

Thesis
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Inhibitory control and children's
mathematical ability.

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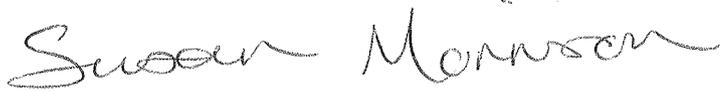
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DECLARATION

I declare that the work undertaken and reported throughout this thesis was completed solely by the undersigned. This work has not been included in any other thesis.



Susan E. Morrison

PUBLICATIONS

The following publications/conference presentations have been adapted from experimental work reported in this thesis:

Davis*, S.E. (2005). Difficulties with arithmetic? The disturbing effect of irrelevant information and increased inhibitory demands. *Proceedings of the British Psychological Society*, 13(1), p. 34. (Published abstract).

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ABSTRACT

Following recent research linking executive functioning to children's skills, this thesis explores the relationship between children's inhibition efficiency and mathematical ability.

This relationship was initially explored using six Stroop task variants containing verbal, numerical or pictorial stimuli. The results indicated that, in the numerical variants only, children of lower mathematical ability possess less efficient inhibition mechanisms, compared to children of higher mathematical ability. Thus, it is proposed that low-ability mathematicians may possess a domain-specific problem with the inhibition of numerical information. The increased interference scores of the low-ability mathematicians, however, were only evident under those conditions which also required a degree of switching between temporary strategies.

A series of experiments also examined children's ability to inhibit prepotent responses and switch between strategies whilst performing mental arithmetic. The aim of these experiments was to provide a more naturalistic and appropriate exploration of the hypothesized relationship between mathematical ability and inhibition efficiency. These results also indicated that low-ability mathematicians possess fewer executive resources to cope with increased inhibition demands. A further systematic manipulation of switching and inhibition demands revealed that the low-ability mathematicians experienced a particular difficulty when both types of inhibitory demands (i.e. inhibiting a prepotent response and inhibiting an established strategy) were present. This suggests that their reduction in inhibition efficiency stems from the amount of demands, rather than the type of demands placed on the executive system. Furthermore, the results indicated that inhibition efficiency may be a specific element of mathematical ability rather than an element of intellectual ability in general.

The final study involved a group of low-ability mathematicians and examined the disturbing impact of irrelevant information on their arithmetic word problem solving ability. This study revealed that irrelevant numerical (IN) information has a more detrimental impact on performance than irrelevant verbal (IV) information. It is proposed that it is more difficult to inhibit IN information, as it appears more relevant to intentions, and thus, enters WM with a higher level of activations.

In sum, the results indicate that low-ability mathematicians have a reduced domain-specific working memory capacity, characterized by inefficient inhibition mechanisms.

Chapter 1

Review of the Stroop task

Introduction

The Stroop task (Stroop, 1935b) has been extremely widely employed and the Stroop phenomenon continues to intrigue and inspire researchers today. It was Cattell's (1886) research which instigated interest in the time difference between colour and picture naming and word reading (cited in MacLeod, 1991). Cattell observed that participants took longer to verbalise the name of objects and colours than they did to read (aloud) the corresponding word. His explanation for this is not unlike those proffered in later years (e.g. Posner & Snyder, 1975; Schneider & Shiffrin, 1977):

“This is because, in the case of words and letters, the association between the idea and name has taken place so often that the process has become automatic, whereas in the case of colors and pictures we must by a voluntary effort choose the name.” (1886, p. 65, cited in Macleod, 1991).

Cattell's observations were the basis for a number of future studies (e.g. Brown, 1915; Hollingworth, 1915; Lund, 1927; Telford, 1930; Ligon, 1932), however, it was not until almost 45 years later that the idea of combining ink colour and colour words was coined. Jaensch is believed to have been the first person to do this (Jaensch, 1929, see Jensen & Rohwer, 1966) however, the test is typically accredited to John Ridley Stroop, following the publication of his doctoral work (Stroop, 1935b).

Stroop's seminal article

Three investigations were actually reported in Stroop's (1935b) article, although the focus is typically placed on his second experiment. The first experiment examined

what is known as the *Reverse Stroop Effect*. This compares the time taken to read colour words presented in black ink with the time taken to read colour words presented in an incongruent ink colour. Participants took only slightly longer (average of 2.3 seconds) to read the incongruously-coloured words. The second experiment is the well-known colour-word naming task. Here the time taken to name the colour of solid coloured patches was compared to the time taken to name the colour of incongruously-coloured words (e.g. BLUE). The *Stroop effect* occurs when the colour naming process is subjected to a response delay caused by the conflicting colour names or colour associations of the words presented. Stroop found that participants took significantly longer to name the colour of the incongruously-coloured words than the colour patches. In a third experiment, Stroop examined practice effects. Participants practised naming the colours of incongruently coloured words over a period of eight days. Over this period, the time taken to name the colours significantly decreased indicating an enhanced ability to inhibit the conflicting dimension (i.e. the colour word). In addition, this experiment was also successful in producing a reverse Stroop effect where the conflicting ink colours significantly interfered with word reading. This reverse interference effect however was short-lived and disappeared in a post-test.

Theoretical Considerations

The Stroop task is an extremely popular tool for studying interference and since its emergence it has provoked much contention over how and why its results are achieved. Many theorists attempted explanations as to how and why the Stroop effect occurred, and two principal hypotheses emerged: the relative speed of

processing view and the automaticity account. Stroop's (1935b, 1938) interpretation of his results is consistent with both of these accounts:

The associations that have been formed between the word stimuli and the reading response are evidently more effective than those that have been formed between the color stimuli and the naming response. Since these associations are the products of training, and since the difference in their strength corresponds roughly to the difference in training in reading words and naming colours, it seems reasonable to conclude that the difference in speed in reading names of colors and in naming colors may be satisfactorily accounted for by the difference in training in the two activities. (Stroop, 1935b, pp. 659-660).

The purpose of this thesis was not to test any theory of the Stroop phenomenon. Nevertheless, a brief review of the main theoretical viewpoints and advances must be considered. The majority of these theories have focused on response competition. A few have proposed that interference may occur at the perceptual encoding stage (e.g. Hock & Egeth, 1970; Tecce & Dimartino, 1965) and also at an intermediate stage between encoding and responding (e.g. Seymour, 1974, 1977). However, it is the response competition theories which have received the most attention and support and a brief review of the main theories is provided below:

Relative Speed of Processing

This account is based on Cattell's (1886) observation that we take longer to name colours than to read words (see also Fraisse, 1969). It is based on the premise that if two competing stimulus dimensions are processed simultaneously then the

processing of one could interfere with the processing of the other, particularly if one dimension is processed more quickly than the other. When faced with the Stroop task, this difference in processing speed becomes clearly apparent. In the incongruent condition two potential responses compete with each other (i.e. the colour word and the ink colour) and this generally results in an increased response time, which is typically described as 'interference'.

Two popular overviews of the relative speed of processing account were offered by Dyer (1973b) and Morton and Chambers (1973). The basic theory behind this hypothesis is that both colour naming and word reading are processed alongside one another until they reach the output port. This port only allows one process to enter at a time, therefore, when responses are in conflict with one another, the delay in response is attributable to the efforts required to overcome this inconsistency.

MacLeod (1991) asserted that in order for any theory to satisfactorily account for the Stroop effect, 18 criteria must be met (see Macleod, 1991, pp. 186-193).

Despite its popularity the relative speed of processing account fails to adequately meet all of these criteria points. For example, the account was crucially based on the premise that interference should be asymmetrical; one dimension (intuitively that which is processed quicker) would interfere with the slower dimension, but not vice versa.

The existence of a Reverse Stroop Effect (RSE) therefore provides contradictory evidence for this hypothesis. Stroop (1935b) initially reported the RSE in his 3rd experiment. Since then a number of studies have reported a RSE and it is now

generally accepted that a RSE does exist (e.g. Abramczyk, Jordan & Hegel, 1983; Chen & Ho, 1986; Dunbar & MacLeod, 1984; Francolini & Egeth, 1980; Glaser & Dolt, 1977; MacLeod & Dunbar, 1988; Martin, 1981; Morikawa, 1981; Nealis, 1974; Pritchatt, 1968, Shor, 1975; Warren & Marsh, 1979). However, the majority of these studies had to deviate from the standard colour word task in order to produce such an effect. For example in the studies by Gumenik & Glass (1970) and Dyer and Severance (1972) the words were partially masked in order to dampen reading ability. Unfortunately, neither of these studies explored interference from the ink colour *and* interference from word reading. Dunbar and MacLeod (1984) examined this and employed the same stimuli in both versions with the only difference being a change in the instructional requirements. They also attempted to slow the reading process by reducing the readability of the words by presenting them in an upside down and reversed format. The results revealed that interference could occur in *both* directions, hence providing evidence against the asymmetrical requirement of the relative speed hypothesis.

Further evidence against the relative speed of processing hypothesis comes from studies by Dyer (e.g. Dyer & Severance, 1972; Severance & Dyer, 1972; Dyer, 1974) and Glaser and colleagues (Glaser & Glaser, 1982; Glaser & Dunglehoff, 1984) which employed 'stimulus onset asynchrony' (SOA), where the ink colour and colour name were presented separately. This research was based on the premise that if the processing of colour naming was initiated prior to any word reading then this 'head start' could reverse Stroop interference. If the time between the two presentations was sufficient to allow the colour response to reach the response buffer first, then this should produce reverse Stroop interference (i.e. the colour

would interfere with the word). Nevertheless, after extensive investigation the SOA studies failed to provide evidence to support the hypothesis that interference is simply due to the faster processing of words versus ink colours.

Theory of automaticity

Another popular theory is the theory of automaticity, which stemmed from the proposals of Posner and Snyder, (1975), LaBerge & Samuels (1974), Shiffrin & Schneider (1977), Logan (1980) and others (see e.g. Hunt & Lansman, 1986).

Proponents of this view consider reading to be an automatic process therefore it is both involuntary and unavoidable. So, when faced with the Stroop task, words are automatically processed and their semantic meaning is accessed. Thus, when the word and colour names are in conflict, interference occurs. The Stroop effect and consequent studies appear to support this, as subjects fail to ignore the words and they appear to extract meaning from them, even when they are consciously attempting not to.

The automaticity account also stresses the asymmetrical nature of interference, where those processes that are more automatic interfere with less automatic processes, but not vice versa. The results of the SOA studies actually support the automaticity view, as this does not rely on processing speed (MacLeod, 1991).

Nonetheless, the automaticity view also failed to meet all of the MacLeod's (1991) 18 criteria points, which must be met for a successful theory. For instance, the view fails to seriously consider the role of attention. Strictly, automatic processes do not require attention. Hence, the development of a strategy should have little impact on the level of interference experienced. However, altering the frequency of

incongruent and congruent trials had an impact on the levels of interference experienced (Zajano & Gorman, 1986; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). Logan & Zbrodoff (1979) increased the frequency of the incongruent trials from 10% to 90% and this resulted in response times shifting from being faster in the congruent trials to being faster in the incongruent trials. Logan & Zbrodoff (1979) asserted that their results suggested that participants were dividing their attention over the two dimensions. Thus, attention does appear to have some impact on performance, hence refuting the all-or-non automaticity view.

Kahneman & Chajcyk's (1983) study also provided evidence against the all-or-none view of automaticity. They found that the presence of irrelevant additional words in the Stroop task continued to produce interference, although the effect was weaker. If word reading was a truly automatic process, then these irrelevant words should have had no impact on the colour naming process. Thus, Kahneman and Chajcyk (1983) proposed that word reading is partly automatic in that it may begin without intention, however, it does require attentional resources: "*A less radical claim is that a mental activity is partly automatic to the extent that it can occur without attention, even if attention can enhance or facilitate it.*" (Kahneman & Chajczyk, 1983, p. 497).

MacLeod & Dunbar (1988) supported this view of a 'continuum of automaticity'. This view holds that practice leads to increased automatization of a process and that the more automatic a process is, the more it interferes with a less automatic process. This continuum of automaticity view, also accounts for occasions where a slower process interferes with a faster process, as it holds that this occurrence is possible if

the '*...degree of automaticity of the slower dimension is sufficient.*' (MacLeod & Dunbar, 1988, p. 127).

In conclusion, the all-or-none account of automaticity fails to fully account for the Stroop phenomenon. However, a theory based on a continuum of automaticity is more compatible with the findings of the reviewed literature.

Parallel Distributed Modelling

More recent developments support this proposal of a continuum of automaticity (cf. Logan, 1985; MacLeod & Dunbar, 1988). Cohen, Dunbar & McClelland (1990) created a parallel distributed processing framework (e.g. McClelland, 1979; Rumelhart, Hinton & McClelland, 1986) to explain the interference experienced in Stroop tasks. Their model is comprised of a network of input, intermediate and output units and processing occurs through a system of interconnected modules. The activation of an input unit results in the choice of a pathway which may include some or all of the units in one or more modules. The collection of units in a pathway is determined by the 'strength' of the knowledge, which in turn specifies the speed and accuracy of the processing. The units in the modules can belong to more than one pathway hence, when two or more pathways are activated at once then interference can occur when pathways containing conflicting information intersect. On the other hand, facilitation may occur if the information coincides.

An additional advantageous feature of this model is that it successfully incorporates learning and practice as the set of connections in a pathway can change over time

and the strength of the pathways can be increased following extensive practice (MacLeod, 1991).

In conclusion, although the speed-of-processing account and the automaticity views possess many virtues, they fail to adequately account for the phenomenon of Stroop interference. The parallel distributed processing model has successfully incorporated many of the virtues of the two models whilst eliminating their imperfections. At present, this model is believed to be the most successful in terms of accounting for Stroop interference. However it needs to be empirically tested.

