues concerning the development of executive function; namely how executive function is measured in children and the patterns of development in executive skills in mid-childhood. Finally some limitations of this work are considered and possibilities for future studies are discussed.

This thesis investigated the development of executive function in mid-childhood. Three specific executive skills; shifting, inhibition and working memory, were examined in a large sample of 5- to 11-year-olds using new experimental measures designed to be appropriate for use with children. Factors affecting performance on these tasks were investigated with a view to examining how, and not just when, these executive skills develop. Finally, the relationships between these executive functions were examined and their developmental trajectories compared.

Overview of Experiments

In Chapter 2 we reported three experiments which explored the development of shifting using an adapted version of the task-switching paradigm commonly used with adults. Our version required the children to shift between making decisions about either the colour or pattern of a footballer's shirt. The ability to keep the rules for both tasks in mind was measured by the *mixing cost*-the difference in RT between pure blocks and non-switch trials in mixed blocks. Specific switching ability was measured in terms of the *switch cost*-the difference in RT between switch and non-switch trials in mixed blocks. We also measured the *congruence effect*-the difference

in RT between congruent and incongruent trials. This indexed the extent to which the interference from overlapping irrelevant stimulus-response (S-R) mappings interfered with performance.

In Experiment 1 we compared the performance of a group of 5- to 8-year-olds and a group of 9- to 11-year-olds. The older children demonstrated smaller mixing and switch costs showing a development in both maintaining two rules in mind and shifting between them. The switch costs were larger for the easier colour task than they were for the pattern task, demonstrating the same asymmetrical pattern as found by Ellefson et al. (2006). Overall, switch costs were reduced but not eliminated with practice. In addition, the difference in switch cost between the two tasks reduced with practice, suggesting that the asymmetry may have been driven by the amount of experience with the two dimensions.

The switch costs were larger when the stimulus-response mappings for the two tasks were incongruent (indicated different correct responses), probably due to the fact that the irrelevant S-R mapping had been relevant on the previous trial. This interaction between switch costs and congruence effects suggests that switching is affected by bottom-up interference from overlapping stimulus-response mappings. The congruence effects reduced with age and showed an interesting pattern of developmental change. In the first session, the older children showed a congruence effect on switch trials only, while the younger children showed this on both switch and non-switch trials suggesting that they experienced more interference from the irrelevant task. Furthermore, after practice the younger children showed greater interference effects on pure blocks, indicating that the irrelevant task was interfering even when it was not relevant during that block. In sum, these results suggest that the ability to ignore task-irrelevant information improves during mid-childhood.

Experiments 2a and 2b, also reported in Chapter 2, explored issues relating to the reliability of our new version of the task-switching paradigm. Experiment 2a compared the Football version of the task-switching paradigm used in Experiment 1 with a parallel form which required making decisions about the colour or shape on the top of a cake. Unexpectedly, the switch costs were very small for both versions of the paradigm, which we hypothesised was because the children tested had previously taken part in Experiment 1 and this had affected their performance one year later. Unfortunately, this meant that Experiment 2a was not a fair test of the extent to which superficial changes in the task affect shifting performance.

The influence of previous experience with the task-switching paradigm was explored in Experiment 2b. The switch costs in session 1 and 2 of Experiment 1 were compared to the switch costs on the Football version in Experiment 2a. The switch costs were relatively stable over a few days but greatly reduced one year later, confirming our hypothesis that the switch costs in Experiment 2a were affected by having performed Experiment 1 one year previously. This was partly due to maturational factors but was also a result of previous experience with the task. This was particularly true for the youngest children, supporting findings that young children (Schouten, Oostrom, Peters, Verloop, & Jennekens-Schinkel, 2000), or those with weaker performance (Lowe & Rabbitt, 1998), benefit most from practice. The fact that switch costs are not reliable over long periods of time suggests that the task-switching paradigm should be used cautiously in longitudinal studies investigating the development of shifting in children.

The experiment reported in Chapter 3 explored the interference from irrelevant S-R mappings found to influence shifting in Experiment 1. In a typical task-switching paradigm the tasks overlap at the level of both the stimulus and the

response and so it is difficult to separate the contribution of these two factors. We systematically manipulated these to examine the effects of stimulus and response conflict independently. It has been found that removing the overlap at both stimulus and response dimensions improves shifting performance in adults (Allport & Wylie, 2000; Brass et al., 2003; Koch & Allport, 2006; Meiran, 2000; Waszak, Hommel, & Allport, 2003), whereas only separating stimulus dimensions seems to improve shifting performance in preschoolers (Brooks, Hanauer, Padowska, & Rosman, 2003; Diamond, Carlson, & Beck, 2005; Perner & Lang, 2002; Rennie, Bull, & Diamond, 2004; Towse, Redbond, Houston-Price, & Cook, 2000). This issue had not previously been addressed in school-age children.

Experiment 1 showed that the interference from the irrelevant task decreased with age, therefore we compared 5- to 7-year-old and 9- to 11-year-olds in this experiment. As in Experiment 1, we found an asymmetry between the two tasks with a larger switch cost on the colour task compared to the shape task. Furthermore, our manipulation to reduce stimulus conflict by separating the stimulus dimensions actually seemed to increase rather than decrease conflict. This meant that not only was there more conflict from the colour task on the shape task, but that this conflict was greatest when the colour surrounded the shape. Separating the response dimensions on the shape task did not reduce the interference from the colour task in the younger children as it did for the older children. In addition, the 5- to 7-year-olds experienced interference from the colour task on both non-switch and switch trials, giving the appearance of a reduced switch cost compared to the older children, who only experienced interference on the switch trials. This showed that the 5- to 7-year-olds were more susceptible to interference from the colour task than the 9- to 11-year-olds.

Separating the stimulus and response dimensions also influenced congruence effects in the colour and shape tasks differently. While separating response locations reduced the congruence effect in the colour task as expected, on the shape task the interference from the colour task was greatest when the stimuli were separated and the responses were incongruent. This latter result provided some evidence of an interaction between stimulus and response conflict. As well as the task influencing performance, the order in which the conditions were completed also had a complex effect, mediating the relationship between stimulus and response overlap on overall speed and switch costs.

These results extend the findings from Experiment 1 to show that there a number of factors that affect shifting performance on the task-switching paradigm; not only the overlap of stimulus and response mappings but also more basic factors such as the tasks used and the order in which conditions are completed. This experiment also supports previous studies showing that the ability to inhibit task-irrelevant information improves during mid-childhood (Cepeda, Kramer, & Gonzalez de Sather, 2001; Crone, Bunge, van der Molen, & Ridderinkhof, 2006).

Chapter 4 moved away from shifting to explore the development of working memory. A group of young adults completed this experiment in addition to the two age groups that took part Experiment 1 (5- to 8-year-olds and 9- to 11-year-olds). The working memory task used was the self-ordered pointing test (SOPT), in which a set of pictures (familiar objects or abstract shapes) were presented and a different picture had to be selected on each trial. This test was originally designed for use with frontal lobe patients (Petrides & Milner, 1982), but has since been used in childhood populations with developmental disorders (Diamond, Briand, Fossella, & Gehlbach, 2004; Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004; Scheres et

al., 2004; Smith, Klim, & Hanley, 2000; van Goozen et al., 2004). However, there are very few normative data for this age-range and a number of task manipulations are often overlooked which may shed more light on developmental changes. To make the task more suitable for children we randomised the location of the pictures rather than presenting them in a grid so that the strategy of repeatedly choosing the same location could be avoided without the need for complicated instructions.

The results showed that performance improved with age but that the older children did not reach adult levels of performance. Age accounted for only a small amount of variance in task performance, however. All participants made more errors as the set-size increased and the difference between age groups was most apparent at the larger set-sizes. This showed that even the youngest children could successfully complete the task with up to six pictures but as the children got older they could monitor and manipulate more items in working memory.

The effect of task repetitions is usually overlooked in the SOPT, however examining these revealed an interesting pattern of results. While the adults showed no difference across repetitions of the object version of the task, the children did better in Game 1 than in Games 2 and 3 of this version. One explanation for this is that the memory trace from the first game interfered in performance in the subsequent games. This effect was greater at larger set sizes, implying that there was more interference when task demands were high. The younger children experienced more of this interference than the older children, while there was no evidence of interference between games in the adults. This suggested that the ability to inhibit the interference of memory traces from previous games develops with age. An opposite pattern of results was found for the abstract condition: The children showed no differences between games, however the adults showed worse performance in

Game 1 than Games 2 and 3. This may be due to the fact that the adults were aware that abstract pictures are less easy to remember and therefore consciously attempted to encode them, resulting in a benefit in performance in the second game once the pictures had been encoded.

The extent to which language was used to help WM performance was also investigated in this experiment. Performance was better in the object condition than the abstract condition, suggesting that all participants were using verbal labels to help remember the stimuli where possible. However, there was no relationship between task performance and verbal ability in the children, as has been found in previous studies (Hongwanishkul, Happaney, Lee, & Zelazo, 2005; Joseph, Steele, Meyer, & Tager-Flusberg, 2005). This finding was unexpected, however we proposed two possible explanations for the results. The first was that it may have been due to the type of verbal measure we used, although this is unlikely. Secondly, the objects we used had an early age of acquisition, therefore all children should have found it easy to name the stimuli despite differences in the more advanced aspects of vocabulary assessed.

It was predicted that there would be a greater difference between the object and abstract conditions in the older children than the younger children, based on evidence that children above 8-years-old use verbal rehearsal strategies to aid memory performance (Halliday, Hitch, Lennon, & Pettipher, 1990; Hitch & Halliday, 1983). This prediction was not supported. This may be because the task did not rely on a verbal output, and therefore the children may not have used verbal rehearsal as a strategy. Another possibility is that the executive demands of having to continuously generate and monitor responses may have prevented a verbal rehearsal strategy from being adopted.

The experiments reported in Chapters 5 and 6 explored the development of response inhibition using a modified version of the go/no-go paradigm. The evidence for a developmental improvement in response inhibition in school-age children is mixed (Archibald & Kerns, 1999; Becker, Isaac, & Hynd, 1987; Brocki & Bohlin, 2004; Johnstone et al., 2007; Jonkman, 2006; Levin et al., 1991). However, this may be due to a problem with task sensitivity rather than a true lack of developmental change. The new modified version introduced a more sensitive measure in the form of a home key which had to be released in order to respond using an adjacent target key. This captured those trials where a response was initiated but then inhibited part-way through completion (partial inhibitions).