The remainder of this chapter will focus on those features of the Stroop task which are relevant for this dissertation. Readers are referred to more comprehensive reviews of the Stroop task for any additional information (e.g. Jensen & Rohwer, 1966; Dyer, 1973b; Macleod, 1991).

Reliability and validity of the Stroop Test

Through extensive examination, Jensen (1965) concluded that the Stroop test was possibly the most reliable psychometric test. A number of other researchers also asserted that the Stroop test has high reliability (e.g., Smith & Nyman, 1974; Schubo & Hentschel, 1977, 1978; Santos & Montgomery, 1962; Uechi, 1972).

A number of other studies also focused on the methodology employed in the Stroop task. Differences between the incongruent and baseline stimuli were highlighted as a potential confound. Zajano, Hoyceanyls, and Ouellete (1981) noted that both ink colour and shape vary in the incongruent stimuli set, whereas there are only ink

colour changes in the baseline stimuli set. To overcome this, they examined the impact of changing the shape of the baseline stimuli; however, interference was still experienced (i.e. this did not alter the basic effect). Numerous studies have similarly examined the impact of slight methodological modifications. The impact of these modifications, however, generally only slightly affects the size of the Stroop effect.

Interference & facilitation

The most popular way of calculating the Stroop effect is to calculate an interference score by subtracting the baseline measure from the conflict measure (i.e. $\text{Interference} = \text{Incongruent RT} - \text{Baseline RT}$). This method was employed in Stroop's original study. Since then a variety of alternative and more intricate scoring systems have been proposed (see for example, Smith & Borg, 1964; Smith & Klein, 1953). One such method is the calculation of a conflict ratio score (Schiller, 1966; White, 1969; McCown & Arnoult, 1981). This score is calculated by dividing the RT for the incongruent card by the RT for the baseline card. Consequently, a score higher than one indicates interference. It was claimed that this score accounted for any differentiation in colour-naming ability between participants. Jensen and Rohwer (1966) investigated the most appropriate method of calculating interference and proposed that the majority of deviations from the popular (incongruent – baseline) calculation were unnecessary and that there was little justification in using any scoring method. The original scoring method remains the most popular and is widely used, hence in order to ensure compatibility with previous research this scoring method was employed throughout this thesis.

Rand, Wapner, Werner & McFarland (1963) argued that the typical scoring method failed to provide a clear picture of the processes actually occurring throughout the Stroop task. They proposed that the error data is actually more informative and they devised an intricate method for categorising the error data. Throughout this thesis, where error rates were sufficiently high to make categorisation of the error data viable, this principle of categorisation was employed.

Naming colours of incongruently coloured words has reliably and consistently been found to produce interference. However, when the words are congruently coloured is there a facilitation effect? The majority of studies find that response time scores are quicker in the congruent condition than the incongruent condition (Sichel & Chandler, 1969; Regan, 1978; Hintzman, Carre, Eskeridge, Owens, Shaff, & Sparks, 1972). However, the majority of studies found that colour naming was still faster in the baseline condition compared with the congruent condition hence it may be more appropriate to suggest that there was reduced interference rather than facilitation.

The most popular method of calculating facilitation effects subtracts the congruent response time from the baseline response time (i.e. $\text{Facilitation} = \text{Baseline RT} - \text{Congruent RT}$).

It has also been consistently revealed that any facilitation effects tend to be much less than interference effects (Dyer, 1973a; Dyer, 1974; Dalrymple-Alford, 1972). However, facilitation effects may be dependent upon the choice of control condition. For example, more facilitation is produced when coloured X's are

employed relative to a control condition of colour patches (Dalrymple-Alford, 1972; Schadler & Thissen, 1981).

Oral versus manual responding

Verbal responses have been the typical output modality in the majority of Stroop experiments. In the first comparison of verbal and manual responding, White (1969) found that manual responding elicited less interference than verbal responding. Other studies directly comparing the two response modes have also generally found that manual responding does produce interference. However, this tends to be smaller than when verbal responses are employed (see Nielsen, 1975; Redding & Gerjets, 1977). Nevertheless, manual responses have consistently been found to produce interference (e.g. Keele, 1972; Logan, Zbrodoff, & Logan, 1984; Roe, Wilsoncroft, & Griffiths, 1980; Schmit & Davis, 1974; Virzi & Egeth, 1985; Warren & Marsh, 1979).

The stimulus-response compatibility issue (Fitts & Posner, 1967) asserts that the difficulty level of a task is related to how closely the required response maps onto the stimulus dimensions. So, for example, in terms of the Stroop effect, is interference experienced simply from the presence of a conflicting word or is it because the verbal nature of the word is more closely matched to the required response (Treisman & Fearnley, 1969). McLain (1983) examined stimulus-response compatibility and found that interference was greater when a verbal response was required than when a manual response was required. Interference was also reduced when the keys were labelled with colour patches as opposed to colour words. Thus, stimulus-response compatibility appears to have an impact on

performance. Nevertheless, although reduced, manual responding tends to produce significant - if reduced - interference.

Manual responding is employed throughout this thesis as it is believed that this provides a more accurate measure of response time to each individual stimulus presentation. In addition, it is proposed that a manual response will provide a more accurate assessment of interference as it will reduce the verbal bias in the linguistic variants of the Stroop tasks. Finally, manual responding also enables RT to be calculated for each individual stimulus presentation.

Developmental Studies

Few studies have actually explored young children's performance on the Stroop task. This is obviously due to the fact that the traditional Stroop task requires reading, hence it would not be an effective measure of interference on non-readers or poor readers. Comalli, Wapner, & Werner (1962) completed a cross-sectional study exploring performance on the Stroop task of participants aged seven to eighty years. The results revealed that children and the elderly experienced the greatest interference. There appears to be a clear developmental trend in the Stroop task: interference is high in children, this then declines with increasing age, to reach a plateau, which then begins to rise again in the later years (see also Tipper, Bourque, Anderson, & Brehaut, 1989; Dash & Dash, 1982).

A number of studies examining children's performance on the Stroop colour-word task have employed the task as a means of comparing different ability levels. For example, Fournier, Mazzarella, Ricciardi, and Fingeret (1975) found that nine-year

old 'good' readers experienced more interference than nine-year old 'poor' readers. Low achieving children aged seven to twelve years have also been found to display no improvement with age compared with normal achievers who exhibited the characteristic developmental pattern (Short, Friebert & Andrist, 1990).

Attention

There clearly exists a relationship between attention and the Stroop task. The task basically requires participants to selectively attend to one dimension whilst simultaneously selectively ignoring another dimension. A number of studies have examined the development of attention in children and the general consensus is that attentional span increases with age (e.g. Kahneman, 1973; Gibson & Rader, 1979). However, it is commonly proposed that attentional capacity does not increase with age, but rather children learn, through practice and experience in everyday life, to operate attentional processes more effectively (Gibson, 1969; Gibson & Rader, 1979).

A wide range of tasks have been employed to assess selective attention. For example, selective listening tasks (Maccoby, Konrad, 1966; 1967), simple memory tasks (Hagen, 1967; Wellman, Ritter, & Flavell, 1975), speeded classification tasks (Strutt, Anderson & Well, 1975; Shepp & Swartz, 1976) amongst others. Most of these tasks examined the impact of extraneous information and they generally revealed that older children are more proficient at focusing on the relevant information. Tipper *et al.* (1989) suggested that children experience difficulty in selectively ignoring irrelevant information because they do not possess a fully mature inhibitory system.

Presentation Effects

Presentation effects also influence the degree of facilitation and interference experienced. If participants have an increased expectancy of congruency then facilitation occurs (Tzelgove, Henik, & Berger, 1992; Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995). A blocked presentation format may increase the expectancy of congruency and participants may also adopt a strategy of word reading as opposed to colour naming. Consequently, increased facilitation may occur as word reading is a quicker process than colour naming. Thus, blocked presentation format may give rise to the development of strategies which can assist performance. For example, when presented with a block of congruently coloured words, participants may notice the matching information and employ the quicker strategy of simply reading the words (Bull & Scerif, 2001). An individual presentation of stimuli is required to overcome this problem. Tecce & DiMartino (1965) were the first to employ the single response procedure and since then, this methodology has grown in popularity and now actually dominates the field. A preliminary study by Bull, Murphy & McFarland (2000) employed an individual stimulus presentation procedure and found that altering the presentation format of the conditions in a numerical Stroop variant had a significant impact on the level of interference experienced (see Chapter 3, p. 50).

Few studies have examined the impact of varying the compositions of the set of trials. However, the available evidence indicates that as the proportion of congruent trials is increased, the irrelevant dimension becomes increasingly more relevant and as a result more interference is experienced in the incongruent trials as the irrelevant dimension is more difficult to inhibit (Lowe & Mitterer, 1985; Logan & Zbrodoff,

1979; Shor, 1975). Bull and Scerif (2001) suggested that under blocked presentation format (i.e. blocks of baseline, congruent and incongruent) participants have the opportunity to establish a strategy of simply attending to the more automatic irrelevant dimension (e.g. word reading in the tradition colour-word variant).

The Stroop task is a prototypical measure of inhibition efficiency. Hence, it was deemed ideal for the requirements of the present research, which aimed to explore the relationship between mathematical ability and inhibition efficiency. The following two introductory chapters provide an overview of arithmetical development and reviews recent literature exploring the relationship between the executive function inhibition and children's proficiency in mathematics.

Chapter 2

***A brief review of working memory, arithmetical
development and common counting problems.***

The working memory model

Contemporary views on short-term memory are commonly based on the work of Baddeley and colleagues; Baddeley and Hitch (1974) argued that the concept of 'working memory' was more appropriate than that of a short-term store. According to their initial models the working memory system is comprised of three components: the central executive, a phonological loop and a visuo-spatial sketchpad. The most essential component of working memory is the central executive which is a limited capacity system and is employed to cope with the more cognitively demanding tasks (a more comprehensive review of the role of central executive and the development of executive functioning is presented in the following chapter, pp. 38-39). The phonological loop and the visuo-spatial sketchpad are slave systems of this central executive. The phonological loop is believed to employ articulatory rehearsal in order to temporarily store both verbal and acoustic material. Furthermore, in a revised account of his initial model, Baddeley (1986, 1990) asserted that auditorily presented words are processed differently from visually presented words. For instance, words which are presented auditorily have direct access to the phonological store, whereas visual presentation only enables indirect access through subvocal articulation. This revision was made in order to account for the finding that articulatory suppression (e.g. where one word is repeated over and over whilst a concurrent task such as mental arithmetic or reading sentences is completed) eliminates the word-length effect (i.e. recall is better for sequences of short words than for long words) with visual presentation, but not with auditory presentation (see Baddeley, Thomson & Buchanan, 1975). The defining characteristics of the visuo-spatial sketchpad, however, are less clearly defined. Baddeley (1986, p. 109) defined it as "*a system especially well adapted to*

the storage of spatial information, much as a pad of paper might be used by someone trying for example to work out a geometric puzzle.”

The concept of working memory has endured the past 30 years and Baddeley and Hitch’s initial theoretical model remains popular today and continues to account for many research findings and theoretical advances. Nonetheless, there exist certain phenomena which this early model and recent adaptations fails to account fully for (see Baddeley, 2000 for a full account). For instance, the model fails to account for the ability of individuals to perform adequately in serial recall tasks whilst performing articulatory suppression. Articulatory suppression involves the repetition of, for example, one word whilst attempting to remember and recall a series of visually presented numbers. According to the model, this suppression should prevent the recognition of the visually presented material in the phonological loop. In accordance with this, Baddeley et al. (1984) found that suppression did have a significant adverse effect on recall. However, it did not have as damaging an effect as the model would predict.

In addition, studies on patients with neurological damage have revealed that patients with grossly impaired STM resulting in an auditory span of only one digit can, on average, recall four digits when presented visually (Baddeley et al., 1987). Recent models (1996, 1998) of WM fail to account for this as the central executive lacks storage capacity and the available evidence suggests that visual and phonological information are intertwined in some way. Thus, it seems logical that some form of ‘back up’ store exists and that this has the capacity to integrate the visual and phonological information during serial recall (Baddeley, 2000).

The Episodic Buffer

In order to deal with the problems presented by certain phenomena, some of which are outlined above, Baddeley (2000) has proposed a recent modification to the three component model. He proposes the addition of the ‘episodic buffer’ which is a limited capacity system that acts as a temporary storage for the sharing and transfer of information between the central executive and the slave systems. It is proposed that the episodic buffer is also under the control of the central executive, however information is primarily retrieved from this buffer via conscious awareness. Thus, it is possible to access the information in the buffer and if necessary to coordinate information from a variety of sources and/or manipulate and modify the information. Thus, the episodic buffer acts as an intermediary between the slave systems and the central executive, by combining them into a unitary multi-dimensional representation. The revised model maintains its emphasis on a multi-component model of working memory, however it places further emphasis on the integration and sharing of information between these components rather than seeing them as distinct entities. In sum, the episodic buffer is designed to fill a gap in the model as none of the three components of the earlier models can be regarded as a general storage that has the capacity to combine several different types of information.

Review of the role of WM in mental arithmetic

A considerable amount of research has revealed that children’s performance in arithmetic is related to WM capacity, with the majority of this research reaching the general conclusion that any additional demands placed on WM have a negative influence on performance (e.g., Hitch, 1978a, b, c; Bull & Johnston, 1997; Dark &

Benbow, 1990, 1991; Geary, Brown, & Samaranayke, 1991; Hitch & McAuley, 1991; Siegel & Ryan, 1989; Swanson, 1993, 1994). In addition, Adams & Hitch (1998) concluded that “...WM is a major factor limiting children’s mental arithmetic.”

The multicomponent model of WM devised by Baddeley and colleagues (Baddeley, 1986; 1996; Baddeley & Hitch 1974; Logie, 1995) has predominantly been employed to guide research on WM and mathematical cognition. On occasion, other models have been used (e.g. Anderson, Reder & Lebiere, 1996), however, it is likely that the multicomponent model remains dominant as mental arithmetic involves a variety of mental codes and processes (DeStefano & Le Fevre 2004). The working memory model is concerned with both the active processing and transient storage of information, thus is highly relevant to activities such as mental arithmetic.

So, in terms of mental arithmetic, the central executive is responsible for directing the activities of the phonological loop and the visuo-spatial sketchpad and it may also for example, monitor which parts of the calculation have been completed. In addition, interim results may be held by the phonological loop (Heathcote, 1994) and the visuo-spatial sketchpad may serve as a mental workbench (Hayes, 1973; Hitch , 1978a, 1978b).

A number of research studies have explored the role of WM in mental arithmetic and findings suggest that all three components of the model are involved in mental arithmetic. However, the role each system plays and the extent of this role is

dependent upon the task requirements. For example, research has indicated that the phonological loop is only involved in the solution of single-digit problems when counting is employed (i.e. as opposed to direct fact retrieval) (Hecht, 2002). Nevertheless, it plays a more prominent role in the solution of multi-digit problems, where there is a greater requirement to maintain operands in WM and hold temporary results (Fürst & Hitch 2000; Heathcote, 1994). The role of the visuo-spatial sketchpad, however, requires further clarification. Early claims proposed that the visuo-spatial sketchpad is utilised as a mental workbench (Hayes, 1973; Hitch 1978a; 1978b). However research findings indicate that the visuo-spatial sketchpad is mainly activated when problems are presented visually and are vertically aligned (Heathcote, 1994; Trbovich & LeFevre 2002). Indeed, it has been suggested that presentation format places varying demands on the WM system and this may be crucial to our understanding of how we solve arithmetic problems (DeStefano & LeFevre, 2004).

Furthermore, the evidence strongly supports the involvement of the central executive in mental arithmetic. For example, a number of studies have revealed that introducing concurrent central executive loads (i.e. random generation of letters, numbers or intervals) whilst performing mental arithmetic significantly impairs calculation, even when completing simple single digit arithmetic (e.g. De Rammelaere et al, 1999, 2001; Fürst & Hitch, 2000; Lemaire, Abdi & Fayol 1996). Recent research also strongly indicates that the central executive plays a crucial role in the solution process of multidigit problems requiring carrying (Ashcraft & Kirk, 2001; Fürst & Hitch, 2000; Ashcraft et al., 1992). In addition, even when the answer to arithmetic problems is activated unintentionally, central executive

resources play a role (LeFevre et al., 1988; Thibodedau, LeFevre & Bisanz, 1996; Zbrodoff & Logan, 1990).

The evidence of further contemporary studies suggests that the level of activation of component subsystems may be largely dependent upon problem complexity. Thus, those problems which can be solved via direct memory retrieval may only impinge upon central executive resources, whereas the more complex problem will require the involvement of the 'slave systems' (De Stefano & LeFevre, 2003).

In sum, the available research exploring the role of WM in mental arithmetic is by no means conclusive. However, a number of conclusions which are relevant to this thesis can be drawn: all three components of the original WM model appear to play some role in mental arithmetic - even single-digit arithmetic places demands upon the central executive and in addition to individual differences in the ability to select appropriate procedures, presentation format, problem complexity and task and response requirements all impinge upon performance in mental arithmetic tasks (see DeStefano & LeFevre, 2004 for a review).

Individual differences in WM and MA

Our level of skill in reading and arithmetic are considerably varied across individuals. A number of contemporary research studies have explored the extent to which differences in WM are the locus of these individual differences in performance in reading and language processing (e.g. Just & Carpenter, 1992; Siegel, 1994; Swanson, 1994) and recent research has examined the relationship

between central executive functioning and differences in arithmetical performance (e.g. Bull et al. 1999, Bull & Scerif, 2001; Siegel & Ryan, 1989).

Daneman and Carpenter (1980) theorised that processing efficiency is the sole determinant of individual differences in WM. In contrast, a large number of researchers have asserted that individual differences in general executive capacity stem from differences in working memory capacity (Conway & Engle, 1994; Engle, Kane, & Tuholski, 1999). Even so, it is possible that individuals retain the capacity to complete the processing or storage requirements of a complex span task independently of their individual general executive capacity. A recent study by Bayliss, Jarrold, Gunn & Baddeley (2003), explored whether individual differences in one or both storage and processing functions may determine an individual's performance on complex span tasks and provide an insight into the relationship between performance on these tasks and tasks requiring higher cognitive abilities. Bayliss et al. explored the nature of constraints underlying complex span tasks which are tasks that require participants to maintain certain information in WM whilst simultaneously completing some sort of online processing such as mental arithmetic or reading. In particular, the aim was to explore the degree to which individual differences in processing efficiency and storage capacity exert independent effects on performance in such tasks and in turn present a challenge to Daneman and Carpenter's (1980) proposal regarding the importance of processing efficiency.

Bayliss et al., (2003) developed four complex span tasks by crossing two types of processing (i.e. verbal and visuospatial) with two types methods of storage (verbal

and visuospatial) and these were orthogonally presented. The results revealed that individual differences in processing efficiency and storage capacity both predict unique variance in performance on complex span tasks and thus place independent constraints on WM capacity. However, these findings do not diminish the importance of processing capacity, but rather they indicate that differences in storage capacity may also be an important determinant of performance in complex span tasks. The results of Bayliss et al's tasks also suggested that the ability to coordinate the storage and processing functions may also make an independent contribution to the development of mathematical and reading skills. Finally, the achieved results supported the existence of domain-general processing abilities and domain-specific storage systems. This finding presents serious complications for resource-sharing models which propose that performance on complex span tasks is constrained by the availability of a single limited pool of resources. Strong support however is provided for the multi-component model of working memory where domain-general processing and domain-specific storage is a defining characteristic.

Gathercole & Pickering (2000) explored whether these previously established relationships between certain features of WM and specific areas of educational attainment also impinge upon children's educational progress in the national curriculum. They employed a WM test battery designed by Gathercole and Pickering (1999) to assess functioning in the CE and its slave systems, the phonological loop and the visuo-spatial sketchpad. Performance in these tests was subsequently compared with the children's performance in national curriculum assessments taken at approximately seven years of age. The rationale underlying this approach was that *"If WM skills do indeed limit children's capacities to*

acquire knowledge and skills in the educational domain, children with low curriculum achievements would be expected to perform poorly on measures of WM function” (Gathercole & Pickering, 2001, p. 179).

The results provided evidence which supported the proposal that children’s educational attainment is closely related to their working memory skills. Those children who were performing below the expected level displayed particular deficits in measures of CE functioning, thus supporting the findings of Bull and colleagues (e.g. Bull et al., 1999; Bull & Scerif, 2001) which suggest that the development of CE skills plays an important role in the development of arithmetic skills (see p.47-50).

Early counting skills

Children live in a quantitatively rich environment and by the time they reach two years, they begin to regularly participate in counting and number activities. These counting activities also tend to naturally lead to linking counting and number names to particular quantities. These activities also provide a starting point for developing the counting principles, which consist of learning to assign cardinal or ordinal meaning to those objects being counted. In order to achieve this, children not only have to memorise the number words in a particular order, but they also have to map this on to their expanding appreciation of quantity and number concepts (see Fuson, 1988; Gelman & Gallistel, 1978; Wynn, 1990).

The majority of children begin formal schooling with a rich informal knowledge of counting, numeral recognition, simple addition and subtraction skills and social

sharing. This knowledge typically matures considerably during the first year in school (Aubrey, 1999). By the end of this first year in school, the majority of children have successfully learned the number sequence and are proficient in counting and joining separate groups of objects, in order to extend their knowledge of quantity and cardinality.

In order to solve simple arithmetic, children employ a number of diverse strategies. These include counting concrete objects, counting fingers, verbal counting, derived fact strategies and fact retrieval. Counting typically begins with counting the actual objects being counted and this often progresses to finger counting. Initially, both numbers are counted out separately before progressing to counting altogether, which is followed by counting on from the first of the numbers (regardless of its size) and then finally, counting on from the largest number. As their development progresses, they will employ decomposition to make an easier sum: for example, $9 + 5 = (9+1) + 4$, and eventually they can retrieve facts from memory. Verbal counting is common in five and six-year olds, but the shift from using concrete representations to verbal counting is gradual, and is dependent upon the child's ability to mentally track the numbers. Eventually children will progress to calculating sums 'mentally'. However, this may continue to be supported with finger counting for a period. The use of 'derived fact' strategies also develops slowly. 'Doubles' facts tend to be learned first (e.g. $4 + 4$) and these are used to support more complex problems, for example: $10 + 12 = 10 + 10 + 2 = 22$. Finally, children are confident in their knowledge to successfully employ fact retrieval where they can access the information directly from memory. Of course,

throughout their development children employ a mix of strategies, and there is a *gradual* shift to those that are more flexible and efficient (Aubrey, 1999).

Common counting errors

When children employ counting based strategies, under- or over-counting by one is the most common error made (Ginsburg, 1989). However, when employing fact retrieval, four types of errors have been identified:

- 1) wild guesses, although these are more common with very young children;
- 2) near-misses, like the counting errors, children incorrectly retrieve a ‘fact’ which is one above or below the correct answer;
- 3) operation confusion, where children employ an alternative operation in order to solve the problem (e.g. $3 - 2 = 5$);
- 4) table errors, these occur when children provide the answer for a related problem, for example, answering 21 for 3×8 , from the remembered related problem of 3×7 (Ashcraft, 1992; Baroody, 1989);

Government Initiatives

Mathematics teaching and attainment levels have been the focus of an extensive number of research studies and government initiatives over recent years (see for example: DfFEE, 1997; www.hmie.gov.uk/documents/publication/saqm.pdf).

Hence, despite the cultural and educational opportunities offered to children, there exists a number who fail to achieve the expected level of attainment.

Nevertheless, some improvements have taken place over recent years. The HM Senior Chief Inspector reports in the *‘Standards and Quality in Primary Schools:*

Mathematics 1998-2001 report that Primary Schools and education authorities have successfully employed the early intervention initiatives in developing early numeracy skills. They have also taken note of the advice in *Improving Mathematics Education 5-14* which stresses that enhanced mental calculation and interactive teaching sessions are necessary. As a result, attainment levels have improved from Primary 1 to Primary 4. However, the performance of children at Primary 7 falls below the required target attainment levels.

Despite these improvements, concern continues to be expressed surrounding children's mathematical achievement and many children are seriously under performing in mathematics. Cockcroft (1982) reported that within an average class of 11 year-olds, a seven year range in arithmetical ability is likely to exist. This marked difference in arithmetical ability also appears to persist through life. Similarly, there tends to be marked differences in reading ability (e.g. Bryant & Bradley, 1985; Frith, 1986; Snowling, 1991). However, most adults after receiving adequate instruction achieve a sufficient level of skill in reading, whereas many persist in experiencing difficulties with arithmetic through life (Cornelius, 1992; Hitch, 1978c; Sewell, 1981). Hence, we clearly need to further our understanding of the wide range of difficulties experienced by certain individuals in order to implement successful intervention strategies.

Mathematical disability and anxiety

As noted above, children typically progress from relying on counting-based strategies to direct fact-retrieval. Geary, Widaman, Little, Cornier (1987) showed that children experiencing difficulties tend to rely heavily on the more time-

consuming counting strategies and that when they do employ a retrieval strategy, they are more likely to be inaccurate (Geary, 1990).

Strang & Rourke (1985) have also suggested three categories of mathematical disability:

- 1) difficulty in fact retrieval and memory for arithmetic tables;
- 2) difficulty with procedures and delays in learning basic number skills; and
- 3) a visuo-spatial difficulty in representing and interpreting arithmetical information.

Hence, a number of diverse problems have been identified. In order to attempt to circumvent and/or overcome any problems with mathematics, teachers are faced with a number of challenges. They must examine their own teaching method (and modify if appropriate) and aim to conceptually understand the difficulties some children are facing. They must also appreciate that some children may be developmentally *delayed* whereas others may be developmentally *different* and that despite suitable opportunities to learn, they may continue to face difficulties. In addition, as arithmetical calculation and problem-solving are dependent upon a range of complex mental processes, then it is unlikely that any single cognitive difficulty causes failure in learning mathematics. Thus, it is likely to be more beneficial to assess which skills the children do possess and determine those areas where they are experiencing the greatest difficulty (Aubrey, 1999).

It is important to identify any difficulties in mathematics as early as possible, as these difficulties may accumulate over the years, sapping confidence and draining esteem and motivation (Aubrey, 1999). Gierl and Bisanz (1995) found that children

become more anxious about mathematics tests as they progress through school and McLeod (1993b) proposed that the critical stage for the development of attitudes and emotional reactions towards mathematics is between the ages 9 to 11 years. These attitudes and anxieties are generally difficult to alter and may persist into adulthood. As a result some children may avoid mathematics, perform more poorly in mathematics (Hembree, 1990) and/or become distressed by mathematics (Tobias, 1978; Buxton, 1981). Furthermore, the anxiety experienced has also been found to interfere with conceptual thinking and memory processes (Skemp, 1986). For example, recent research has revealed that math anxious individuals have been found to display a deficient inhibition mechanism (Hopko, Ashcraft, Gute, Ruggiero, & Lewis, 1998).

Recent Research

Recent research has examined the relationship between children's performance on executive functioning tasks and their ability level in mathematics (Bull *et al.*, 1999; Bull & Scerif, 2001; Rourke, 1993). Numerous studies have considered executive functioning (EF) in relation to children's skills and these have typically revealed that EF is a useful predictor of performance (e.g. Cornoldi, Barbieri, Gaiani, & Zocchi, 1999; McLean & Hitch, 1999; Swanson, 1993). In particular, for example, children with learning difficulties (e.g. reading and comprehension difficulties, mathematics difficulties and learning disabled children) often demonstrate less efficient inhibition of irrelevant information (Bull & Scerif, 2001; Lorschach & Reimer, 1997; Swanson, 1999). Following on from this research, the present series of studies focus primarily on inhibition efficiency in relation to children's proficiency in mathematics.