In Chapter 5 behavioural performance on the modified task was investigated in a group of 5- to 7-year-olds and a group of 9- to 11-year-olds. Treating the task as a standard go/no-go paradigm showed more accurate performance on both go and no-go trials in the older age group, demonstrating that performance on the task improved with age. We predicted that this was due to an improvement in the efficiency of response inhibition, such that as children get older they become able to inhibit a response at an earlier stage during the movement. Investigating the partial inhibitions showed that this prediction was correct: As children got older they made fewer partial inhibitions and more successful inhibitions, becoming more likely to stop a response before any movement was made. This finding is consistent with Logan and Cowan's (1984; Logan, Cowan, & Davis, 1984) horse-race model of response inhibition (developed for the stop-signal paradigm) which also predicts an improvement in the efficiency of response inhibition during development. Also consistent with this model was the finding that partial inhibitions were faster than

responses on go trials, suggesting that these faster responses are initiated before inhibitory processes are completed.

The amount of time given to respond was manipulated in Chapter 5 following suggestions that this may influence the inhibitory demands of the task (Simpson & Riggs, 2006). It was predicted that a shorter ISI (2000ms vs. 3000ms) would have a greater effect in the 5- to 7-year-olds as they would be slower to respond and therefore experience greater time pressure. Contrary to this prediction, the pattern of results for both age groups was very similar, with greater accuracy on go trials than on no-go trials for both ISIs. This demonstrated that the task was posing inhibitory demands in both conditions and suggests that small changes in ISI do not affect patterns of performance in school-age children.

In Chapter 6, ERPs were used to explore the neural responses to the modified go/no-go paradigm in 7- and 9-year-old children. The N2 and no-go P3 ERP components, which have been linked to response inhibition processes, and the go P3, related to target detection, were examined for correct go trials (hits) and successful and partial inhibitions. Behaviourally, the same pattern of results was found as in Chapter 5, with an increase in successful inhibitions and a decrease in partial inhibitions in the older children, however the difference was not significant. The ERPs showed more evidence of a developmental change, with a decrease in N2 latency with age reflecting an increase in the efficiency of response inhibition. The amplitude of the N2 correlated with behavioural performance in the 7-year-olds, suggesting that a greater N2 reflects better response inhibition (Johnstone et al., 2007). This could indicate that the larger N2 in 9-year-olds than 7-year-olds on successful inhibitions reflects stronger inhibition on these trials, however the 9-year-

olds did not show a correlation between N2 amplitude and behavioural performance, making these results more difficult to interpret.

Consistent with previous studies (Johnstone, Pleffer, Barry, Clarke, & Smith, 2005; Jonkman, Lansbergen, & Stauder, 2003), the no-go P3 was not enhanced compared to go trials in the children and there were no developmental differences in this component. In contrast, the go P3 was larger in the older children. Furthermore, the go P3 for partial inhibitions was similar to successful inhibitions in the 7-year-olds, but go trials in the 9-year-olds. This may indicate that the partial inhibitions were processed differently in the two age groups, although this needs further investigation. With regards to the partial and successful inhibitions, the N2 component was later on partial inhibitions. This suggested that the duration of stopping is not constant and that as well as resulting from faster responses, partial inhibitions may also be due to slower inhibitory processes on these trials. There was no difference in N2 amplitude between partial and successful inhibitions, however the no-go P3 was larger on successful inhibitions. While the reason for this difference is not clear, it suggests that there may be differences in processing between the partial and successful inhibitions rather than just a difference in when the response is stopped.

Chapter 7 took a broader focus and investigated the relationships between shifting, working memory and inhibition and also compared their developmental trajectories. First of all, as the measures used were newly developed for this thesis, they were validated against existing standardised tests. The Football task-switching paradigm correlated well with standardised measures of shifting and the SOPT had more in common with backwards than forwards digit span, as predicted. The go/no-go task did not correlate with the Opposite World subtest of the TEA-Ch, however

this may be because they measure different types of inhibition. We did not find any strong evidence to support the idea that general intelligence and executive function are highly related. There were no correlations between our measures of shifting, working memory and inhibition, supporting the fractionation of executive function. This meant that we did not find evidence for a strong link between inhibition and working memory, as has been suggested in the literature (Bjorklund & Harnishfeger, 1990; Roberts & Pennington, 1996), although again this may be because our inhibition measure indexed response inhibition. Another question addressed was the extent to which inhibition and working memory predicted shifting performance. While working memory and response inhibition had no relation with switching performance, there was some evidence that interference suppression may play some role in shifting, as measured by the task-switching paradigm.

Despite no apparent relationship between shifting and working memory, the two showed a very similar pattern of development between the ages of 5 and 11 years, with a slight decrement in performance between 6 and 7 years, followed by a linear increase to age 10 and then another small decrement in performance. This suggests that the development of executive function in mid-childhood is not strictly linear, although this should be confirmed in further longitudinal studies. Response inhibition showed less development during this period than shifting and inhibition, as has been found in previous studies (Becker et al., 1987; Brocki & Bohlin, 2004), suggesting that some executive functions do mature at different rates.

New measures of executive skills

One of the aims of this thesis was to develop new measures of executive skills that were appropriate for use with school-age children. The new measures aimed to appeal to children by using bright colourful stimuli, and where possible

involving scenarios that helped to make the task instructions more meaningful. For example, in the go/no-go paradigm the children were asked to kick footballs but not rugby balls into a football goal. The children tested seemed to thoroughly enjoy taking part and were motivated to perform well, encouraged by regular feedback within the task. The use of a touchscreen in the switching and working memory tasks, which was novel to the children, seemed to particularly increase their enjoyment.

The measures were also chosen or designed to be as sensitive as possible to developmental change. The task-switching paradigm, which uses RT as the dependent variable, was chosen because adults show a cost in performance when shifting on this task, suggesting that the task would also be a sensitive measure of shifting in childhood. The self-ordered pointing test (SOPT) involved levels of increasing difficulty such that all children did well at the easiest levels but that age differences were apparent at larger set sizes, when the task became more difficult. Increasing levels of difficulty is a useful feature as it enables comparison of a wide range of ages while avoiding floor and ceiling effects. The standard go/no-go paradigm used in the literature is not a particularly sensitive measure of developmental change in older children. To increase its sensitivity, we modified the task so that responses that were started but then inhibited part-way through could be recorded. This proved to be very useful and was more sensitive to developmental change than the standard measure of failed inhibitions. It showed that as children get older they become able to inhibit their responses at an earlier stage during the movement, suggesting an increase in the efficiency of response inhibition.

To try and avoid the problem of children doing badly because of difficulties with non-executive processes, extraneous demands were minimised. For example,

no linguistic stimuli were used and there were no demands on reading. In the task-switching paradigm the cues remained on the screen once the target appeared so that the locations for the responses did not have to be remembered and by randomising the picture locations in the SOPT the use of a spatial strategy was avoided. Despite this, there were of course non-executive processes that affected task performance. In the SOPT, language was used to help remember the pictures of objects, as shown by better performance in the object condition compared to a condition where abstract stimuli, which were difficult to name, had to be remembered. The role of language in the switching and inhibition tasks was not investigated further than correlations with verbal IQ, however the extent to which children use internal language to guide behaviour on executive tasks would be an interesting avenue for further research. This may also function as a window into the development of strategy use in executive tasks, which seems to be a particular area in which children and adults differ.

The task-switching paradigm is usually seen as a relatively pure measure of shifting, especially compared to tasks such as the WCST which involves a number of additional task demands. However, as shown in Chapters 2 and 3, task-switching performance seems to be affected by a number of non-executive factors such as the specific tasks switched between and their relative strength, task experience, the order in which conditions are completed, and particularly the overlap between the stimulus-response mappings for the two tasks. While it may not be the case for all shifting tasks, the task-switching paradigm definitely seems to involve some form of conflict resolution or interference suppression created by the overlapping mappings. The susceptibility of the shifting measure to extraneous factors suggests that even if

shifting is an independent executive construct, it is highly influenced by other processes.

The development of executive function in mid-childhood

We know that executive function shows a protracted development throughout childhood and adolescence, yet there is little research exploring the development of these skills in school-age children. This thesis clearly shows that the skills of shifting, inhibition and working memory improve during mid-childhood. Furthermore, in response inhibition, which is generally thought not to show much improvement in this age range, it was demonstrated that there are developmental changes in the efficiency of response inhibition which are apparent if a more sensitive measure is used.

Although a wide range of ages were sampled for the shifting and working memory experiments reported in Chapters 2 and 4, the children were split into two groups for analysis as the youngest children differed from the oldest children but there were no significant differences in performance within these groups. This pattern was reflected in the developmental trajectories examined in Chapter 7 where a substantial increase in performance between the ages of 7 and 10 years was apparent in shifting and working memory. Interestingly, development either side of this spurt was non-linear, with a slight decrement in performance between the ages of 6-7 and again at 10-11 years. This is difficult to interpret without examining age groups either side of these to determine if these are better represented as plateaus in performance or if there is indeed a more turbulent pattern to the development of executive function. The developmental trajectories of shifting, inhibition and working memory should also be explored and compared using different task in larger

samples where more detailed developmental changes can be examined, to see whether this pattern of results generalises.

One of the processes that seemed to show the most striking developmental changes was resistance to interference from irrelevant stimulus-response mappings in the task-switching paradigm. Not only did the younger children show a larger congruence effect (the difference in RT between trials where there was and wasn't any conflict) they also showed interference from the irrelevant task information on more trials than the older children, including those in which the conflicting task was not even relevant during that block. Furthermore, as shown in Chapter 3, the younger children seemed to find it particularly difficult to ignore irrelevant yet salient colour information when it conflicted with the shape task they were supposed to be performing. These results suggest that the ability to suppress irrelevant information improves greatly during mid-childhood.

Results from the SOPT also seem to support this idea. It was found that children's performance on repetitions of the object version of the SOPT was worse than the first time they used particular set of pictures. This suggested that memory traces from the previous game were interfering with performance. Moreover, this decrement in performance was greater in the younger children, suggesting that they experienced more interference. Unfortunately we did not include an experimental measure of interference control such as the Eriksen flanker task or a type of Stroop paradigm in this thesis. However, it would have been interesting to see how similar development on a task like this compared to development on our measures of shifting and working memory. It would also have been interesting to examine the relationship between response inhibition, as measured by the go/no-go paradigm, and

interference suppression to determine the relationship between different types of inhibition during development.

From another viewpoint, an improvement in the ability to inhibit distractors can be seen as an improvement in selective attention. This is an area of research that has not been explored in this thesis, however there is obvious overlap between these issues. Indeed, it could be argued that selective attention is in some ways synonymous with the idea of a working memory that focuses on or strengthens the relevant aspects of the task at hand, such as suggested in models proposing an interactive relationship between inhibition and working memory (Miller & Cohen, 2001; Munakata, 2001; Roberts & Pennington, 1996). Are we simply faced with differences in terminology here or are there fundamental differences in these constructs? Again we encounter the problem that while it may be easy to separate these processes conceptually, dissociating them empirically is a much more difficult pursuit.