Chapter 3

Executive functions and children's arithmetical ability

What are executive functions?

A broad range of important functions of the human brain are summarized under the headings 'executive functions' or 'executive control'. For example, executive functions include the capacity to selectively attend and switch attention, the ability to generate hypotheses, plan and formulate goals and carry out goal-directed tasks and the ability to construct, maintain and inhibit strategies (e.g. Baddeley, 1996; Lezak, 1982; Logan, 1985a; Stuss & Benson, 1984). To put it simply executive functions refer to a complex group of skills that allow humans to adapt to novel situations through effective problem solving. The term is extremely non-specific, but as such it is very economical, as it is employed to represent a wide range of abilities which are believed to underlie effective problem solving.

The following definition of executive functions demonstrates how broad ranging they are considered to be:

“[Executive functions are] ... the ability to maintain an appropriate problem-solving set for attainment of future goals. This set can involve one or more of the following: (a) an intention to inhibit a response or to defer it to a later more appropriate time, (b) a strategic plan of action sequences, and (c) a mental representation of the task, including the relevant stimulus information encoded into memory and the desired future goal-state.” (Welsh & Pennington, 1998, pp. 201-202)

So, despite the substantial progress, over the past few decades, in the range of complicated cognitive models and theories which have been developed (e.g. object perception, face recognition, word recognition etc.) not to mention the increase in

research into executive functions, a precise theoretical and operational definition is proving difficult. Monsell (1996) stated that “*an embarrassing zone of almost total ignorance*” (p.93) surrounds the theory of executive functioning (cited in Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

The majority of studies examining executive functions are imprecise in their definition of the central executive, tending to regard it as a unitary system rather than striving to understand why we experience difficulties on executive tasks and what these difficulties suggest in regards to cognitive functioning (Miyake *et al.*, 2000). However, there is evidence which suggests that executive functions are not unitary. Baddeley (1996, 1998) initiated research aiming to understand how the central executive may be fractionated. He employed a range of executive tasks which are believed to draw on functions considered to be controlled by the central executive. In addition, clinical observations have revealed that some patients may succeed on some executive tasks yet fail on others, thus indicating a non-unitary nature of executive functions (e.g. Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999; Shallice, 1988).

A number of studies have also found that the performance of a variety of target populations, (e.g. normal adults (Lehto, 1996), normal elderly adults (Lowe & Rabbitt, 1997), and brain-damaged adults (Burgess, 1997; Burgess, Alderman, Evans, Elmslie, & Wilson, 1998; Duncan, Johnson, Swales, & Freer, 1997)) display low correlations between scores on a range of executive tasks like the Wisconsin Card Sorting Task (WCST) and the Tower of Hanoi (TOH). These findings have been taken as an indication that executive functions are not unitary and need to be

fractionated. However, it is possible that other cognitive processes (e.g. language, visuo-spatial processing) implicated in the executive task may have masked any indication of unity amongst the executive tasks (Miyake et al, 2000, p. 52).

Nevertheless, the existing research clearly indicates that at present the cognitive processes underpinning executive functions are underspecified and the tests designed to measure executive functioning lack purity.

Miyake *et al.* (2000) attempted to overcome some of the problems which have plagued previous studies of executive functioning. They focused on three common executive functions: *shifting*, *updating* and *inhibition*, and chose a number of tasks which are believed to tap each of these target executive functions. Using confirmatory factor analysis, Miyake *et al.* (2000) found that the three target functions moderately correlated with each other, but that they were distinguishable. They also employed structural equation modelling to examine the differential contribution of these three functions on complex popular executive functioning measures such as the Tower of Hanoi and the Wisconsin Card Sorting Task. The results revealed that the three target functions moderately correlated with each other, but were distinguishable and that each of these functions has a differential contribution to performance on the more complex executive tasks (e.g. the WCST relies more heavily on Shifting). Inhibition was proposed as the source of the correlation, as they each required some degree of inhibition in order to function efficiently. For example, in the Updating task participants must ignore irrelevant incoming information and suppress information which is no longer relevant, and in the switching task participants must suppress a previous mental set in favour of a new one. The inhibitory requirements of each of these executive tasks are

conceptually different. Nevertheless, the common factor of inhibition emphasises the important role this executive function plays in a range of cognitive tasks.

Barkley's (1997) hybrid model of executive functions also proposes that inhibition may be a unifying function in executive processes. This model asserts that inhibition enables executive functions to perform effectively (e.g. working memory and self-regulation) and consequently enhances the ability to produce goal-directed behaviour in novel situations.

Clearly, a wide range of functions have been ascribed to the central executive, although the most commonly proposed executive functions are planning, updating and monitoring of working memory contents, shifting between mental sets or tasks and inhibition of prepotent responses (Miyake *et al.*, 2000; Welsh & Pennington, 1988).

The development of executive functions

The development of executive functioning begins in childhood (DeLoache & Brown, 1984; Rakic, Bourgeois, Zecevic, Eckenhoff, & Goldman-Rakic, 1986; see also Hughes, 1998), and recent years have seen an upsurge in research in executive functioning with a wide variety of populations being studied. For example, studies have revealed that children's performance on a range of executive functioning measures can predict learning difficulties, mathematical ability, reading comprehension difficulties and behaviour problems (e.g. Bull, *et al.*, 1999; Gathercole & Pickering, 2000b; Hughes & Richards, 1998; Lehto, 1995; Lorschach, Wilson & Reimer, 1996; McLean & Hitch, 1999; Swanson, 1993, 1999; Swanson,

Ashbaker & Lee, 1996). In addition, a number of studies have demonstrated that children suffering from a variety of neurodevelopmental disorders display a different pattern of performance compared with normal children on tasks designed to tap the central executive (see Pennington & Ozonoff, 1996, for a review). For instance, research has revealed that children with ADHD, Autism, Tourettes Syndrome and early treated PKU display EF deficits (Diamond, Prevor, Callender, & Druin, 1997; Pennington & Ozonoff, 1996; Russell, Jarrold & Henry, 1996; Cornoldi, Barbieri; Gaiani & Zocchi, 1999). The cited studies also found that executive task scores are fairly reliable predictors of performance and this typically held even after controlling for potential confounding variables.

Developmental neuropsychology studies have also noted that those functions considered to be under the control of the central executive, are very similar to those believed to be under the control of the frontal lobes. Consequently, the frontal lobes are considered to be the neurological location of executive functioning (e.g. Welsh, Pennington & Groisser, 1991). Between the ages of seven and ten years the main developmental advances in frontal lobe functioning occurs and by ten years the majority of children are performing at adult level on a range of executive functioning measures (e.g. Case, 1995; Welsh *et al.*, 1991). Consequently, any individual differences in performance around seven years may be attributable to a developmental delay in frontal lobe development.

The central executive

Baddeley's (1986) influential model of working memory, has frequently been considered to characterise the central executive. The central executive is believed to

control working memory and to organise the input and functioning of the two slave systems, the articulatory loop and the visuo-spatial sketchpad. These slave systems serve as temporary storage and rehearsal systems for verbal information and visual or spatial material. They also take some pressure off the central executive, which is required when performing more complex cognitive tasks. For example, the central executive is not only responsible for storing and retrieving information from long-term memory, but it is also essential for goal-directed functioning and decision-making. However, there has been relatively little research focusing on the central executive compared with the other two components of Baddeley & Hitch's (1974) initial model.

A number of functions have been ascribed to the central executive, and Baddeley concedes that the concept of the central executive was influenced by Norman and Shallice's (1980) Supervisory Activating System (SAS) (see also Shallice, 1982). This model proposes that one source of action control deals with routine, well-learned tasks, whilst another manages attention, making it possible for a habitual pattern to be overcome in favour of a new schema when faced with a novel situation. Shallice & Burgess (1996) further elaborated on this model by describing the different stages involved in the establishment of a new strategy or schema: first a strategy is generated (either spontaneously or through problem-solving), then this new strategy is maintained in working memory and finally the effectiveness of this new strategy is reviewed.

Inhibition

Inhibition is one of the most commonly proposed executive functions.

Nevertheless, definition is also a problem for the construct of inhibition. The apparent problems in defining inhibition seem to stem from the fact that the term is typically employed to describe a range of functions, at various levels of complexity (Kok, 1999) and as a result various conceptions and typologies of inhibition have been proposed. The concept of inhibition focused on throughout this dissertation is that of the deliberate inhibition of prepotent or automatic responses. Other typologies include:

- 1) The type of inhibition which occurs in connectionist networks and spreading activation models. This form of inhibition typically refers to reduction in activation of an activated unit through for example, negative priming and the influence of intention here is typically indirect (see Arbuthnott, 1995).
- 2) Reactive inhibition (Logan, 1994), where inhibition occurs due to a residual effect experienced after executing a process, which subsequent processes must overcome. Again, the inhibitory effect is usually unintentional.

The Stroop task (Stroop, 1935b) is a popular measure of the ability to inhibit irrelevant information from entering working memory. A number of theoretical models have been developed in attempts to explain why we experience interference in Stroop-like tasks (see Chapter 1, pp. 3-10 for review). However, these fail to explain how we manage to overcome this interference. Hasher & Zacks (1988; Stoltzfus, Hasher, & Zacks, 1996) inhibition-suppression hypothesis aimed to

provide such an explanation¹. They proposed that an attentional suppression (or inhibition) mechanism strives to control any distracting elements which may have a detrimental impact on performance. When this mechanism is operating efficiently, individuals can successfully complete a task without experiencing too much interference, as the inhibitory mechanisms only allow relevant information to enter working memory. If this mechanism fails to cope with the level of interference, task-irrelevant information will gain access to working memory. As a result, interference will be experienced, as working memory becomes consumed by the irrelevant information. When this occurs the inhibitory mechanisms strive to quickly “*dampen the activation of non-goal path thoughts*” (Hasher & Zacks, 1988, p.12). However, the longer the irrelevant information is allowed to remain active, the more detrimental its impact on performance will be. So, this model proposes that the degree of interference experienced is dependent upon the efficiency of an inhibition mechanism.

Bjorklund & Harnishfeger (1990) extended Hasher and Zacks (1988) model in order to account for developmental changes in performance. Developmental improvements have been observed on a number of cognitive tasks. For example, Comalli, Wapner, & Werner (1962) found that performance on the Stroop task improved with age. These improvements have been attributed to improvements in the efficiency of inhibition mechanisms with age (see Lorschach & Reimer, 1997).

It is also useful to distinguish between inhibition and interference. These two terms

¹ Their original hypothesis concerned ‘cognitive ageing’ effects but it is extended here to low-ability mathematicians.

are often used interchangeably in the literature, despite being essentially different. Inhibition refers to an active suppression process (i.e. the removal of task irrelevant information from working memory), whereas interference refers to susceptibility to performance decrement experienced from competing stimuli (Harnishfeger, 1995). This distinction is important for this thesis as the degree of interference experienced is believed to directly reflect inhibition efficiency. This distinction also fits with Hasher and Zacks (1996) general processing model, which proposed that an inhibition mechanism strives to control the detrimental impact that irrelevant information may have. So, the level of interference experienced is dependent upon the effectiveness of this inhibition mechanism (i.e. if interference is low, then the inhibition mechanism is functioning effectively).

Switching

Another candidate executive function examined throughout this thesis is switching (also referred to as shifting) and includes switching between tasks, operation and mental sets (Monsell, 1996). The SAS (Norman & Shallice, 1980) and other similar models believe that *switching* is an essential feature of executive functioning and past research has convincingly demonstrated that switching between mental sets can be a costly process (e.g. Jersild, 1927; Rogers & Monsell, 1995).

A popular explanation of the switching ability simply refers to the ability to disengage from one task and engage in a new task with different processing requirements. In addition, in order to successfully switch from one task to another (e.g. from addition to subtraction), it has recently been proposed that participants may also have to overcome proactive interference or negative priming (Allport &

Wylie, 2000). So, the carry-over from the previously active task set may interfere with the current task and as a result, participants may experience greater difficulty switching between tasks, schemas or operations. Rogers and Monsell (1995) propose that switch costs reflect internal control processes which have to reconfigure the cognitive system in order to cope with external task alterations.

The switching requirements are varied throughout this thesis by altering the presentation format of the stimuli. Thus, two types of inhibition are examined throughout this thesis: 1) the inhibition of prepotent responses; and 2) the inhibition of established schemas. The latter type of inhibition is of course examined in a less direct way than the former, as it can only be assumed that certain presentation formats enable the establishment of a strategy and hence, increases the switching demands.

Executive functions and arithmetical ability

The working memory model (Baddeley & Hitch, 1974) has influenced a great deal of research into the role of memory and educational attainment and a number of studies have proposed that short-term memory plays an important role (e.g. Daneman & Carpenter, 1980; Siegel & Ryan, 1989; Swanson, 1993). Recent research has examined short-term memory in relation to arithmetical ability, which is not surprising considering that short-term memory processes appear to have a clearly defined role when performing mental arithmetic. For example, most of us will recall experiencing subvocally rehearsing (articulatory loop) and noting partial results when completing multidigit addition and subtraction (i.e. $56 + 17 = (6 + 7 = 13, \text{ so carry } 1 \text{ over and remember } 3 \text{ then } 5 + 1 + 1 = 7, \text{ the answer is } 73)$)

(Butterworth, 1999). Thus, it seems reasonable to suggest that the articulatory loop and the visual-spatial sketchpad work together in the solution of arithmetic problems. For example, the articulatory loop will maintain the problem question and withhold partial results, whilst the visual-spatial sketchpad is employed as a “mental blackboard or workbench” (Heathcote, 1994). A number of studies have found that short-term memory span correlates highly with arithmetical ability. However, it is possible that a number of other cognitive abilities are influencing performance on span tests (Butterworth, 1999, p. 176).

The majority of studies examining the relationship between short-term memory and educational attainment assessed short-term memory capabilities through verbal recall tasks, which are believed to tax the articulatory loop component. A recent study by Bull & Johnston (1997) challenged the proposed relationship between short-term memory and arithmetic ability. They found that when reading ability was controlled for, there were no performance differences between low- and high-ability mathematicians on a number of short-term memory measures (i.e. word span, digit span and counting span tasks). It was proposed that this discrepancy may be the result of a number of methodological differences. For example, previous studies allegedly examining specific arithmetical difficulties have often employed lenient selection criteria and arithmetical difficulties were often strongly correlated with reading difficulties (e.g. Geary, Brown, & Samaranayke, 1991; Hitch & McAuley, 1991; Siegel & Ryan, 1989). Hence, it is impossible to determine whether the results achieved were specifically due to arithmetical difficulties or the result of a more global learning difficulty (Bull & Johnston, 1997).

Neuropsychological evidence also suggests that short-term memory is not essential for arithmetic. For example, a stroke patient with an extremely limited short-term memory span (span length of 2 digits) displayed above average performance on number estimation tasks, comparison tasks and tests of arithmetic. It was concluded that “*short-term memory measured by span, has a very marginal role in arithmetic.*” (Butterworth, Cipolatti, & Warrington, 1996, cited in, Butterworth, 1999, p. 178).

It is possible that low-ability mathematicians may actually be deficient in other areas of working memory, for example the visual-spatial sketchpad and/or executive functioning (Bull, Johnston, & Roy, 1999). The role of the visual-spatial sketchpad has been considered in relation to arithmetic ability in a number of studies.

However, the majority of these were conducted with adults or neuropsychological populations (e.g., Dehaene, 1992; Hayes, 1973; Heathcote, 1994; Hope & Sherrill, 1987; Moyer & Landauer, 1967; Restle, 1970; Smyth, Morris, Levy, & Ellis, 1987). Nevertheless, a number of developmental studies have also considered the role of the visual-spatial sketchpad and revealed that the difficulties faced by some adults and children stem from a visual-spatial problem. For example, Geary (1993) identified a sub-type of arithmetic difficulties where individuals display problems organising the numerical information. For instance, confusing numbers in columns, difficulties reading arithmetic signs and misaligning numbers in columns when performing multi-digit calculations.

The role of the central executive in arithmetic development, however, has received very little attention. Lehto (1995) conducted one of few studies exploring the

relationship between scholastic achievement, the articulatory loop and the central executive. The results revealed that on the whole, scholastic achievement is more closely related to the central executive than to the articulatory loop and that foreign language success is linked to the phonological loop.

Similarly, Logie, Gilhooly & Wynn (1994) found that disrupting the functioning of the central executive had a more damaging impact on mental addition compared with disrupting the performance of the articulatory loop or the visual-spatial sketchpad. Hence, it is suggested that the central executive may be more involved in mental addition than the other two subsidiary components.

Bull *et al.* (1999) further explored the roles of both the visual-spatial sketchpad and the central executive in relation to children's performance in arithmetic. They employed the Corsi Blocks to assess visual-spatial skills and the Wisconsin Card Sorting Task (WCST-Revised and Expanded, Heaton, Chelune, Talley, Kay & Curtiss, 1993) to examine central-executive functioning. The children also completed a series of simple single-digit addition questions in order to explore strategy use. Performance on the Corsi Blocks task was not found to be related to mathematical ability. Nevertheless, the self-reports from the addition questions revealed that a number of them were employing imagery techniques. For example, they reported imagining a series of dots when presented with a number. Thus, imagery may indeed be employed to aid the counting process and this may be particularly evident when dealing with complex multi-digit problems (Heathcote, 1994). So, even though no significant relationship between visual-spatial skills and mathematical ability was revealed, it seems that visual imagery may be employed in

arithmetic. Also, the tasks employed to assess visual-spatial skills are typically memory-span tasks, which tend to correlate well with many cognitive abilities and so are more likely to be indicative of general mental ability rather than specifically mathematical ability (Butterworth, 1999). A visual-spatial task without the memory-span requirement may remove the contribution of these other cognitive abilities and as a result be more predictive of arithmetical ability (Bull *et al.*, 1999).

However, even after controlling for IQ and reading ability, performance in the central executive task (WCST) was found to be related to mathematical ability (Bull *et al.*, 1999). The WCST requires participants to sort the cards according to a certain sorting criteria and when this criteria changes the child must switch strategy. Low-ability participants made more perseverative errors, indicating a difficulty switching from one sorting set to another. In terms of the SAS model (Shallice, 1982) this would suggest that their central executive is failing to effectively interrupt the established schema. Rourke (1993) found that the error patterns of children with specific arithmetic difficulties revealed that they experienced difficulty in switching psychological set. For example, they carried on using a practised procedure (e.g. addition) when a new procedure was required (e.g. subtraction).

A more recent study by Bull & Scerif (2001) further explored the relationship between executive functions and children's mathematical development. The aim was to identify what type of executive functioning difficulties were experienced by low-ability mathematicians and to further examine the proposal that executive functions are dissociable and may be selectively impaired (Miyake *et al.*, 2000).

They employed a number of measures of executive functioning: the WCST, two variants of the Stroop task (verbal and numerical), a counting span task and dual task performance (Baddeley, Della Sala, Papagno, & Spinnler, 1997). Each of these measures correlated significantly with mathematical performance except dual-task performance. The results from the WCST revealed no relationship between mathematical ability and the ability to generate an appropriate strategy. However, lower ability mathematicians experienced greater difficulty inhibiting an established strategy and switching to a new more favourable strategy. A significant positive correlation between mathematical ability and counting span was also found, indicating that mathematical ability is related to the ability to maintain information in working memory. In addition, this task also required the use of rehearsal strategies to assist recall and inhibition of the information previously held in working memory and the distracter items.

The results from the Stroop task indicated that mathematical ability was related to performance on the numerical Stroop variant, but not the colour-word variant. Bull & Scerif (2001) proposed that the most likely explanation for this result is that low-ability mathematicians experience greater difficulty inhibiting prepotent responses when dealing with numerical information, resulting in more irrelevant information entering working memory. This proposal is in accordance with recent research which has considered the role of inhibition in relation to listening/reading span and reading comprehension (De Beni, Palladino, Pazzaglia & Cornoldi, 1998), attentional difficulties (Marzocchi, Lucangeli, De Meo, Fini, & Cornoldi, 2002), poor comprehension (De Beni & Palladino, 2001) and poor arithmetic word problem solving (Passolunghi, Cornoldi, & De Liberto, 1999; Passolunghi & Siegel,

2001). Each of these studies proposed that a working memory deficit is related to a failure of inhibitory mechanisms in processing information. Passolunghi *et al.* (1999) found that the poor arithmetic problem solvers were successful at identifying the relevant information. However, during recall they experienced poorer recall of the relevant information and greater recall of the irrelevant information. It was subsequently proffered that the difficulties in selecting and processing relevant information stem from an inability to inhibit irrelevant information (Passolunghi *et al.*, 1999). This difficulty inhibiting irrelevant information may be due to insufficient attentional resources (Conway & Engle, 1994; Conway, Tuholski, Shishler, & Engle, 1999) and/or the efficiency with which working memory is able to focus on relevant information (Daneman & Carpenter's processing hypothesis, 1980; 1983).

These proposals explain the relationship between performance on the numerical Stroop task variant and mathematical ability, but why was there no such correlation with the colour-word task? It is possible that low-ability mathematicians experience a domain-specific problem in inhibiting numerical information (see Swanson, 1993) or alternatively, it's also possible that they possess a limited working memory capacity for dealing with numerical information (Dark & Benbow, 1994). However, before either of these proposals can be validated, future research must examine performance across a wider range of Stroop-like tasks.

Bull & Scerif's (2001) results also support Miyake *et al.*'s (2000) proposal that the executive measures of working memory span, inhibitory control and perseveration all have an independent contribution to make in predicting mathematical ability.

However, in spite of this proposed differentiation, the measures all correlated significantly with one another suggesting some unity. Miyake *et al.* (2000) proposed that inhibition may be the unifying factor, as all EFs require some inhibitory processes in order to function properly. Bull & Scerif's (2001) work supports this, since an element of inhibition was required in all three of the executive functioning measures which correlated with mathematics ability.

Bull and Scerif (2001) noted that presentation format in the Stroop task may have had an impact on the results, since each condition (i.e. baseline, congruent, incongruent) was presented on a separate card. Thus, it is possible that the children may have noticed the matching information in the congruent condition (e.g. **RED**; 22) and then adopted a strategy of simply reading off the word or number. A preliminary study by Bull, Murphy, and McFarland (2000) explored this issue of presentation format by examining performance across both blocked (i.e. 10 baseline, 10 congruent, 10 incongruent) and random (mixture of baseline, congruent and incongruent) presentation formats. It was hypothesised that if the difficulty is with inhibiting an automatic response, then low-ability children should experience more interference than high-ability children under both presentation formats. However, if the difficulty is with inhibiting an established strategy, then lower-ability mathematicians should experience more interference than higher-ability mathematicians under blocked presentation compared to random presentation, as this enables a strategy to be put in place. Indeed, the results supported this latter proposal; low-ability mathematicians experienced greater interference under blocked presentation format, indicating a difficulty inhibiting an established schema and switching to a new one.

Goals of Studies 1 & 2

The goal of this research is to further our understanding of the relationship between mathematical ability and inhibition efficiency. The first two studies in this thesis adopted a similar methodology to Bull *et al.*'s (1999) in an attempt to further validate their proposal that low-ability mathematicians experience difficulty in inhibiting established strategies. In addition, the proposal that low-ability mathematicians may have a domain-specific problem with the inhibition of numerical information was also further explored through the adoption of a more varied range of stimuli.

Chapter 4

General Method

The participating schools

All children involved in this study belonged to Denend Primary School, Cardenden or Lochgelly West Primary School, Lochgelly. Both schools are situated in South-West Fife and are both former mining areas and remain predominantly working class.

There is no national curriculum in Scotland. Instead there exist national guidelines for curriculum and assessment for pupils aged 5 to 14. Assessment policy in Scotland is fundamentally different from that in England and Wales, as in contrast to the formal assessments at ages 7, 11 and 14, teachers in Scotland determine when it is appropriate for each individual child to be given a national assessment. There are no school league tables published on the basis of these tests and there is considerably more emphasis placed on teacher's judgement of pupil's levels of attainment. The National Guidelines 5-14 set out the appropriate targets and levels in relation to level of primary school education. The national assessments are employed on the basis that sufficient evidence is available from the child's day-to-day work in class to indicate that s/he is ready to progress to the next level. Thus, teachers employ the national assessments to confirm his/her judgement.

The National Guidelines Mathematics 5-14 guidance states the following in relation to attainment target levels (Curriculum and Assessment in Scotland, National, Guidelines, Mathematics 5-14, August, 1991, p. 10):

- Level A: should be attainable in the course of P1-P3 by almost all pupils.
- Level B: should be attainable by some pupils in P3 or even earlier, but certainly by most in P4.
- Level C: should be attainable in the course of P4 – P6 by most pupils.
- Level D: Should be attainable by some pupils in P5 – P6 or even earlier, but certainly by most in P7.
- Level E: should be attainable by some pupils in P7/S1, but certainly by most in S2.

The Scottish Executive does not publish school-by-school 5-14 attainment levels, therefore it was not considered appropriate to ask the participating schools to provide attainment levels for publication in this thesis. The Scottish Executive does however publish 5-14 attainment levels for each local authority. The performance of publicly funded schools in Fife and Scotland as a whole are displayed below in Table 4.1.

Table 4.1: Attainment summary of P3-P6 pupils in Scotland and Fife local authority by June 2001/02 – 2003/04 school years

	Year	% of P3 roll Level A or above	% of P4 roll Level B or above	% of P5 roll Level B or above	% of P5 roll Level C or above	% of P6 roll Level C or above
Fife	2001/02	93.9	73.5	90.5	37.6	75.5
	2002/03	92.8	73.3	88.7	38	76.2
	2003/04	95	76.9	91.1	41.4	76.6
SCOTLAND	2001/02	95.1	78.5	91.7	43.1	78.6
	2002/03	95	78.4	91.5	44.1	79.4
	2003/04	95.9	80.8	92.7	47.4	82

Attainment levels have generally improved from 2001/02 to 2003/04 in Fife and Scotland as a whole. In general, the percentage of pupils in Fife attaining the target

levels was generally slightly lower than the figures for Scotland as a whole across the period 2001-2004.

Both Denend PS and Lochgelly West PS had undergone recent HMIE inspections prior to any testing began and in order to gain a picture of the levels of attainment in these schools a brief summary of these findings are presented below. The HM Inspectors evaluated learning, teaching and attainment, examined pupils work and interviewed staff and pupils. Evaluations are made using the following HMIE quality indicators:

- * Very good: major strengths
- * Good: strengths outweigh weaknesses
- * Fair: some important weaknesses
- * Unsatisfactory: major weaknesses

For Denend PS the HMIE report was published in September 2002 (inspection took place in April, 2002) and in relation to mathematics, the overall quality of attainment was fair with most pupils performing in their assigned classroom work and the mathematics programme itself was considered good. At P1 and P2, most were making very good progress in developing early numerical skills. At P3, almost all pupils were attaining the appropriate target levels in *information handling, number, money and measurement* and *shape, position and movement*. However, many experienced some difficulty when dealing with money. In contrast, in P7 only slightly more than half were attaining appropriate national levels. In addition, the report indicated that the majority of children coped well with mental calculations, although a number were slow recalling basic number and

multiplication facts. Finally, it was noted that pupils were lacking skills in selecting and using appropriate strategies for *problem-solving and enquiry*.