An important point to note is that although performance on these tasks improved during mid-childhood, there were also substantial individual differences. This variation did not appear to be accounted for by differences in general intelligence, showing that it is not simply the case that clever children have good cognitive control. It would be interesting to explore these individual differences further and see how variation in executive function relates to other areas of development such as literacy, maths and social development.

Limitations and Future Directions

One of the main limitations of this thesis was that the parallel-form reliability of the task-switching was investigated in a group of children who had performed this task a year earlier. It was not expected that previous task experience would have

such a profound effect on performance one year later. As it did however, it meant that Experiment 2a was not a fair test of the parallel form reliability of the task-switching paradigm. To assess this properly, the experiment needs to be replicated in a new sample of children with no previous experience of the task-switching paradigm. Another limitation relating to this issue is that to separate the effects of maturation and task experience on switching performance in Experiment 2b, the performance of each year group at Time 1 constituted the control group for the year group below them at Time 2. This meant that the data was not independent and so could not be entered into one single ANOVA, thus reducing the power to detect the effects of task experience. Recruiting a new independent sample, matched to the existing sample on age, would provide a much better idea of the relative effects of maturation and task experience on performance one year later. The limitations of using one sample across two timepoints were also seen when comparing developmental trajectories. All three measures were completed by the same children but as the go/no-go task was completed a year later than the shifting and working memory tasks when the children were older, the tasks could not all be statistically compared.

The interpretation of the effects of stimulus and response overlap on task-switching performance in Chapter 3 was limited as the manipulation to decrease stimulus conflict by separating colour from shape actually resulted in an increase in conflict. While this meant that it was difficult to address our hypotheses, it nevertheless revealed some interesting developmental differences. Questions remain as to why colour was so salient when part of a separate object, and if the resulting conflict occurred because colour was previously task-relevant or purely because of perceptual interference. A further avenue to explore from this experiment concerns

the responses. As the touchscreen was used to respond, the response locations were separated both visually and physically. It would be interesting to see which of these is important in reducing conflict and switch costs by separating the response locations visually on the screen but then using overlapping responses on a keyboard. It would also be useful to re-run Experiment 3 using a manipulation of stimulus conflict that does actually reduce interference, such as degrading one of the dimensions or using univalent stimuli, to address the original hypotheses about the role of stimulus conflict in task-switching in children.

Chapter 6 raised interesting questions concerning differences in processing on partially and successfully inhibited trials on the go/no-go task based on differences in the no-go P3 component of the ERP. It was difficult to interpret this however, not only because this was the first experiment to compare partial and successful inhibitions on the go/no-go task using ERPs but also because the children did not show an enhanced no-go P3 component on no-go trials as is typically found in adults. It would therefore be useful to replicate this experiment in adults where the no-go P3 component is more robust.

As mentioned in Chapter 1, the development of executive function is closely linked to the maturation of the frontal lobes. This thesis focussed on behavioural changes rather than underlying physiological development. However, the new experimental measures designed for this thesis would be useful to use in experiments attempting to elucidate the neural correlates of these behaviours as they are valid measures of the executive skills they were designed to tap into, with non-executive demands minimised where possible. Furthermore, the tasks appeal to children so they would be less likely to get bored during the large numbers of trials needed in neurophysiological and imaging studies.

As well as simply helping us to understand how behavioural improvements in executive function are linked to maturational changes in the brain, neurophysiological and imaging studies may be able to help answer some of the questions investigated in this thesis. This has already been started by investigating differences between partial and successful inhibitions on the go/no-go paradigm using ERPs. Physiological measures may also help to separate stimulus- and response-related processing in the task-switching paradigm. Moreover, while some recent studies have been carried out investigating the neural basis of individual executive skills such as shifting (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey et al., 2004; Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006), inhibition (Booth et al., 2003; Casey et al., 1997; Durston et al., 2002) and working memory (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006; Klingberg, 2006) in children, very few have compared the neural bases of different executive skills in the same group of children. This would be a useful avenue for future research to help understand the unity and diversity of executive function during development.

References

- Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 421-452). Cambridge, MA: MIT Press.
- Allport, A., & Wylie, G. (2000). Task switching, stimulus-response bindings, and negative priming. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 35-70). Cambridge, MA: MIT Press.
- Anderson, M. (2001). Annotation: Conceptions of intelligence. *Journal of Child Psychology and Psychiatry*, 42(3), 287-298.
- Anderson, M., Reid, C., & Nelson, J. (2001). Developmental changes in inspection time: What a difference a year makes. *Intelligence*, 29, 475-486.
- Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology*, 8(2), 71-82.
- Anderson, V. (1998). Assessing executive functions in children: Biological, psychological, and developmental considerations. *Neuropsychological Rehabilitation*, 8(3), 319-349.
- Anderson, V., Levin, H. S., & Jacobs, R. (2002). Executive functions after frontal lobe injury: A developmental perspective. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 504-527). Oxford: Oxford University Press.
- Archibald, S. J., & Kerns, K. A. (1999). Identification and description of new tests of executive functioning in children. *Child Neuropsychology*, 5(2), 115-129.
- Arffa, S., Lovell, M., Podell, K., & Goldberg, E. (1998). Wisconsin card sorting test performance in above average and superior school children: Relationship to intelligence and age. *Archives of Clinical Neuropsychology*, 13(8), 713-720.
- Aron, A. A., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, 8(4), 170-177.
- Baddeley, A. D. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology*, 49A(1), 5-28.
- Band, G. P. H., van der Molen, M. W., & Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychologica*, 112, 105-142.
- Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unified theory of ADHD. *Psychological Bulletin*, 121(1), 65-94.
- Becker, M. G., Isaac, W., & Hynd, G. W. (1987). Neuropsychological development of nonverbal behaviors attributed to "frontal lobe" functioning. *Developmental Neuropsychology*, 3, 275-298.
- Bedard, A., Nichols, S., Barbosa, J. A., Schachar, R., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the lifespan. *Developmental Neuropsychology*, 21(1), 93-111.
- Bell, M. A., & Fox, N. A. (1992). The relations between frontal brain electrical activity and cognitive development during infancy. *Child Development*, 63, 1142-1163.
- Berwid, O. G., Curko Kera, E. A., Marks, D. J., Santra, A., Bender, H. A., & Halperin, J. M. (2005). Sustained attention and response inhibition in young children at risk for attention deficit/hyperactivity disorder. *Journal of Child Psychology and Psychiatry*, 46(11), 1219-1229.

- Beveridge, M., Jarrold, C., & Pettit, E. (2002). An experimental approach to executive fingerprinting in young children. *Infant and Child Development*, 11(2), 107-123.
- Bishop, D. V. M. (1997). Cognitive neuropsychology and developmental disorders: Uncomfortable bedfellows. *The Quarterly Journal of Experimental Psychology*, 50A(4), 899-923.
- Bishop, D. V. M., Aamodt-Leeper, G., Cresswell, C., McGurk, R., & Skuse, D. H. (2001). Individual differences in cognitive planning on the tower of hanoi task: Neuropsychological maturity or measurement error? *Journal of Child Psychology and Psychiatry*, 42(4), 551-556.
- Bjorklund, D. F., & Harnishfeger, K. K. (1990). The resources construct in cognitive development: diverse sources of evidence and a theory of inefficient inhibition. *Developmental Review*, 10, 48-71.
- Bokura, H., Yamaguchi, S., & Kobayashi, S. (2001). Electrophysiological correlates for response inhibition in a go/nogo task. *Clinical Neurophysiology*, 112(12), 2224-2232.
- Booth, J. R., Burman, D. D., Meyer, J. R., Lei, Z., Trommer, B. L., Davenport, N. D., et al. (2003). Neural development of selective attention and response inhibition. *NeuroImage*, 20, 737-751.
- Brass, M., Ruge, H., Meiran, N., Rubin, O., Koch, I., Zysset, S., et al. (2003). When the same response has different meanings: recoding the response meaning in the lateral prefrontal cortex. *NeuroImage*, 20(2), 1026-1031.
- Brocki, K. C., & Bohlin, G. (2004). Executive functions in children aged 6 to 13: A dimensional and developmental study. *Developmental Neuropsychology*, 26(2), 571-593.
- Brooks, P. J., Hanauer, J. B., Padowska, B., & Rosman, H. (2003). The role of selective attention in preschoolers' rule use in a novel dimensional card sort. *Cognitive Development*, 18(2), 195-215.
- Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching and working memory. *Developmental Neuropsychology*, 19(3), 273-293.
- Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, 33, 301-311.
- Burgess, P. W. (1997). Theory and methodology in executive function research. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 81-116). Hove, U.K.: Psychology Press.
- Carroll, D. J., Apperly, I. A., & Riggs, K. J. (2007). The executive demands of strategic reasoning are modified by the way in which children are prompted to think about the task: Evidence from 3- to 4-year-olds. *Cognitive Development*, 22(1), 142-148.
- Casey, B. J., Davidson, M. C., Hara, Y., Thomas, K. M., Martinez, A., Galvan, A., et al. (2004). Early development of subcortical regions involved in non-cued attention switching. *Developmental Science*, 7(5), 534-542.
- Casey, B. J., Giedd, J. N., & Thomas, K. M. (2000). Structural and functional brain development and its relation to cognitive development. *Biological Psychology*, 54(1-3), 241-257.

- Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., et al. (1997). A developmental functional MRI study of prefrontal activation during performance of a go-nogo task. *Journal of Cognitive Neuroscience*, 9, 835-847.
- Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. C. M. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology*, 37(5), 715-730.
- Chelune, G. J., & Baer, R. A. (1986). Developmental norms for the wisconsin card sorting test. *Journal of Clinical and Experimental Neuropsychology*, 8, 219-228.
- Chugani, H. T., & Phelps, M. E. (1986). Maturational changes in cerebral function in infants determined by FDG positron emission tomography. *Science*, 231, 840-843.
- Ciesielski, K. T., Harris, R. J., & Cofer, L. F. (2004). Posterior brain ERP patterns related to the go/no-go task in children. *Psychophysiology*, 41(6), 882-892.
- Cinan, S. (2006). Age-related changes in concept formation, rule switching, and perseverative behaviors: A study using WCST with 12 unidimensional target cards. *Cognitive Development*, 21(3), 377-382.
- Conklin, H. M., Luciana, M., Hooper, C. J., & Yarger, R. S. (2007). Working memory performance in typically developing children and adolescents: Behavioral evidence of protracted frontal lobe development. *Developmental Neuropsychology*, 31(1), 103-128.
- Coolican, H. (2004). *Research methods and statistics in psychology* (4th ed.). London: Hodder and Stoughton.
- Crone, E. A., Bunge, S. A., van der Molen, M. W., & Ridderinkhof, K. R. (2006). Switching between tasks and responses: a developmental study. *Developmental Science*, 9(3), 278-287.
- Crone, E. A., Donohue, S. E., Honomichl, R., Wendelken, C., & Bunge, S. A. (2006). Brain regions mediating flexible rule use during development. *The Journal of Neuroscience*, 26(43), 11239-11247.
- Crone, E. A., Ridderinkhof, K. R., Worm, M., Somsen, R. J. M., & van der Molen, M. W. (2004). Switching between spatial stimulus-response mappings: a developmental study of cognitive flexibility. *Developmental Science*, 7(4), 443-455.
- Crone, E. A., Wendelken, C., Donohue, S. E., & Bunge, S. A. (2006). Neural evidence for dissociable components of task-switching. *Cerebral Cortex*, 16, 475-486.
- Damasio, A. R. (1993). The frontal lobes. In K. M. Heilman & E. Valenstein (Eds.), *Clinical neuropsychology* (3rd ed.). New York: Oxford University Press.
- Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, 44(11), 2037-2078.
- Davis, E. P., Bruce, J., Snyder, K., & Nelson, C. A. (2003). The X-trials: Neural correlates of an inhibitory control task in children and adults. *Journal of Cognitive Neuroscience*, 15(3), 432-443.
- De Luca, C. R., Wood, S. J., Anderson, V., Buchanan, J. A., Proffitt, T. M., Mahony, K., et al. (2003). Normative data from the Cantab. I: Development of executive function over the lifespan. *Journal of Clinical and Experimental Neuropsychology*, 25(2), 242-254.

- Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review*, 12, 45-75.
- Dempster, F. N. (1993). Resistance to interference: Developmental changes in a basic processing mechanism. In M. L. Howe & R. Pasnak (Eds.), *Emerging themes in cognitive development: Vol. 1. Foundations* (pp. 3-27). New York: Springer-Verlag.
- Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by infants' performance on AB. *Child Development*, 56, 868-883.
- Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 466-503). Oxford: Oxford University Press.
- Diamond, A., Briand, L., Fossella, J., & Gehlbach, L. (2004). Genetic and neurochemical modulation of prefrontal cognitive functions in children. *American Journal of Psychiatry*, 161(1), 125-132.
- Diamond, A., Carlson, S. M., & Beck, D. M. (2005). Preschool children's performance in task switching on the dimensional change card sort task: Separating the dimensions aids the ability to switch. *Developmental Neuropsychology*, 28(2), 689-729.
- Diamond, A., & Doar, B. (1989). The performance of human infants on a measure of frontal cortex function, the delayed response task. *Developmental Psychobiology*, 22, 271-294.
- Diamond, A., & Goldman-Rakic, P. S. (1989). Comparison of human infants and rhesus monkeys on Piaget's AB task: Evidence for dependence on dorsolateral prefrontal cortex. *Experimental Brain Research*, 74, 24-40.
- Diamond, A., & Kirkham, N. Z. (2005). Not quite as grown-up as we like to think. Parallels between cognition in childhood and adulthood. *Psychological Science*, 16(4), 291-297.
- Diamond, A., Prevor, M. B., Callender, G., & Druin, D. P. (1997). Prefrontal cortex cognitive deficits in children treated early and continuously for PKU. *Monographs of the Society for Research in Child Development*, 62(4), 1-205.
- Dibbets, P., & Jolles, J. (2006). The switch task for children: Measuring mental flexibility in young children. *Cognitive Development*, 21(1), 60-71.
- Donkers, F. C. L., & van Boxtel, G. J. M. (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition*, 56(2), 165-176.
- Dowsett, S. M., & Livesey, D. J. (2000). The development of inhibitory control in preschool children: Effects of "executive skills" training. *Developmental Psychobiology*, 36(2), 161-174.
- Duncan, J. (2005). Frontal lobe function and general intelligence: Why it matters. *Cortex*, 41, 215-217.
- Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organisation of goal-directed behaviour. *Cognitive Psychology*, 30, 257-303.
- Duncan, J., Johnson, R., Swales, M., & Freer, C. (1997). Frontal lobe deficits after head injury: Unity and diversity of function. *Cognitive Neuropsychology*, 14(5), 713-741.
- Dunn, L. M., & Dunn, L. M. (1997). *Peabody picture vocabulary test* (3rd ed.). Circle Pines, MN: American Guidance Service.

- Durston, S., & Casey, B. J. (2006). What have we learned about cognitive development from neuroimaging? *Neuropsychologia*, 44(11), 2149-2157.
- Durston, S., Thomas, K. M., Worden, M. S., Yang, Y., & Casey, B. J. (2002). The effect of preceding context on inhibition: an event-related fMRI study. *NeuroImage*, 16, 449-453.
- Durston, S., Thomas, K. M., Yang, Y., Ulug, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, 5(4), F9-F16.
- Eimer, M. (1993). Effects of attention and stimulus probability on ERPs in a go/nogo task. *Biological Psychology*, 35(2), 123-138.
- Ellefson, M. R., Shapiro, L. R., & Chater, N. (2006). Asymmetrical switch costs in children. *Cognitive Development*, 21(2), 108-130.
- Elliott, C. D., Smith, P., & McCullouch, K. (1983). *British ability scales* (2nd ed.). London: nferNelson.
- Emslie, H., Wilson, F. C., Burden, V., Nimmo-Smith, I., & Wilson, B. A. (2003). *Behavioural assessment of the dysexecutive syndrome for children (BADS-C)*. London: Harcourt Assessment/The Psychological Corporation.
- Espy, K. A. (1997). The shape school: Assessing executive function in preschool children. *Developmental Neuropsychology*, 13(4), 495-499.
- Espy, K. A., & Bull, R. (2005). Inhibitory processes in young children and individual variation in short-term memory. *Developmental Neuropsychology*, 28(2), 669-688.
- Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). ERP components in go/nogo tasks and their relation to inhibition. *Acta Psychologica*, 101(2-3), 267-291.
- Fassbender, C., Murphy, K., Foxe, J. J., Wylie, G. R., Javitt, D. C., Robertson, I. H., et al. (2004). A topography of executive functions and their interactions revealed by functional magnetic resonance imaging. *Cognitive Brain Research*, 20(2), 132-143.
- Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General*, 133(1), 101-135.
- Frye, D., Zelazo, P. D., & Palfai, T. (1995). Theory of mind and rule-based reasoning. *Cognitive Development*, 10(4), 483-527.
- Fuster, J. M. (1997). *The prefrontal cortex: Anatomy, physiology, and neuropsychology of the frontal lobe* (3rd ed.). Philadelphia: Lippincott-Raven.
- Garner, W. R. (1970). The stimulus in information processing. *American Psychologist*, 25(4), 350-358.
- Garner, W. R., & Felfoldy, G. L. (1970). Integrality of stimulus dimensions in various types of information processing. *Cognitive Psychology*, 1(3), 225-241.
- Gerstadt, C. L., Hong, Y. J., & Diamond, A. (1994). The relationship between cognition and action: performance of children 31/2-7 years old on a stroop-like day-night test. *Cognition*, 53(2), 129-153.
- Geurts, H. M., Verté, S., Oosterlaan, J., Roeyers, H., & Sergeant, J. A. (2004). How specific are executive functioning deficits in attention deficit hyperactivity disorder and autism? *Journal of Child Psychology and Psychiatry*, 45(4), 836-854.

- Golden, C. J. (1981). The Luria-Nebraska children's battery: Theory and formulation. In G. W. Hynd & J. E. Obrzut (Eds.), *Neuropsychological assessment and the school-age child* (pp. 277-302). New York: Grune & Stratton.
- Grant, D. A., & Berg, E. A. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card sorting problem. *Journal of Experimental Psychology*, 38, 404-411.
- Hale, S. (1990). A global developmental trend in cognitive processing speed. *Child Development*, 61(3), 653-663.
- Halliday, M. S., Hitch, G. J., Lennon, B., & Pettipher, C. (1990). Verbal short-term memory in children: The role of the articulatory loop. *European Journal of Cognitive Psychology*, 2, 23-38.
- Happé, F., Booth, R., Charlton, R., & Hughes, C. (2006). Executive function deficits in autism spectrum disorders and attention-deficit/hyperactivity disorder: Examining profiles across domains and ages. *Brain and Cognition*, 61(1), 25-39.
- Hill, E., L. (2004). Evaluating the theory of executive dysfunction in autism. *Developmental Review*, 24, 189-233.
- Hitch, G. J., & Halliday, M. S. (1983). Working memory in children. *Philosophical Transactions of the Royal Society, Series B*, 302, 324-340.
- Hongwanishkul, D., Happaney, K. R., Lee, W. S. C., & Zelazo, P. D. (2005). Assessment of hot and cool executive function in young children: Age-related changes and individual differences. *Developmental Neuropsychology*, 28(2), 617-644.
- Hughes, C., & Graham, A. (2002). Measuring executive functions in childhood: Problems and solutions? *Child and Adolescent Mental Health*, 7(3), 131-142.
- Hughes, C., Plumet, M. H., & Leboyer, M. (1999). Towards a cognitive phenotype for autism: Increased prevalence of executive dysfunction and superior spatial span amongst siblings of children with autism. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, 40(5), 705-718.
- Huizinga, M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*, 44(11), 2017-2036.
- Huizinga, M., & van der Molen, M. W. (2007). Age-group differences in set-switching and set-maintenance on the wisconsin card sorting task. *Developmental Neuropsychology*, 31(2), 193-215.
- Isquith, P. K., Crawford, J. S., Espy, K. A., & Gioia, G. A. (2005). Assessment of executive function in preschool-aged children. *Mental Retardation and Developmental Disabilities Research Reviews*, 11(3), 209-215.
- Jackson, S. R., Jackson, G. M., & Roberts, M. (1999). The selection and suppression of action: ERP correlates of executive control in humans. *Neuroreport*, 10(4), 861-865.
- Jennings, J. R., van der Molen, M. W., Pelham, W., Debski, K. B., & Hoza, B. (1997). Inhibition in boys with attention deficit hyperactivity disorder as indexed by heart rate change. *Developmental Psychology*, 33, 308-318.
- Jodo, E., & Kayama, Y. (1992). Relation of a negative ERP component to response inhibition in a go/no-go task. *Electroencephalography and Clinical Neurophysiology*, 82, 477-482.