For Lochgelly West PS the HMIE report was published in January, 2000 (inspection took place, October, 1999). Pupil's attainment in mathematics was fair and the majority of pupils were attaining the appropriate standards in *information handling, number, money and measurement and shape, position and movement*. However, at P7 less than half of pupils were reaching the national standards in these aspects of the curriculum. Finally, on the whole it was felt that pupils needed strengthen and improve existing skills in basic number work.

Thus, in both schools participating in this study, pupils were generally achieving adequate levels of success in mathematics, despite, some weaknesses in performance being identified.

Participants

A total of 96 children participated in the following studies. The children all participated in testing over a two and a half year period. Over this period, each child was involved in only four of the six Stroop-based studies (Studies 1 to 6) in an attempt to minimise any practice effects. At the start of the research the children were in Primary 3 and Primary 4 and by the end of testing they were in Primary 5 and Primary 6.

A research proposal was initially submitted to Fife Council's Education Department and approval was granted. The schools were approached by telephone and a

meeting was arranged with the headteacher to discuss the research and the level of commitment required from the school. Consent forms were then sent to the parents/guardians asking them to respond only if they did not want their child to take part in the study.

Before the testing began the experimenter spent a few days in each class in order to ensure that the children were familiar with her and that they felt at ease during the testing sessions. The children were informed that they were participating in a research study investigating children's difficulties in mathematics and that the aim was to explore what makes some mathematical problems more difficult than others. They were reassured that it was not a test and that their participation was completely voluntary and that they could withdraw from the study at any time.

Screening tests

Each child was initially screened for general intelligence, mathematics and reading ability. General intelligence was estimated using the Vocabulary and Matrix Reasoning subtests of the Wechsler Abbreviated Scale of Intelligence (WASI) (The Psychological Corporation, 1999). These two subtests were employed as they correlate highly with full scale IQ and have a consistently high reliability.

Mathematics ability was assessed using the Wechsler Objective Numerical Dimensions (WOND) (The Psychological Corporation, 1996). This assessment included both the Mathematics Reasoning and Numerical Operations subtests. In the former, children are required to respond to questions that are read out by the experimenter which relate to pictures, diagrams or word problems presented in a 'flip-book'. In the Numerical Operations subtest the children were invited to

complete a series of written problems involving both single and multi-digit addition, subtraction, multiplication and division problems. Finally, reading ability was estimated using the Wechsler Objective Reading Dimension (WORD) (The Psychological Corporation, 1992). This task employs 3 subtests: Basic Reading, Spelling and Reading Comprehension. For the Basic Reading subtest the children are simply required to read out a series of words, which become increasingly difficult. In the Spelling subtest the children are asked to spell words which are read out to them by the experimenter and in the Reading Comprehension task they are asked to read a short passage and then answer a question relating to that passage. The WOND and WORD tests were chosen as they have both been standardised on British children.

Furthermore, test re-test stability coefficients indicated that all three screening measures possess adequate stability over time for children aged 6 to 16 years. The average test-retest reliability coefficients for children across the three tests follows below:

WORD: .94 for both the basic reading and spelling subtests and 0.84 for reading comprehension.

WASI: the average stability coefficients range from .77 to .86 for the subtests and from .88 to .93 for the IQ scales.

WOND: 0.89 for mathematics reasoning, 0.86 for numerical operations, 0.91 for the WOND composite.

For each of these screening measures, test-retest stability was assessed by testing a group of children twice with a gap in between testing sessions: WOND & WORD 12 -52 days; WASI 2 to 12 weeks.

Participants in the present series of experiments were not re-tested on any of these measures due to time constraints and the limitations on access to the schools. The screening tests were conducted at the beginning of the two and a half year testing period, thus issues of stability over time must be considered. Steps were taken to ensure that the performance of the children on these tests reflected their performance in class and on national tests. The results of their performance on the WORD and WOND were given to the teachers and they were asked to highlight any significant discrepancies between the children's performance on these tests and their performance in class. Only two children were identified here and they were removed from any statistical analysis. When testing was complete the children's performance was discussed once again with the teachers to ensure that the standardised scores awarded more than two years previous were still appropriate in that they continued to adequately reflect each child's level of ability. This method failed to identify any children whose ability in mathematics had significantly improved/worsened over the years to require them to be moved from one ability level to another.

The children were tested individually and testing was completed within two sessions: Session 1: WASI and WOND; Session 2: WORD. Following the results of these screening measures, the children were separated into low-, average- and

high-ability mathematics groups. The cut-off point for low math-ability was scores below the 35th percentile, average-ability 35th-70th percentile and for high-ability any score above the 70th percentile. These are rather lenient classification criteria however, they were essential to ensure adequate group sizes. Out of the total sample size of 96 children, there were 35 low-ability, 31 average- ability and 30 high-ability mathematicians. The performance characteristics of the three ability groups in each of the screening tests is displayed below in Table 4.2.

Table 4.2 Performance in mathematics, IQ and reading screening tests

Math ability group	Standardised Scores		
	IQ (WASI)	Mathematics (WOND)	Reading (WORD)
Low	86	91	88
Average	96	99	98
High	104	114	107

Within the low-ability mathematics group there were a high number of children who also achieved scores below the 35th percentile in the WASI (62%) and the WORD (71%). However, almost one in four low-ability mathematicians achieved an ‘average’ IQ score (24%) or reading score (22%) (see Table 4.3).

Table 4.3: IQ and reading ability in relation to mathematical ability

Math ability	IQ			Reading		
	Low	Average	High	Low	Average	High
Low	62%	29%	9%	71%	22%	8%
Average	35%	42%	23%	32%	39%	29%
High	13%	50%	37%	31%	42%	27%

In addition, 48% of the low-ability mathematicians achieved low scores in **both** the WASI and the WORD (i.e. below the 35th percentile). Consequently, a high proportion of the low-ability mathematicians may therefore be described as children with general learning difficulties. Nevertheless, the aim of this research was not to conduct a study on the small proportion of children who experience only specific difficulties in mathematics. The goal was to examine the inhibition efficiency of a **typical** group of low-ability mathematicians, which more aptly represents the variations within a group of low-ability children in any classroom. In addition, this research will provide a greater insight for educationists into the difficulties experienced by a significant proportion of low-ability mathematicians, as opposed to research which focuses on a small and select group of children with only very specific difficulties.

As a consequence, however, any relationship found between math ability and inhibition efficiency in the following studies may be somewhat tentative in nature due to the high correlations between mathematical ability and reading ability and IQ. Attempts are taken, however, to control for reading ability and IQ using partial correlation coefficients and analyses of covariance. If a significant relationship between mathematical ability and inhibition efficiency is found in any of the following studies then it is appropriate to argue that a specific relationship between these variables does exist, as this would have to be particularly strong in order to maintain significance after controlling for reading ability and IQ.

Materials

A Compaq Presario 700 laptop computer was used to administer the tests. The software computer package *E-Prime Version 1.1* (Psychology Software Tools, Inc.,

2001) was used to design and run the tests. This package also recorded response time scores and accuracy rates for each stimulus presentation and calculated mean RT scores per stimulus and total error scores for each condition (e.g. baseline, congruent and incongruent).

Participants responded by pressing one of the appropriate buttons on the computer keyboard. The response selection for each task was depicted by appropriately coded stickers placed over the computer keyboard. The materials and instructions to participants vary slightly across experiments, thus further details will be provided in the appropriate methodology section.

A manual key press response was employed despite the findings that verbal responses typically provide more interference (Fitts & Posner, 1967; McLain, 1983). In addition, McLain (1983) proposed that in the traditional colour-word task more interference was experienced when verbal responding was employed as a verbal response is more compatible with word reading than a manual response. Nevertheless, manual responding was employed here throughout as the conditions were presented in a randomised format. Hence the response time (RT) for each individual stimulus presentation was required in order to calculate mean RT scores for each condition.

Procedure

For each of the studies reported throughout this thesis, testing was completed on an individual basis in a room away from the classroom. In each study the instructions for the task were presented on the computer screen and read out for the children.

The children then completed a practice session where 75-80% accuracy was required before they could continue to the testing session. During the practice session the children were informed if their answers were correct or incorrect. This feedback helped to clarify the instructions and helped to ensure that they were aware of what was required. Participants were given two attempts at the practice session if required. If they failed to achieve 75-80% accuracy on their second attempt testing was terminated (this only happened on a couple of occasions). The stimuli were all presented individually in the centre of the computer screen and each presentation was preceded by a fixation point (*) which was flashed for 0.5s prior to every stimulus presentation. The stimuli were exposed until a response was elicited from the child. Response time and accuracy rates were recorded for each stimulus presentation.

The children were asked to concentrate on the task and to really try to ignore the experimenter and any outside noise. They were asked to work as quickly as they could, but it was stressed that they should not sacrifice accuracy for speed. They were told not to worry if they made a mistake and that they should try to forget about it and move on to the next item. The experimenter sat a few feet away from the children to ensure that they did not feel that someone was watching over them.

In each study, a 'Take a break' screen flashed up on the screen in between each presentation format (i.e. blocked or random)¹ and the children were invited to have a

¹ A description of each presentation format is provided in the individual Method section for each study.

little rest and to resume testing when they were ready. They were also reminded of the rules before commencing the testing again.

Scoring

The computer package (E-Prime v1.1) recorded RT scores and error rates for each stimulus presentation. However, prior to any direct comparisons between ability levels, within participant interference and facilitation scores were calculated.

Interference scores were calculated by subtracting the baseline measure from the response time/error scores of the conflict measure:

$$\text{INTERFERENCE} = \text{INCONGRUENT} - \text{BASELINE}$$

The decision to employ this scoring method was discussed in Chp. 1 (p. 11-12) and is consistent with Jensen & Rohwer (1966).

A facilitation score was also calculated by subtracting time taken to respond to the congruent stimuli from the baseline measure:

$$\text{FACILITATION} = \text{BASELINE} - \text{CONGRUENT}$$

Thus, for both of these scores a positive difference indicates interference in the incongruent condition or facilitation in the congruent condition.

If the child displayed off-task behaviour e.g., talking to the experimenter, looking away from the computer, fidgeting etc., they were reminded to concentrate and the experimenter noted the particular stimulus presentation and voided that particular RT score prior to any analysis. In addition, response time scores for each individual

presentation were also examined and any score which severely skewed the mean RT was removed. Participants achieving less than approximately 70% accuracy (in at least one of the conditions) were removed from the analysis. In addition, only response times to correct responses were included in the analysis in order to acquire a pure assessment of inhibition efficiency.

Analysis

The statistical package SPSS 11.5 for Windows was employed to analyse the data. A repeated measures analysis of variance was typically employed to determine whether there existed main effects of presentation format, condition, ability level and/or an interaction effect between these dependent and independent variables. In each of the following studies 2(presentation format) x 3(ability) x 2(age group) mixed design analysis of variance (ANOVA) were initially conducted testing for differences between presentation format, ability levels and age groups. However, these typically revealed no difference between the two age groups on any of the experimental measures², hence 2(switching) x 3(ability) mixed design analyses exploring the impact of presentation format and ability level are reported.

² The children were split into two age groups (i.e. younger and older), however, the children were drawn from consecutive primary school classes hence the age range was small. Thus, it is not surprising that there was little evidence of developmental trends.

Chapter 5

Studies 1 & 2: An exploration of the relationship between children's mathematical ability and their performance across six Stroop task variants.

Overview

Chapter 1 provided a brief review of the existing Stroop literature and theories surrounding this phenomenon. Chapter 3 revealed that the Stroop task is commonly employed as a measure of inhibition, which is considered to be essential for the efficient running of working memory. It also reviewed recent research, which has revealed that a relationship between mathematical ability and inhibition efficiency may exist. For example, Bull and Scerif (2001) showed that children experiencing difficulties with mathematics demonstrated reduced inhibition efficiency.

INTRODUCTION

The purpose of the first two studies (i.e. Study 1 and Study 2) is to examine these findings of Bull and Scerif (2001) and further explore their proposal that presentation format may have a significant impact on the degree of interference experienced (see Bull *et al.*, 2000). In addition, the indication that low-ability mathematicians may have a domain-specific problem (see Chapter 3, p. 49) with the inhibition of numerical information was further explored. However, before any justification can be given to this hypothesis it is essential that more varied stimuli are employed. Hence, in the present study, a wider range of Stroop variants are employed. These include two verbal, two numerical and two pictorial Stroop variants. The experimental design and the general methodology employed in Studies 1 and 2 were influenced by the task requirements and the findings of previous research. A brief review of each task and some of these methodological considerations follow below:

Verbal Variants

The traditional colour-word task is employed in Study 1 and the Reverse Stroop Effect (RSE) is examined in Study 2. Please refer to Chapter 1 for an overview and discussion of the colour-word task (pp. 2-4).

Colour-word

The colour-word variant is the most commonly employed Stroop task. The variant employed here consists of comparing the time taken to name the ink colour of a row of coloured X's (e.g. **XXXX**) with the time taken to name the colour of incongruously coloured words (e.g. **BLUE**).

Reverse Stroop Effect (RSE)

Stroop (1935b) reported a reverse Stroop effect (RSE) in his third experiment where the ink colour interfered with word reading. However, this effect was only witnessed following extensive practice in colour naming and it was rather short-lived (see also Dulaney & Rogers, 1994). Since then a number of studies have successfully produced a RSE although less interference is generally found in comparison to the colour-word task (e.g. Stroop, 1935b; Gumenik & Glass, 1970; Dyer & Severance, 1972; Dunbar & MacLeod, 1984; MacLeod & Dunbar, 1988; Pritchatt, 1968). In addition, in order to produce a RSE the experimental design is often considerably altered. For example, many studies have reduced the readability of the target word (Gumenik and Glass, 1971; Dyer and Severance, 1972).