- Johnstone, S. J., Dimoska, A., Smith, J. L., Barry, R. J., Pleffer, C. B., Chiswick, D., et al. (2007). The development of stop-signal and go/nogo response inhibition in children aged 7-12 years: Performance and event-related potential indices. *International Journal of Psychophysiology*, 63(1), 25-38.
- Johnstone, S. J., Pleffer, C. B., Barry, R. J., Clarke, A. R., & Smith, J. L. (2005). Development of inhibitory processing during the go/nogo task: A behavioral and event-related potential study of children and adults. *Journal of Psychophysiology*, 19(1), 11-23.
- Jonkman, L. M. (2006). The development of preparation, conflict monitoring and inhibition from early childhood to young adulthood; a go/nogo ERP study. *Brain Research*, 1097(1), 181-193.
- Jonkman, L. M., Lansbergen, M., & Stauder, J. E. A. (2003). Developmental differences in behavioral and event-related brain responses associated with response preparation and inhibition in a go/nogo task. *Psychophysiology*, 40(5), 752-761.
- Joseph, R. M., Steele, S. D., Meyer, E., & Tager-Flusberg, H. (2005). Self-ordered pointing in children with autism; failure to use verbal mediation in the service of working memory? *Neuropsychologia*, 43, 1400-1411.
- Kail, R. (1986). Sources of age differences in speed of processing. *Child Development*, 57(4), 969-987.
- Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin*, 109(3), 490-501.
- Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences*, 2(10), 389-398.
- Kiefer, M., Marzinzik, F., Weisbrod, M., Scherg, M., & Spitzer, M. (1998). The time course of brain activations during response inhibition: Evidence from event-related potentials in a go/no go task. *Neuroreport*, 9(4), 765-770.
- Kipp, K. (2005). A developmental perspective on the measurement of cognitive deficits in attention-deficit/hyperactivity disorder. *Biological Psychiatry*, 57(11), 1256-1260.
- Kirk, U., & Kelly, M. S. (1986). Children's differential performance on selected dorsolateral prefrontal and posterior cortical functions: A developmental perspective. *Journal of Clinical and Experimental Neuropsychology*, 7, 604.
- Kirkham, N. Z., & Diamond, A. (2003). Sorting between theories of perseveration: performance in conflict tasks requires memory, attention and inhibition. *Developmental Science*, 6(5), 474-476.
- Kirkham, N. Z., Cruess, L., & Diamond, A. (2003). Helping children apply their knowledge to their behavior on a dimension-switching task. *Developmental Science*, 6(5), 449-476.
- Klingberg, T. (2006). Development of a superior frontal-intraparietal network for visuo-spatial working memory. *Neuropsychologia*, 44(11), 2171-2177.
- Kloo, D., & Perner, J. (2005). Disentangling dimensions in the dimensional change card-sorting task. *Developmental Science*, 8(1), 44-56.
- Kloo, D., Perner, J., & Dabernig, S. (2007). *Reversal shifts vs. extra-dimensional shifts in preschoolers: Evidence against a selective attention account*. Poster presented at the biennial meeting of the Society for Research in Child Development, Boston, MA.
- Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory & Cognition*, 34(2), 433-444.

- Kochanska, G., Murray, K. T., Jacques, T. Y., Koenig, A. L., & Vandegeest, K. A. (1996). Inhibitory control in young children and its role in emerging internalization. *Child Development*, 67, 490-507.
- Kok, A., Ramautar, J. R., De Ruiter, M. B., Band, G. P. H., & Ridderinkhof, K. R. (2004). ERP components associated with successful and unsuccessful stopping in a stop-signal task. *Psychophysiology*, 41(1), 9-20.
- Kopp, B., Mattler, U., Goertz, R., & Rist, F. (1996). N2, P3 and the lateralized readiness potential in a nogo task involving selective response priming. *Electroencephalography and Clinical Neurophysiology*, 99(1), 19-27.
- Kray, J., Eber, J., & Lindenberger, U. (2004). Age differences in executive functioning across the lifespan: The role of verbalization in task preparation. *Acta Psychologica*, 115(2-3), 143-165.
- Kray, J., & Eppinger, B. (2006). Effects of associative learning on age differences in task-set switching. *Acta Psychologica*, 123(3), 187-203.
- Kray, J., Li, K. Z. H., & Lindenberger, U. (2002). Age-related changes in task-switching components: The role of task uncertainty. *Brain and Cognition*, 49, 363-381.
- Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging*, 15, 126-147.
- Kuntsi, J., Stevenson, J., Oosterlaan, J., & Sonuga-Barke, E. J. S. (2001). Test-retest reliability of a new delay aversion task and executive function measures. *British Journal of Developmental Psychology*, 19(3), 339-348.
- Lamm, C., Zelazo, P. D., & Lewis, M. D. (2006). Neural correlates of cognitive control in childhood and adolescence: Disentangling the contributions of age and executive function. *Neuropsychologia*, 44(11), 2139-2148.
- Lavric, A., Pizzagalli, D. A., & Forstmeier, S. (2004). When 'go' and 'nogo' are equally frequent: ERP components and cortical tomography. *European Journal of Neuroscience*, 20(9), 2483-2488.
- Lehto, J. E., Juujarvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, 21, 59-80.
- Levin, H. S., Culhane, K. A., Hartmann, J., Evankovich, K., Mattson, A. J., Harward, H., et al. (1991). Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology*, 7(3), 377-395.
- Levy, F. (1980). The development of sustained attention (vigilance) and inhibition in children: Some normative data. *Journal of Child Psychology and Psychiatry*, 21, 77-84.
- Lewis, M. D., Lamm, C., Segalowitz, S. J., Stieben, J., & Zelazo, P. D. (2006). Neurophysiological correlates of emotion regulation in children and adolescents. *Journal of Cognitive Neuroscience*, 18(3), 430-443.
- Liston, C., Matalon, S., Hare, T. A., Davidson, M. C., & Casey, B. J. (2006). Anterior cingulate and posterior parietal cortices are sensitive to dissociable forms of conflict in a task-switching paradigm. *Neuron*, 50(4), 643-653.
- Livesey, D. J., & Morgan, G. A. (1991). The development of response inhibition in 4- and 5-year-old children. *Australian Journal of Psychology*, 43(3), 133-137.
- Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: a theory of an act of control. *Psychological Review*, 91, 295-327.
- Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit thought and action: A model and a method. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 276-291.

- Lowe, C., & Rabbitt, P. (1998). Test/re-test reliability of the CANTAB and ISPOCD neuropsychological batteries: Theoretical and practical issues. *Neuropsychologia*, 36(9), 915-923.
- Luciana, M. (2003). Practitioner review: Computerized assessment of neuropsychological function in children: Clinical and research applications of the cambridge neuropsychological testing automated battery (CANTAB). *Journal of Child Psychology and Psychiatry*, 44(5), 649-663.
- Luciana, M., & Nelson, C. A. (1998). The functional emergence of prefrontally-guided working memory systems in four- to eight-year-old children. *Neuropsychologia*, 36(3), 273-293.
- Luciana, M., & Nelson, C. A. (2002). Assessment of neuropsychological function through use of the cambridge neuropsychological testing automated battery: Performance in 4- to 12-year-old children. *Developmental Neuropsychology*, 22(3), 595-624.
- Luria, A. R. (1959). Experimental study of the higher nervous activity of the abnormal child. *Journal of Mental Deficiency Research*, 3, 1-22.
- Manly, T., Robertson, I. H., Anderson, V., & Nimmo-Smith, I. (1999). *The test of everyday attention for children (TEA-Ch)*. London: Harcourt Assessment.
- Mayr, U. (2001). Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging*, 16(1), 96-109.
- Mayr, U., & Bryck, R. L. (2007). Outsourcing control to the environment: Effects of stimulus/response locations on task selection. *Psychological Research*, 71(1), 107-116.
- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22(6), 1423-1442.
- Meiran, N. (2000). Reconfiguration of stimulus task sets and response task sets during task switching. In S. Monsell & J. S. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 377-399). Cambridge, MA: MIT Press.
- Meiran, N., Gotler, A., & Perlman, A. (2001). Old age is associated with a pattern of relatively intact and relatively impaired task-set switching abilities. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 56(2), P88-P102.
- Mesulam, M. M. (2002). The human frontal lobes: Transcending the default mode through contingent encoding. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 8-30). Oxford: Oxford University Press.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24(1), 167-202.
- Milner, B. (1963). Effects of different brain lesions on card sorting: The role of the frontal lobes. *Archives of Neurology*, 9, 90-100.
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, 41(1), 49-100.
- Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, 7(3), 134-140.
- Monsell, S., Yeung, N., & Azuma, R. (2000). Reconfiguration of task-set: Is it easier to switch to the weaker task? *Psychological Research*, 63(3), 250-264.

- Morton, J. B., & Munakata, Y. (2002). Active versus latent representations: A neural network model of perseveration, dissociation, and decalage. *Developmental Psychobiology*, 40(3), 255-265.
- Müller, U., Dick, A. S., Gela, K., Overton, W. F., & Zelazo, P. D. (2006). The role of negative priming in preschoolers' flexible rule use on the dimensional change card sort task. *Child Development*, 77(2), 395-412.
- Munakata, Y. (2001). Graded representations in behavioral dissociations. *Trends in Cognitive Sciences*, 5(7), 309-315.
- Munakata, Y., & Yerys, B. E. (2001). All together now: When dissociations between knowledge and action disappear. *Psychological Science*, 12(4), 335-337.
- Nation, K., Adams, J. W., Bowyer-Crane, C. A., & Snowling, M. J. (1999). Working memory deficits in poor comprehenders reflect underlying language impairments. *Journal of Experimental Child Psychology*, 73(2), 139-158.
- Nieuwenhuis, S., Yeung, N., van den Wildenberg, W., & Ridderinkhof, K. R. (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. *Cognitive, Affective, & Behavioural Neuroscience*, 3(1), 17-26.
- Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, 126(2), 220-246.
- Okazaki, S., Hosokawa, M., Kawakubo, Y., Ozaki, H., Maekawa, H., & Futakami, S. (2004). Developmental change of neurocognitive motor behavior in a continuous performance test with different interstimulus intervals. *Clinical Neurophysiology*, 115(5), 1104-1113.
- Overman, W. H., Bachevalier, J., Schuhmann, E., & Ryan, P. (1996). Cognitive gender differences in very young children parallel biologically based cognitive gender differences in monkeys. *Behavioral Neuroscience*, 110(4), 673-684.
- Ozonoff, S., South, M., & Provençal, S. (2005). Executive functions. In F. Volkmar, R. Paul, A. Klin & D. Cohen (Eds.), *Handbook of autism and pervasive developmental disorders: Vol. 1. Diagnosis, development, neurobiology, and behavior* (3rd ed., pp. 606-627). Hoboken, NJ: Wiley.
- Passler, M. A., Isaac, W., & Hynd, G. W. (1985). Neuropsychological development of behavior attributed to frontal lobe functioning in children. *Developmental Neuropsychology*, 1(4), 349-370.
- Pennington, B. F. (1998). Dimensions of executive functions in normal and abnormal development. In N. A. Krasnegor, G. R. Lyon & P. S. Goldman-Rakic (Eds.), *Development of the prefrontal cortex: Evolution, neurobiology, and behavior* (pp. 265-281). Baltimore: Brookes.
- Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry*, 37(1), 51-87.
- Perner, J., & Lang, B. (2002). What causes 3-year-olds' difficulty on the dimensional change card sorting task? *Infant and Child Development*, 11(2), 93-105.
- Petrides, M., & Milner, B. (1982). Deficits on subject-ordered tasks after frontal- and temporal-lobe lesions in man. *Neuropsychologia*, 20(3), 249-262.
- Pfefferbaum, A., Ford, J. M., Weller, B. J., & Kopell, B. S. (1985). ERPs to response production and inhibition. *Electroencephalography and Clinical Neurophysiology*, 60, 423-434.

- Phillips, L.H., MacPherson, S. & Della Sala, S. (2002). Age, cognition and emotion: the role of anatomical segregation in the frontal lobes. In J. Grafman (Ed.), *Handbook of neuropsychology: Vol. 7. The frontal lobes* (2nd ed., pp 73-97). Amsterdam: Elsevier Science B.V.
- Reimers, S., & Maylor, E. A. (2005). Task switching across the life span: Effects of age on general and specific switch costs. *Developmental Psychology*, 41(4), 661-671.
- Rennie, D. A. C., Bull, R., & Diamond, A. (2004). Executive functioning in preschoolers: Reducing the inhibitory demands of the dimensional change card sort task. *Developmental Neuropsychology*, 26(1), 423-443.
- Rhodes, S. M., Coghill, D. R., & Matthews, K. (2004). Methylphenidate restores visual memory, but not working memory function in attention deficit-hyperkinetic disorder. *Psychopharmacology*, 175, 319-330.
- Ridderinkhof, K. R., Band, G. P. H., & Logan, G. D. (1999). A study of adaptive behavior: Effects of age and irrelevant information on the ability to inhibit one's actions. *Acta Psychologica*, 101(2-3), 315-337.
- Ridderinkhof, K. R., van der Molen, M. W., Band, G. P. H., & Bashore, T. R. (1997). Sources of interference from irrelevant information: A developmental study. *Journal of Experimental Child Psychology*, 65(3), 315-341.
- Roberts, R. J., Hager, L. D., & Heron, C. (1994). Prefrontal cognitive processes: Working memory and inhibition in the antisaccade task. *Journal of Experimental Psychology: General*, 123(4), 374-393.
- Roberts, R. J., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology*, 12, 105-126.
- Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, 124(2), 207-231.
- Rubia, K., Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., et al. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of go/no-go and stop tasks. *NeuroImage*, 13, 250-261.
- Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 31(6), 1477-1491.
- Scerif, G. (2006). What is so special about modules? Defining mechanisms of developmental change. *Infancia y Aprendizaje*, 29, 281-287.
- Schachar, R., & Logan, G. D. (1990). Impulsivity and inhibitory control in normal development and childhood psychopathology. *Developmental Psychology*, 26(5), 710-720.
- Scheres, A., Oosterlaan, J., Geurts, H., Morein-Zamir, S., Meiran, N., Schut, H., et al. (2004). Executive functioning in boys with ADHD: Primarily an inhibition deficit? *Archives of Clinical Neuropsychology*, 19(4), 569-594.
- Schouten, A., Oostrom, K. J., Peters, A. C. B., Verloop, D., & Jennekens-Schinkel, A. (2000). Set-shifting in healthy children and in children with idiopathic or cryptogenic epilepsy. *Developmental Medicine and Child Neurology*, 42(6), 392-397.
- Segalowitz, S. J., & Davies, P. L. (2004). Charting the maturation of the frontal lobe: An electrophysiological strategy. *Brain and Cognition*, 55(1), 116-133.

- Semlitsch, H. V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology*, 23(6), 695-703.
- Shepp, B. E., & Barrett, S. E. (1991). The development of perceived structure and attention: Evidence from divided and selective attention tasks. *Journal of Experimental Child Psychology*, 51(3), 434-458.
- Shue, K. L., & Douglas, V. I. (1992). Attention deficit hyperactivity disorder and the frontal lobe syndrome. *Brain and Cognition*, 20(1), 104-124.
- Simpson, A., & Riggs, K. J. (2005). Factors responsible for performance on the day-night task: Response set or semantics? *Developmental Science*, 8(4), 360-371.
- Simpson, A., & Riggs, K. J. (2006). Conditions under which children experience inhibitory difficulty with a "button-press" go/no-go task. *Journal of Experimental Child Psychology*, 94(1), 18-26.
- Smith, M. L., Klim, P., & Hanley, W. B. (2000). Executive function in school-aged children with phenylketonuria. *Journal of Developmental and Physical Disabilities*, 12(4), 317-332.
- Sohn, M., & Anderson, J. R. (2003). Stimulus-related priming during task switching. *Memory & Cognition*, 31(5), 775-780.
- Somsen, R. J. M. (in press). The development of attention regulation in the wisconsin card sorting task. *Developmental Science*.
- Stige, S., Fjell, A. M., Smith, L., Lindgren, M., & Walhovd, K. B. (2007). The development of visual P3a and P3b. *Developmental Neuropsychology*, 32(1), 563-584.
- Strutt, G. F., Anderson, D. R., & Well, A. D. (1975). A developmental study of the effects of irrelevant information on speeded classification. *Journal of Experimental Child Psychology*, 20(1), 127-135.
- Stuss, D. T. (1992). Biological and psychological development of executive functions. *Brain and Cognition*, 20(1), 8-23.
- Stuss, D. T., Alexander, M. P., Floden, D., Binns, M. A., Levine, B., McIntosh, A. R., et al. (2002). Fractionation and localization of distinct frontal lobe processes: Evidence from focal lesions in humans. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 392-407). Oxford: Oxford University Press.
- Stuss, D. T., & Benson, D. F. (1986). *The frontal lobes*. New York: Raven Press.
- Szekely, A., Jacobsen, T., D'Amico, S., Devescovi, A., Andonova, E., Herron, D., et al. (2004). A new on-line resource for psycholinguistic studies. *Journal of Memory and Language*, 51(2), 247-250.
- Tekok-Kilic, A., Shucard, J. L., & Shucard, D. W. (2001). Stimulus modality and go/nogo effects on P3 during parallel visual and auditory continuous performance tasks. *Psychophysiology*, 38(3), 578-589.
- Towse, J. N., Redbond, J., Houston-Price, C. M. T., & Cook, S. (2000). Understanding the dimensional change card sort: Perspectives from task success and failure. *Cognitive Development*, 15(3), 347-365.
- van Boxtel, G. J. M., van der Molen, M. W., Jennings, J. R., & Brunia, C. H. M. (2001). A psychophysiological analysis of inhibitory motor control in the stop-signal paradigm. *Biological Psychology*, 58, 229-262.
- van Goozen, S. H. M., Cohen-Kettenis, P. T., Snoek, H., Matthys, W., Swaab-Barneveld, H., & van Engeland, H. (2004). Executive functioning in children: A comparison of hospitalised ODD and ODD/ADHD children and normal controls. *Journal of Child Psychology and Psychiatry*, 45(2), 284-292.

- Walker, I., & Hulme, C. (1999). Concrete words are easier to recall than abstract words: Evidence for a semantic contribution to short-term serial recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25(5), 1256-1271.
- Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology*, 46, 361-413.
- Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*. London: The Psychological Corporation.
- Welsh, M. C., & Pennington, B. F. (1988). Assessing frontal lobe functioning in children: Views from developmental psychology. *Developmental Neuropsychology*, 4(3), 199-230.
- Welsh, M. C., Pennington, B. F., & Groisser, D. B. (1991). A normative-developmental study of executive function: A window on prefrontal function in children. *Developmental Neuropsychology*, 7(2), 131-149.
- Williams, B. R., Ponesse, J. S., Schachar, R., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the lifespan. *Developmental Psychology*, 35(1), 205-213.
- Williams, K. T. (1997). *Expressive vocabulary test*. Circle Pines, MN: American Guidance Service.
- Wright, I., Waterman, M., Prescott, H., & Murdoch-Eaton, D. (2003). A new Stroop-like measure of inhibitory function development: Typical developmental trends. *Journal of Child Psychology and Psychiatry*, 44(4), 561-575.
- Wylie, G., & Allport, A. (2000). Task switching and the measurement of "switch costs". *Psychological Research*, 63(3-4), 212-233.
- Yerys, B. E., & Munakata, Y. (2006). When labels hurt but novelty helps: Children's perseveration and flexibility in a card-sorting task. *Child Development*, 77(6), 1589-1607.
- Yeung, N., & Monsell, S. (2003a). The effects of recent practice on task switching. *Journal of Experimental Psychology: Human Perception and Performance*, 29(5), 919-936.
- Yeung, N., & Monsell, S. (2003b). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception and Performance*, 29(2), 455-469.
- Zelazo, P. D., Craik, F. I. M., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica*, 115(2-3), 167-183.
- Zelazo, P. D., & Frye, D. (1998). Cognitive complexity and control: II. The development of executive function in childhood. *Current Directions in Psychological Science*, 7(4), 121-126.
- Zelazo, P. D., Frye, D., & Rapus, T. (1996). An age-related dissociation between knowing rules and using them. *Cognitive Development*, 11(1), 37-63.
- Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development*, 68(3).