The majority of previous studies did not examine interference in both directions (i.e. by asking participants to name the colour *and* read the word). One of the few

studies exploring this was conducted by Dunbar & MacLeod (1984). They employed the exact same procedure for each task with only an instructional difference (i.e. read the word / state the colour) and found that interference could occur in both directions. This conflicts with the relative speed of processing hypothesis which asserts that interference should be asymmetrical (i.e. the faster process should always and not conversely interfere with the slower one).

Many of the studies investigating RSE employed nonverbal responding and research has revealed that manual responses are more likely to reveal the RSE than verbal responses (Pritchatt, 1968; Martin, 1981; Chmiel, 1984).

Finally, most studies exploring RSE have been conducted on adults. Few studies have explored the RSE with children, although Bryson (1983) found that seven-year old boys displayed interference from the incongruent ink colour when word reading.

Thus, consideration of these earlier findings was taken when designing the RSE variant employed in Study 2. Following Pritchatt's (1968) findings a manual key press response is required. Past research has also revealed that the RSE is quite difficult to produce, particularly if no changes are made to the traditional task. Nevertheless, it is proposed that it may be easier to produce the RSE with children as their reading skills may be less automatic. Hence, they may experience more interference from the conflicting ink colour than adults, since the conflicting ink colour has greater opportunity to interfere with word reading. Some of the children involved in the study are also poor readers. It is predicted that these children, in particular, may experience more interference from the incongruent ink colours.

Similarly, it is predicted that the poor readers may experience less interference in the colour-word variant as word reading may be a less automatic process for them.

Pictorial Variants

The majority of studies examining Stroop interference have involved words and reading. However, in studies involving poor readers, interference effects may be diminished for those whose reading skills are less developed. Less popular alternatives involve the use of shapes, pictures or numerical information. Hence, the pictorial variants employed in the present study overcome any of the above problems associated with reading ability.

Shor (1971) employed a wide range of stimulus domains in an attempt to test the generality of the Stroop phenomena. He asserted that colours, geometric forms, common objects and quantities can all be considered as basic concepts, which can be expressed in a number of ways. Generally, these basic concepts tend to be symbolised by pictorial and linguistic representations. For example, 'up' could be symbolised by an arrow pointing up (pictorial) or the word up (linguistic).

Pictorial variants were contained in both studies 1 and 2. Study 1 contained the 'Global-local Shape' variant and Study 2 contained the 'Colour-picture' variant.

Global-local shapes

In an attempt to include a pictorial-pictorial contrast in Study 1, a variant of Shor's *Three Geometric Forms in Two Levels* was employed (Shor, 1971, pp. 192-194).

This consists of the outline of a shape being composed of smaller examples of a

conflicting shape. For example, the outline of a triangle made up of little circles (see p. 82 for example).

Previous research has found that the processing of global features overrides that of local features. For instance, Navon (1977) presented participants with a letter (global feature) made up of smaller letters (local feature) and found that they experienced more interference when instructed to name the local feature than when asked to name the global feature (see also Stirling & Coltheart, 1977). This is not conclusive, however, as the sparsity and density of the local features has been found to affect the degree of interference experienced. For example, Martin (1979) found that in a multiple-element presentation global features rule, whereas in a few-element presentation local features rule (Martin, 1979).

Consideration of the above findings was taken when designing the *Global-local shape* Stroop variant employed in Study 1. Participants are instructed to identify the *local* feature of a two-dimensional stimulus: a large shape (global feature) constructed of tightly packed smaller shapes (local feature). Hence, following the findings of Navon (1977) and Martin (1979) that global features rule when local features are dense, it is anticipated that the global feature will interfere with the processing of the local feature.

Colour-picture

Cramer (1967) designed a colour-picture Stroop task variant for pre-literate children (see also Árchová, 1971). This task consisted of colour-specific objects coloured in an inappropriate colour. Participants were asked to name either the colour or form

of the picture. The children experienced some interference, although it is not clear whether this was significant or not as Cramer's (1967) results are unclear. Árchová, (1971) conducted a similar study and found that children experienced interference when naming forms coloured in an uncharacteristic colour.

The objects employed in both Cramer and Árchová's studies can be criticised in terms of their colour specificity as they were sometimes presented in an acceptable colour in the incongruent condition. For example, trees were employed yet these can be red, yellow or orange as well as green.

Santostefano (1978) also employed coloured objects in his Fruit Distraction Task, but the participants were actually instructed to prescribe the correct colour of the objects (see also Sebová & Árchová, 1986). Participants were instructed to state the correct colour for characteristically and uncharacteristically coloured objects. The time taken to state the colours of the characteristically-coloured objects was employed as a baseline measure. However, response times to achromatic outline drawings would have been a more effective baseline measure, as this contains the same memory requirements as the uncharacteristically coloured pictures, without the inhibition requirement (Murray, 1997). Hence, the time differential between these two scores should reflect inhibition and not any memory effects. Murray (1997) employed this baseline measure and her results revealed that children took significantly longer to prescribe the correct colour of an inappropriately coloured picture in comparison with an outline drawing.

Study 2 employs a similar colour-picture prescribing task as Santostefano (1978)

and includes the methodological improvements proposed by Murray (1997).

Participants are presented with 6 drawings of colour-specific objects. Care is taken to ensure that the objects chosen possessed a single highly characteristic colour.

The baseline measure employed is achromatic outline drawings because as with the inappropriately coloured pictures these also required recall of the correct colour from memory (Murray, 1997). In addition, highly familiar objects are employed in order to reduce the demands on memory.

However, it must be noted that due to the additional memory component of this task, it is different from other Stroop variants. Nevertheless, the adoption of achromatic outline drawings as a baseline measure controlled for this to some extent. Also, in the other Stroop variants the two potential responses are presented simultaneously, whereas in this prescribing task interference occurs from the presented incongruent ink colour and recalling the correct colour from memory.

Nevertheless, despite these differences, there are many similarities between this task and the Stroop variants; the main and most important similarity, for present purposes, being that they all require the inhibition of a prepotent response. In addition, previous studies revealed that Stroop-like interference was produced hence further justifying the use of this task as a measure of inhibition.

Numerical Variants

Stroop-like interference effects have also been revealed using numerical stimuli and recent research has revealed a relationship between mathematical ability and the

level of interference experienced in numerical Stroop variants. Hence, numerical variants were included with Study 1 containing the 'Number-quantity' variant and Study 2 containing the 'Highest Number' variant.

Number-quantity

A number of studies have employed numbers to examine Stroop-like interference (e.g. Windes, 1968; Shor, 1971; Fox, Shor, & Steinman, 1971; Morton, 1969; Flowers, Warner, & Polansky, 1979; Bull & Scerif, 2001; Bull, Murphy & McFarland, 2000; Bryson, 1983). These studies typically consist of numerals with a matching or mismatching number of items (i.e. 6 occurrences of the digit 3). Windes (1968) was the first to demonstrate that interference is experienced when the stimuli being counted were incompatible Arabic numerals, and a number of studies have successfully replicated this phenomenon (e.g. Shor, 1971; Flowers *et al.*, 1979). Bryson (1983) demonstrated interference effects in autistic children when an incongruous number-object pair were presented (e.g. the number 4 presented beside 2 circles). The substantial degree of interference found by these researchers suggests that the number Stroop variant is comparable with the colour-word variant.

Study 1 employs a numerical Stroop variant similar to that employed by Windes (1968) where participants are required to count an array of numerals, or X's in the baseline condition. In the incongruent condition the numeral presented conflicts with the total number of items (e.g. 2222). Bull & Scerif (2001) and Bull *et al.* (2000) also employed this numerical Stroop variant and the results revealed that

low-ability children experienced greater difficulty in inhibiting an established strategy than the high-ability children.

Highest Number

This numerical Stroop variant, employed in Study 2, requires participants to determine which of two single-digit numbers is the highest. Past research has found that interference can occur if the physical size and numerical magnitude of the numeral conflict. For example, participants were presented with both a congruent condition (e.g. 2 9) and an incongruent condition (e.g. 2 9). Participants consistently achieved slower response times to the incongruent stimuli. This occurred regardless of whether they were asked to determine which number was *physically* larger (Girelli, Lucangeli, & Butterworth, 2000) or *numerically* larger (Foltz, Poltrock, & Potts, 1984).

Girelli *et al.* (2000) examined performance on these two versions of the Stroop task from four years to adulthood. When required to state the numerically larger number, conflicting physical size resulted in interference for all age groups. However, in the physical variant, conflicting numerical size did not result in interference for the youngest children. This suggests that the association between the numeral and its numerical value wasn't strong enough to interfere with the very fast comparison between physical sizes (Butterworth, 1999). In addition, more interference was experienced in every age group from physical size (i.e. in the numerical task where participants had to state the highest number).

In addition, research has revealed *The Distance Effect*, where participants are quicker to determine which of two numbers is the larger the greater the difference is between the two numbers in terms of their magnitude (e.g. higher RT when presented with 2 3, than when presented with 2 9.) (Moyer & Landauer, 1967; Dehaene, Dupoux, & Mehler, 1990; Tzelgov, Meyer, & Henik, 1992). Sekular & Mierkiewicz (1977) conducted the first study to reveal that the distance effect is robust/evident in children. Moyer & Landauer (1967) suggested that the “*displayed numerals are converted to analogue magnitudes and the comparison is then made between these magnitudes in much the same way that comparisons are made between physical stimuli such as loudness or length of line*” (p. 1520).

Consideration is also taken of this ‘Distance Effect’ in Study 2 where steps are taken to ensure that each condition has the same mean distance between the two numerals.

Hypotheses

In each of these six variants of the Stroop task, the stimuli are presented in both blocked and random presentation formats. Blocked presentation format consists of blocks of congruent and incongruent stimuli (e.g. 8 congruent, 8 incongruent, 8 congruent, 8 incongruent), whereas random presentation format consists of a completely randomised presentation of congruent and incongruent stimuli.

Following the results of Bull and colleagues (Bull & Scerif, 2001; Bull *et al.*, 2000) it is predicted that greater interference will be experienced under blocked presentation format, in comparison to random presentation, as this format enables a strategy to be put in place during the recurrent presentation of the congruent stimuli. So, under random presentation format the inhibitory requirements consist of

inhibiting the irrelevant dimension, whereas under blocked presentation format the inhibitory demands are increased, as not only do participants have to inhibit the irrelevant dimension but they also have to inhibit any temporary schema they may have established.

In addition, following Bull and colleagues' finding that greater interference is experienced under blocked presentation format, the present study also examines the impact of the order of presentation of the blocks (i.e. baseline, congruent, incongruent) on interference scores. For instance, it was proposed that greater difficulty would be experienced when required to switch from the congruent block to the incongruent block as participants would not only have to inhibit the irrelevant information, but they would also have to inhibit any alternative strategy employed for the congruent block. However, when switching from the baseline block to the incongruent block interference scores should be lower as no alternative strategy should be initiated.

Finally, if the low-ability mathematicians possess a domain-specific problem with the inhibition of numerical information, it is predicted that they will experience greater interference than the average- and high-ability mathematicians in both of the numerical Stroop variants. Consequently, no significant impact of mathematical ability is expected on the interference scores in the verbal and pictorial Stroop variants.

STUDY 1

Study 1 explores the domain-specificity hypothesis and children's inhibition efficiency in relation to their mathematical ability using the traditional colour-word variant, the number-quantity variant and the colour-picture variant.

METHOD

Participants

48 children from two classes (mean age = 7 years 9 months, SD = 6.35 months, range = 6;11 – 8;09) participated in this study. The sample consisted of 26 girls and 22 boys. The total number of participants included in the analysis of each of the three Stroop task variants employed varies slightly as a consequence of some children being excluded in the analysis of one or more variants due to their failure to achieve a sufficient level of accuracy.

As described in the General Method (Chapter 4, p. 59-60), the children were split into three mathematical groups according to their performance on the standardised mathematics test. This resulted in 17 low-ability, 16 average-ability and 15 high-ability. The performance characteristics of these three groups on each of the screening tests are displayed in Table 5.1.1 below.

Table 5.1.1: Mean IQ, mathematics and reading standard scores (& standard deviations) for low-, average- and high-ability mathematics groups

Ability	Screening Measure		
	IQ	Mathematics	Reading
Low (N = 17)	91.41 (9.33)	87.00 (7.19)	87.47 (12.28)
Average (N = 16)	99.75 (9.94)	99.94 (3.28)	100.62 (9.7)
High (N = 15)	100.14 (7.32)	110.36 (3.5)	100.21 (11.25)

The computer keys were labelled with stickers depicting colours, numbers or shapes. Thus, there were three rows (i.e. one for each variant) of labelled keys. In order to reduce any potential distractions, those keys which were unnecessary for each particular task were covered with plain white card and any surrounding keys had plain white stickers placed over them.

The specific methodology for each variant follows below:

Variant 1: Colour-word

Participants

The results from 47 children are included in the analysis (mean age 7 years 10 months, SD = 6.25 months, range 6;11 – 8;09). The mathematical groups comprised of 17 low-ability, 16 average-ability and 14 high-ability. There were 26 girls and 21 boys.

Stimulus Materials

Participants were instructed to name the *colour* of each item by pressing one of the four appropriately colour coded keys (either a blue, red, green or yellow sticker).

The font used was Times New Roman, point size 48. Each condition took the following format:

Baseline condition: consisted of a row of X's in either blue, red, green or yellow ink colour (e.g. XXXX).

Congruent condition: consisted of a colour word presented in the corresponding ink colour (e.g. BLUE).

Incongruent condition: consisted of a colour-word presented in a conflicting ink colour (e.g. GREEN).

(In each case the correct response was 'blue'.)

Variant 2: Number-quantity

Participants

The final sample consisted of 45 children (mean age = 7 years 9 months, SD = 6.45 months, range of 6;11-7;09). The mathematics ability groups comprised of 16 low-ability, 14 average-ability and 15 high-ability. 22 boys and 23 girls participated.