Appendices

Appendix I: Means and Standard Deviations for Experiments Reported in Chapter 2

Experiment 1

<u>Task</u>	<u>Trialtype</u>	<u>Congruence</u>	<u>Young Children</u>				<u>Old Children</u>			
			<u>Session 1</u>		<u>Session 2</u>		<u>Session 1</u>		<u>Session 2</u>	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Colour	Pure	Incongruent	1075	210.5	1043	234.7	818.7	121.3	797.3	131.5
		Congruent	1062	208.5	1027	218.0	811.5	121.8	793.1	131.8
	Non-switch	Incongruent	1328	377.1	1142	249.6	925.6	190.0	865.3	154.8
		Congruent	1229	328.6	1195	340.5	879.7	149.1	852.3	136.5
	Switch	Incongruent	1475	396.6	1308	356.6	974.8	197.6	904.8	167.4
		Congruent	1320	373.7	1206	358.8	917.9	178.2	870.9	153.2
Pattern	Pure	Incongruent	1177	247.9	1131	283.1	889.4	128.8	841.5	141.4
		Congruent	1182	258.8	1098	247.5	887.4	144.3	828.5	137.5
	Non-switch	Incongruent	1383	438.7	1213	285.8	941.5	174.0	891.0	152.3
		Congruent	1295	324.5	1214	303.3	927.4	165.2	898.2	155.9
	Switch	Incongruent	1433	363.4	1337	350.1	985.4	201.8	925.2	188.9
		Congruent	1354	357.7	1255	330.6	945.3	162.4	897.8	178.2

Experiment 2a: Football version

<u>Task</u>	<u>Trialtype</u>	<u>Congruence</u>	<u>6 to 8 yrs</u>		<u>9 yrs</u>		<u>10 to 11 yrs</u>	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Colour	Pure	Incongruent	943.0	180.8	823.8	155.4	758.6	138.9
		Congruent	945.9	174.2	812.1	142.5	745.4	148.9
	Non-switch	Incongruent	997.7	196.7	901.0	170.2	757.2	132.4
		Congruent	1013	201.0	871.7	170.3	726.1	130.8
	Switch	Incongruent	1096	284.7	933.6	160.6	761.8	155.7
		Congruent	987.3	205.5	878.6	187.9	741.0	121.1
Pattern	Pure	Incongruent	1027	195.5	879.3	140.5	780.2	137.2
		Congruent	1019	173.2	897.2	153.0	795.5	151.9
	Non-switch	Incongruent	1080	250.3	926.4	173.4	794.3	201.1
		Congruent	1073	241.1	892.9	161.5	775.8	162.9
	Switch	Incongruent	1136	308.2	983.3	211.6	787.6	140.9
		Congruent	1095	237.6	928.7	161.9	783.7	146.7

Experiment 2a: Cake version

<u>Task</u>	<u>Trialtype</u>	<u>Congruence</u>	<u>6 to 8 yrs</u>		<u>9 yr</u>		<u>10 to 11 yrs</u>	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Colour	Pure	Incongruent	919.5	147.0	839.3	114.0	704.1	103.5
		Congruent	915.0	159.8	836.5	112.2	706.9	109.3
	Non-switch	Incongruent	967.6	202.9	918.0	181.3	738.1	138.7
		Congruent	975.3	204.3	850.2	105.1	725.9	121.6
	Switch	Incongruent	996.3	187.1	937.2	237.9	739.6	129.8
		Congruent	995.5	223.9	901.8	159.8	733.6	133.4
Shape	Pure	Incongruent	973.4	178.6	837.0	87.9	764.6	122.2
		Congruent	975.4	159.2	840.6	84.7	769.2	118.0
	Non-switch	Incongruent	1055	247.2	888.3	171.2	754.9	151.7
		Congruent	1074	309.8	909.0	137.1	738.3	118.9
	Switch	Incongruent	1082	261.5	939.7	161.2	774.8	148.0
		Congruent	1068	245.0	915.8	180.3	748.9	135.0

Appendix II: Means and Standard Deviations for Chapter 3

Colour Task

<u>Condition</u>	<u>Trialtype</u>	<u>Congruence</u>	<u>Order One</u>				<u>Order Two</u>			
			<u>5 to 7 yrs</u>		<u>9 to 11 yrs</u>		<u>5 to 7 yrs</u>		<u>9 to 11 yrs</u>	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
RI-SI	Non-switch	Incongruent	1253	250.5	817.6	179.7	1164	349.9	833.3	192.2
		Congruent	1203	254.0	796.3	123.2	1085	211.3	799.8	224.6
	Switch	Incongruent	1292	218.0	843.3	200.0	1243	320.2	856.8	244.9
		Congruent	1244	221.3	805.4	143.2	1162	320.9	814.7	163.6
RI-SS	Non-switch	Incongruent	1238	226.6	794.1	168.9	1193	252.4	897.6	130.8
		Congruent	1118	202.8	786.3	119.9	1183	249.4	879.0	155.9
	Switch	Incongruent	1261	232.4	802.0	127.2	1385	386.7	978.6	212.5
		Congruent	1209	319.5	802.9	161.5	1258	296.8	917.4	129.9
RS-SI	Non-switch	Incongruent	1252	157.9	824.7	106.9	1087	253.0	843.9	201.7
		Congruent	1246	177.0	816.4	114.4	1076	223.4	804.9	177.2
	Switch	Incongruent	1387	257.1	859.0	141.7	1073	227.9	844.4	194.4
		Congruent	1333	186.0	851.6	126.1	1096	256.5	816.6	166.1
RS-SS	Non-switch	Incongruent	1212	343.2	785.1	152.4	1107	235.7	807.2	113.2
		Congruent	1214	364.5	786.4	139.2	1197	411.2	814.5	127.4
	Switch	Incongruent	1366	396.0	796.0	142.9	1230	304.7	857.2	167.8
		Congruent	1254	337.8	800.8	141.9	1191	266.9	844.0	156.7

Shape Task

<u>Condition</u>	<u>Trialtype</u>	<u>Congruence</u>	<u>Order One</u>				<u>Order Two</u>			
			<u>5 to 7 yrs</u>		<u>9 to 11 yrs</u>		<u>5 to 7 yrs</u>		<u>9 to 11 yrs</u>	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
RI-SI	Non-switch	Incongruent	1275	222.5	871.3	217.6	1201	275.7	818.1	149.5
		Congruent	1289	244.6	827.2	162.1	1221	290.7	813.0	125.0
	Switch	Incongruent	1304	287.6	856.6	160.4	1214	277.8	840.5	169.9
		Congruent	1381	265.1	888.3	180.3	1287	382.0	827.6	161.3
RI-SS	Non-switch	Incongruent	1326	358.7	835.8	189.1	1316	262.6	950.7	164.5
		Congruent	1315	335.5	806.1	154.6	1302	410.1	929.5	166.6
	Switch	Incongruent	1295	252.6	879.3	251.6	1398	306.3	1007.7	150.0
		Congruent	1314	294.6	833.7	149.6	1362	268.4	969.2	116.8
RS-SI	Non-switch	Incongruent	1235	184.5	909.9	125.5	1142	283.5	902.9	290.0
		Congruent	1320	239.9	927.3	186.3	1137	268.8	901.5	326.9
	Switch	Incongruent	1392	206.6	898.2	126.3	1222	310.2	866.7	190.7
		Congruent	1432	261.7	937.5	123.8	1189	314.2	846.2	169.7
RS-SS	Non-switch	Incongruent	1399	311.3	865.9	148.0	1315	301.7	884.4	148.2
		Congruent	1379	370.8	881.2	179.1	1274	281.1	900.0	114.9
	Switch	Incongruent	1437	433.8	888.1	154.5	1322	260.7	913.4	174.0
		Congruent	1410	300.5	846.4	137.0	1266	276.7	889.7	146.7

Appendix III: Means and Standard Deviations for Chapter 4

Errors

<u>Condition</u>	<u>Set Size</u>	<u>Game</u>	<u>Younger Children</u>		<u>Older Children</u>		<u>Adults</u>	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
<u>Object</u>	6	1	0.58	0.72	0.69	0.70	0.27	0.46
		2	1.00	0.71	0.64	0.83	0.27	0.46
		3	1.07	0.86	0.60	0.65	0.00	0.00
	8	1	1.16	0.88	0.87	0.84	0.20	0.41
		2	1.73	0.86	1.29	0.76	0.33	0.49
		3	1.76	0.93	1.20	0.84	0.60	0.63
	10	1	1.40	1.05	1.22	1.08	0.60	0.63
		2	2.80	1.29	1.84	1.00	1.07	0.70
		3	2.38	0.89	1.82	1.01	0.93	0.88
<u>Abstract</u>	6	1	1.47	0.73	0.89	0.78	1.07	0.70
		2	1.33	0.83	1.13	0.79	0.73	0.80
		3	1.62	0.75	1.24	0.74	0.67	0.62
	8	1	2.20	0.92	1.73	0.96	1.47	0.74
		2	2.13	1.01	1.78	1.00	0.73	0.59
		3	2.38	1.17	1.84	1.02	1.27	0.80
	10	1	3.16	1.36	2.42	1.25	1.53	0.92
		2	3.20	1.18	2.69	0.95	1.33	0.72
		3	3.31	1.62	2.40	1.01	1.53	0.83

Span

<u>Condition</u>	<u>Set Size</u>	<u>Game</u>	<u>Younger Children</u>		<u>Older Children</u>		<u>Adults</u>	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
<u>Object</u>	6	1	5.11	1.25	5.00	1.13	5.60	0.83
		2	4.60	1.21	5.00	1.35	5.47	1.13
		3	4.13	1.47	5.20	0.94	6.00	0.00
	8	1	5.93	1.84	6.20	1.79	7.80	0.41
		2	4.78	1.52	5.67	1.71	7.67	0.49
		3	4.56	2.01	5.91	1.70	6.87	1.68
	10	1	6.73	2.81	7.22	2.46	8.87	1.30
		2	5.09	2.12	6.47	2.55	8.27	1.58
		3	5.40	1.98	6.40	2.29	7.73	2.63
<u>Abstract</u>	6	1	3.82	1.15	4.62	1.28	4.53	0.83
		2	3.47	1.56	4.24	1.40	5.00	1.13
		3	3.62	1.19	4.11	1.25	4.93	1.22
	8	1	3.98	1.94	4.80	1.89	4.73	1.87
		2	3.84	2.13	4.71	1.87	6.07	2.25
		3	3.78	2.04	4.20	1.85	6.07	1.67
	10	1	4.22	2.09	5.18	2.09	6.80	2.24
		2	4.38	1.86	4.73	1.92	6.53	2.56
		3	4.02	1.89	5.22	2.13	6.60	2.47

Appendix IV: Means and Standard Deviations for Chapter 5

Accuracy

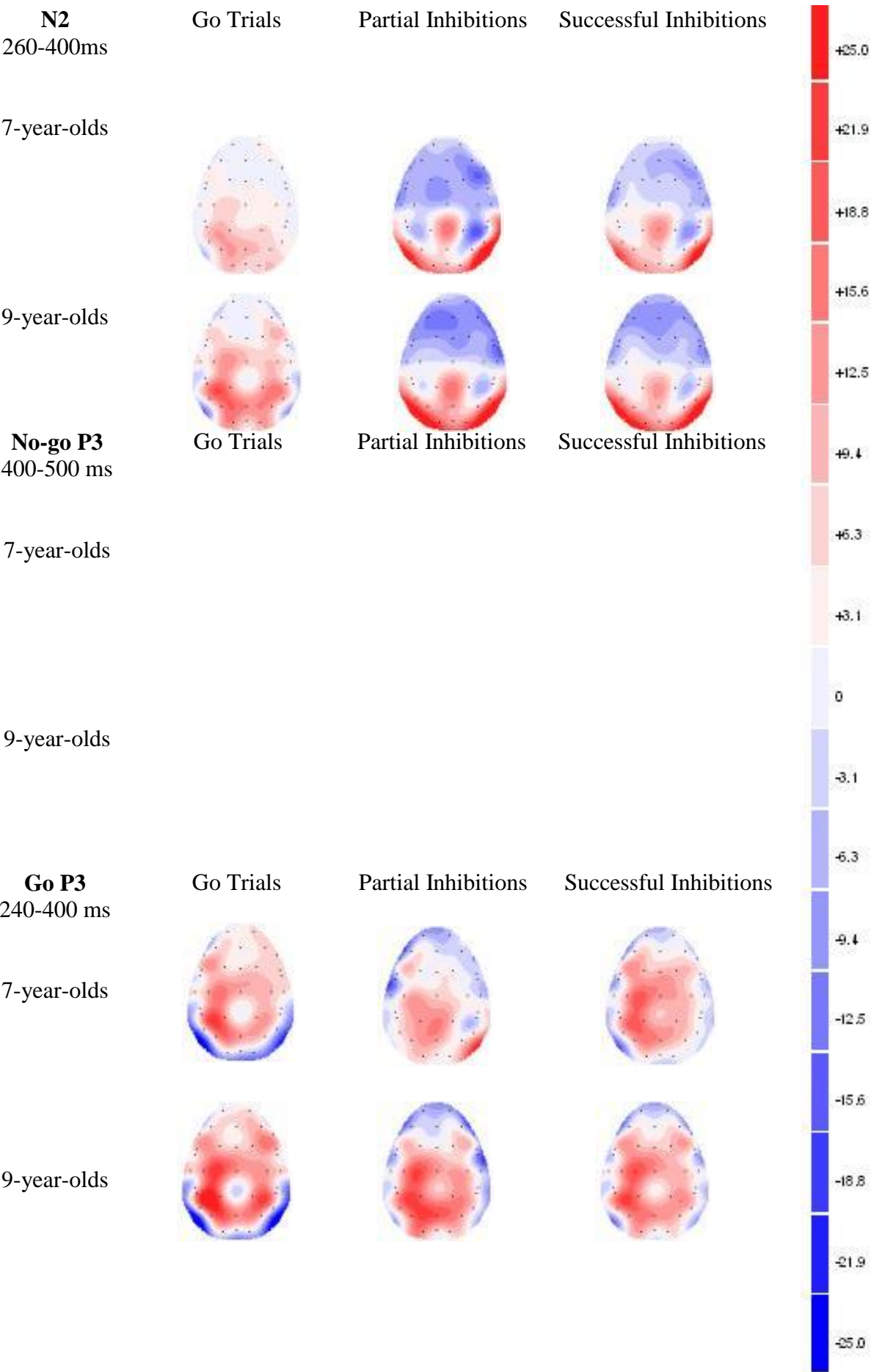
<u>ISI</u>	<u>Trialtype</u>	<u>5 to 7 years</u>		<u>9 to 11 years</u>	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
3000ms	Hits	84.7	11.1	89.2	9.60
	Misses	9.03	6.37	7.52	7.39
	Successful Inhibitions	29.2	21.6	39.9	23.4
	Partial Inhibitions	45.1	16.6	37.8	19.3
	Failed Inhibitions	20.1	17.9	20.8	20.4
2000ms	Hits	78.4	12.4	88.3	9.98
	Misses	11.4	7.67	6.64	5.51
	Successful Inhibitions	31.8	22.1	46.3	27.5
	Partial Inhibitions	38.5	17.8	29.2	18.9
	Failed Inhibitions	19.6	20.8	20.1	19.4

RT*

<u>ISI</u>	<u>Trialtype</u>	<u>5 to 7 years</u>		<u>9 to 11 years</u>	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
3000ms	Hits	452.8	57.6	306.9	23.9
	Partial Inhibitions	427.0	62.6	294.9	36.3
2000ms	Hits	437.0	57.5	295.6	30.4
	Partial Inhibitions	403.9	61.9	277.3	34.1

Note. This analysis only included participants who made more than 5 partial inhibitions in each ISI condition.

Appendix V: Scalp Topographies for Chapter 6



Appendix VI: Means and Standard Deviations for Chapter 7

Task	Dependent Variable	Yr 2 _{T2}	Yr 3 _{T2}	Yr 4 _{T2}	Yr 5 _{T2}	Yr 6 _{T2}	Total
		<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
		(<i>n</i> =14)	(<i>n</i> =13)	(<i>n</i> =15)	(<i>n</i> =14)	(<i>n</i> =14)	(<i>n</i> =70)
Football task-switching paradigm	Switch cost (session 1)	85.8 (102)	132 (88.7)	60.8 (58.6)	48.6 (46.2)	20.1 (49.7)	68.5 (79.4)
TEA-Ch Creature Counting	Accuracy (raw score)	3.79 (2.49)	3.23 (2.09)	4.47 (1.68)	5.64 (1.01)	4.71 (1.77)	4.39 (1.99)
	Accuracy (standard score) ¹	9.64 (3.97)	7.23 (2.98)	8.47 (2.95)	9.93 (2.30)	8.14 (3.23)	8.70 (3.20)
	Switches	13.6 (9.29)	11.5 (8.39)	16.5 (6.61)	20.7 (4.12)	17.1 (6.84)	15.9 (7.70)
	Time (raw score)	6.02 (2.08)	6.71 (4.51)	4.91 (1.13)	4.27 (1.10)	3.46 (0.65)	4.97 (2.41)
	Time (standard score) ¹	10.4 (2.60)	10.1 (3.40)	8.77 (3.11)	9.29 (3.00)	10.7 (2.61)	9.77 (2.94)
BADS-C Playing Cards	Errors (+ self corrections)*	4.29 (2.27)	3.77 (2.92)	3.33 (1.68)	3.71 (2.37)	2.93 (1.59)	3.60 (2.18)
	Time	15.7 (10.0)	13.0 (11.0)	9.19 (4.92)	8.19 (5.17)	5.28 (3.86)	10.2 (8.12)
Go/no-go task	Partial inhibitions	33.0 (19.0)	35.5 (17.2)	35.9 (10.2)	36.8 (7.94)	33.0 (19.0)	37.1 (14.2)
TEA-Ch Opposite Worlds	Time taken (raw score)	41.6 (10.8)	42.1 (7.47)	34.4 (7.28)	30.0 (4.30)	26.8 (4.22)	34.9 (9.29)
	Standard score ¹	10.1 (2.85)	7.54 (2.54)	8.60 (2.87)	9.43 (2.03)	10.0 (2.91)	9.16 (2.76)

Task	Dependent Variable	Yr 2 _{T2}	Yr 3 _{T2}	Yr 4 _{T2}	Yr 5 _{T2}	Yr 6 _{T2}	Total
		<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
		(<i>n</i> =14)	(<i>n</i> =13)	(<i>n</i> =15)	(<i>n</i> =14)	(<i>n</i> =14)	(<i>n</i> =70)
Self-ordered pointing test (SOPT)	Errors	1.92 (0.45)	2.08 (0.59)	1.76 (0.48)	1.38 (0.49)	1.35 (0.41)	1.70 (0.55)
	Span	4.44 (0.73)	4.30 (0.92)	4.90 (0.80)	5.33 (0.93)	5.44 (0.72)	4.89 (0.92)
Digit Span	Forward span	4.64 (0.63)	4.62 (0.87)	4.87 (0.72)	5.25 (0.78)	5.39 (1.04)	4.96 (0.85)
	Backward span	3.00 (0.59)	2.92 (0.57)	3.23 (0.59)	3.54 (0.72)	3.61 (0.53)	3.26 (0.65)
	Standard score ¹	10.6 (2.44)	9.08 (2.47)	9.33 (2.13)	10.0 (1.92)	9.21 (2.39)	9.66 (2.28)
WASI Vocabulary	Raw score	20.9 (4.61)	24.1 (5.12)	29.6 (8.59)	32.9 (6.12)	43.6 (6.27)	30.3 (10.0)
	Standard score ²	48.9 (7.14)	50.7 (8.62)	52.5 (13.3)	50.6 (9.28)	59.6 (8.96)	52.5 (10.2)
WASI Matrices	Raw score	10.4 (6.47)	14.5 (6.59)	16.3 (7.32)	19.1 (5.05)	20.6 (5.02)	16.2 (6.98)
	Standard score ²	54.1 (10.9)	56.8 (11.8)	52.1 (12.5)	51.2 (8.57)	50.0 (7.96)	52.8 (10.5)

Note. ¹ Scaled scores: *M*=10, *SD*=3. ² T scores: *M*=50, *SD*=10. *Norms not available for children under 8 yrs old and based on errors only so standard scores not included.

Appendix VII: Timeline of Data Collection

TIME 1: SPRING 2005

Sample A: 90 5-11-yr-olds (15 of each school year group 1-6)

Football task-switching paradigm (Ch.2, Ch.7)

Self-ordered pointing test (SOPT) (Ch.4, Ch.7)

Go/no-go task

Motor tasks

WASI Vocabulary (Ch.7)

WASI Matrices (Ch.7)

(These tasks (except for WASI Vocabulary) were also completed by 15 young adults (18-22-yrs-old). The adult data for the SOPT are presented in Ch.4)

TIME 2: SPRING 2006

Sample A: 71 of original sample

Football task-switching paradigm (Ch.2)

Cake task-switching paradigm (Ch.2)

Go/no-go task (Ch.7)

Digit Span (Ch.7)

TEA-Ch:

 Opposite worlds subtest (Ch.7)

 Creature Counting subtest (Ch.7)

BADS-C

 Playing Cards subtest (Ch.7)

SNAP-IV rating scale

(completed by teachers)

Sample B: 30 5-7-yr-olds, 30 9-11-yr-olds

Cake task-switching paradigm:
(S-R overlap manipulation) (Ch.3)

Go/no-go task (Ch.5)

Digit Span

TEA-Ch:

 Opposite worlds subtest

 Creature Counting subtest

BADS-C

 Playing Cards subtest

SNAP-IV rating scale

(completed by teachers) (Ch.5)

WASI Vocabulary (Ch.5)

WASI Matrices (Ch.5)

TIME 3: SUMMER 2006

Sample C: 44 7-yr-olds, 41 9-yr-olds

Go/no-go task with ERPs (Ch.6)

(administered as part of a large battery of standardised and experimental measures)