Stimulus materials

In this variant, participants were instructed to state the quantity of the items, by pressing the corresponding key (stickers numbered 1, 2, 3 and 4). The font used was Times New Roman, point size 48. Each condition took the following format:

Baseline condition: consisted of a row of X's (e.g. XXX)

Congruent condition: the stimuli were numbers presented in a corresponding quantity (e.g. 333).

Incongruent condition: the stimuli were numbers, presented in a conflicting quantity (e.g. 222).

(In each case the correct response was '3'.)

Variant 3: Global-local shapes

Participants

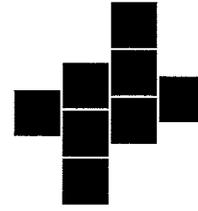
The results from 47 children were included in the analysis (mean age 7 years 9 months, SD = 6.42, range of 6;11 – 8;09). The ability groups comprised of 17 low-ability, 15 average-ability and 15 high-ability. There were 26 girls and 21 boys.

Stimulus Materials

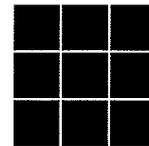
For this variant participants were instructed to identify the *small* shape and respond by pressing the appropriately labelled key (i.e. triangle, circle, square or rectangle).

The conditions were presented in the following way:

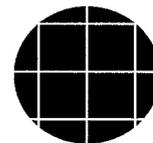
Baseline condition: the stimuli consisted of small squares, rectangles, circles or triangles presented in a random configuration;



Congruent condition: this consisted of small shapes contained within a larger 'matching' shape, for example:



Incongruent condition: the stimuli were small shapes contained within a larger 'different' shape, for example:



(In each case the correct response was 'square'.)

Procedure

The children completed all three variants of the Stroop task in a single session which lasted approximately 15 minutes. The presentation order of the Stroop variants was randomised across participants. In each variant, the children initially completed a practice session, which consisted of 8 stimuli presentations. 75%

accuracy was required in this practice session before proceeding to the testing session. In the testing phase, they were presented with 48 stimuli presentations. 24 of these were presented in a blocked presentation format: blocks of 8 baseline, 8 congruent and 8 incongruent stimuli were presented. The presentation order of these blocks was randomised across participants. The remaining 24 stimuli were presented in a random presentation format, consisting of a random mix of 8 baseline, 8 congruent and 8 incongruent were presented. Half of the children completed the blocked then the random presentation format and for the other half this order was reversed.

Analysis

Mean RT scores were calculated for each condition under both presentation formats and interference and facilitation scores were calculated using the traditional equations detailed on p. 64.

Post-hoc comparisons were made in order to explore the impact of block position. For instance, under blocked presentation format there are three block conditions (i.e. baseline, congruent, incongruent) and as the order of presentation of these blocks is randomised across participants there are six potential orders of presentation¹. Splitting the sample size up according the order of presentation resulted in small and varied group sizes (i.e. varying in participant number and ability level). In

¹ Baseline – congruent – incongruent
Baseline – incongruent – congruent
Congruent – baseline – incongruent
Congruent – incongruent - baseline

Incongruent – baseline - congruent
Incongruent – congruent - baseline

order to overcome this, interference scores were explored in relation to the position of each block condition (i.e. position one, two or three).

RESULTS

Colour-word

The mean stimulus response time (RT) scores indicate that the performance of the three ability levels was highly comparable: they achieved very similar response time scores and every ability group took longer to respond to the incongruent stimuli (see Table 5.1.2).

Table 5.1.2: Mean RT scores and standard deviations (ms) for low-, average- and high-ability mathematicians.

Ability	Measure	Random			Blocked		
		Baseline	Congruent	Incongruent	Baseline	Congruent	Incongruent
Low	Mean	1365.23	1240.19	1416.78	1229.20	1223.54	1520.80
	SD	424.72	198.70	334.64	279.32	309.08	563.37
Average	Mean	1221.30	1150.03	1390.52	1201.42	1101.74	1402.34
	SD	221.60	192.02	285.99	306.32	156.68	266.95
High	Mean	1298.2	1248.11	1438.08	1236.59	1239.37	1556.95
	SD	242.00	183.48	280.01	207.79	207.73	489.88
Overall	Mean	1297.9	1213.94	1415.2	1222.69	1189.72	1494.53
	SD	314.8	192.79	296.77	262.8	239.96	457.62

A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed a significant main effect of condition, $F(2,88) = 32.39, p < 0.01$ and a significant interaction between condition and presentation format, $F(2,88) = 3.62, p < 0.05$. RT scores were higher in the incongruent condition than both the baseline and

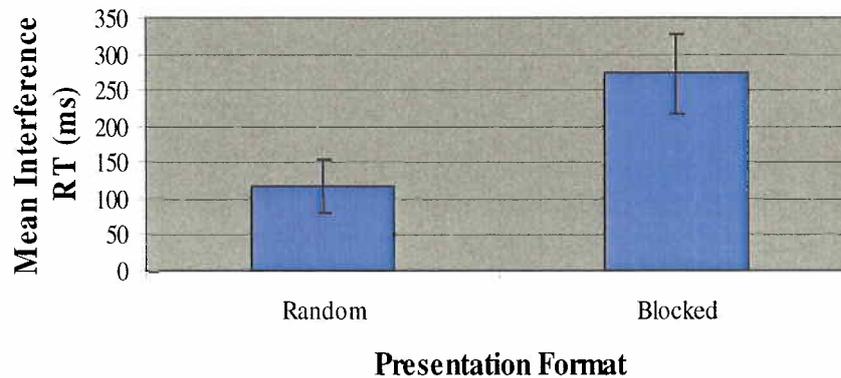
congruent conditions. Also, in comparison to random presentation format, blocked presentation reduced RT scores in the baseline and congruent conditions and increased the RT scores in the incongruent condition.

Paired t-tests were employed to further explore the significant main effect of condition and these confirmed the presence of the predicted classic Stroop effect; participants took significantly longer to respond to the incongruent stimuli than the baseline stimuli under both Random ($t = 3.121$, $df = 46$, $p < 0.01$) and Blocked ($t = 4.87$, $df = 46$, $p < 0.01$) presentation formats. A facilitation effect was also found under random presentation format where participants were significantly quicker to respond to the congruent stimuli compared with the baseline stimuli ($t = 2.097$, $df = 46$, $p < 0.05$). There was no such facilitation effect found under blocked presentation format although the results did follow the predicted pattern.

Interference scores

A 2 (presentation format) x 3 (ability level) mixed design analysis of variance was conducted on the interference scores and revealed a significant main effect of presentation format ($F(1,44) = 4.92$, $p < 0.05$) only. Overall, more interference was experienced under blocked presentation compared to random presentation format (see Fig. 5.1.1).

Fig. 5.1.1. Mean interference under random & blocked presentation



The higher interference scores under blocked presentation format compared with random presentation supports the proposal that blocked presentation introduces an additional switching requirement which places increased demands on the executive system.

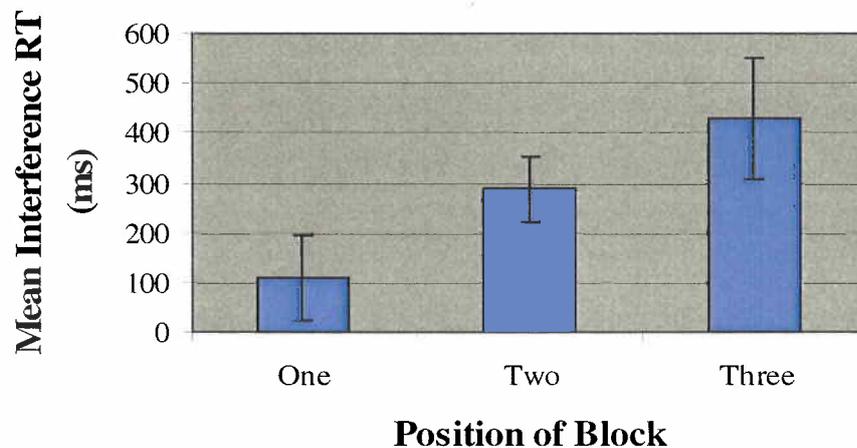
No significant main effects of ability level or interaction effects were found. Hence, mathematical ability does not appear to be related to children's ability to inhibit irrelevant information in the colour-word variant of the Stroop task.

It was proposed that the raised levels of interference levels under blocked in comparison to random presentation format may be related to the order of presentation of the three blocks (i.e. baseline, congruent, incongruent).

In order to examine the impact of the position of the three conditions, 3(block position) x 3(ability level) ANOVAs were conducted on blocked interference scores for each condition (i.e. baseline, congruent, incongruent). These revealed no significant main effects or interaction effects for each of the three conditions. The

impact of the position of the incongruent condition on blocked interference scores, however approached significance, $F(2,38) = 2.92$, $p = 0.066$ (see Fig. 5.1.2.).

Fig. 5.1.2. Mean 'blocked' interference in relation to incongruent block position



Interference RT scores increased linearly as the position of the incongruent block shifted from one to three. Independent t-tests confirmed that significantly more interference was experienced when the incongruent block was in position 3 compared with position 1, $t = 2.16$, $df = 29$, $p < 0.05$. So, these findings suggest that the children experienced greater difficulty inhibiting word reading when the incongruent block followed the two comparatively 'easy' blocks.

It was proposed that the children would experience a particular difficulty inhibiting the irrelevant dimension when a switch was required from the congruent to the incongruent block due to the potential switch in strategy requirement. This proposal was further explored in order to determine whether switching to the incongruent block from a congruent block resulted in greater interference than when switching from the baseline block. Table 5.1.3. contains the mean interference scores for

those orders of presentation format where the incongruent block follows the baseline block and where the incongruent block follows congruent block.

Table 5.1.3. Mean blocked interference scores (ms) in relation to the order of block presentation

Measure	Order of presentation	
	Congruent – Incongruent	Baseline - Incongruent
Mean Interference	333.44	381.82
SD	365.78	401.34
N	16	15

There was little difference in terms of interference scores when the incongruent block followed the baseline block in comparison to when it followed the congruent block. A 2(order of presentation) x 3(ability) ANOVA on blocked interference scores confirmed that there was no significant impact of these orders of presentation and no significant interaction effect between order of presentation and ability level.

Facilitation scores

Facilitation effects were modest and no significant main effects or interaction effects were found.

Correlational analyses

Correlational analyses revealed the expected positive relationships between mathematical ability and IQ ($r = .37, p < 0.05$) and reading ability ($r = .5, p < 0.01$) and between reading ability and IQ ($r = .47, p < 0.01$). There was no significant

relationship found between any of the three screening measures and the interference or facilitation RT scores. The analyses did reveal, however, a significant negative relationship between interference and facilitation scores indicating that a higher amount of interference was associated with a lower level of facilitation under both blocked ($r = -.5, p < 0.01$) and random ($r = -.48, p < 0.01$) presentation formats. This removes the possibility that greater interference was due to more automatic activation of the irrelevant dimension.

There was no significant relationship between reading ability and interference scores providing no support to the proposal that poor readers would experience less interference.

Errors

In order to be included in the analysis, participants had to achieve over 80% accuracy. Only one person in the present study failed to achieve this, hence error rates were extremely low with the majority of children making no errors at all.

Global-local shapes

Mean response time scores for each presentation format are shown below in Table 5.1.4. As expected, the longest response time scores were in the incongruent condition where the global and local shapes conflicted. Low-ability participants generally took longer to respond than the average- and high-ability participants across all conditions.

Table 5.1.4. Mean RT scores and standard deviations (ms) for low-, average- and high-ability mathematicians.

Ability	Measure	Random			Blocked		
		Baseline	Congruent	Incongruent	Baseline	Congruent	Incongruent
Low	Mean	1526.78	1580.75	1600.53	1524.16	1432.39	1590.12
	SD	441.89	427.7	483.78	502.06	380.83	563.5
Average	Mean	1329.1	1306.95	1437.61	1246.68	1259.38	1338.45
	SD	247.64	222.15	285.07	297.91	287.32	276.05
High	Mean	1463.2	1468.58	1627.3	1277.03	1373.00	1475.54
	SD	244.3	311.67	339.65	303.55	239.28	301.82
Overall	Mean	1440.55	1454.13	1553.04	1356.08	1355.8	1470.31
	SD	334.67	347.41	384.26	398.95	314.7	415.21

A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed RT scores were significantly higher under random compared with blocked presentation format, $F(1,44) = 5.36, p < 0.05$ and a significant main effect of condition, $F(2,88) = 10.37, p < 0.01$, indicating that blocked presentation format in this variant failed to introduce any additional demands. Paired t-tests further explored the impact of condition and confirmed the presence of Stroop-like interference as they took longer to respond to the incongruent stimuli than the baseline stimuli under both random ($t = -3.11, df = 46, p < 0.01$) and blocked presentation formats ($t = -2.3, df = 46, p < 0.05$). There was little difference between the baseline and congruent RT scores indicating little facilitation.

Interference & facilitation scores

Both interference and facilitation scores were low across ability levels and statistical analyses revealed no significant main effects or interaction effects of ability and no significant presentation effects.

Correlational analyses

Correlational analyses were conducted in order to determine whether there existed any significant relationship between the Stroop-like interference and facilitation scores and the screening measures. These correlation coefficients revealed the anticipated significant positive relationship between mathematical ability and IQ ($r = .37, p < 0.05$) and reading ability ($r = .49, p < 0.01$) and between reading ability and IQ ($r = .49, p < 0.01$). Interference and facilitation scores also correlated negatively with one another under both blocked ($r = -.74, p < 0.01$) and random ($r = -.56, p < 0.01$) presentation formats, indicating that an increase in interference scores was associated with a decrease in facilitation scores. There was no significant relationship found between interference and facilitation scores and performance on the screening measures under blocked or random presentation formats.

Errors

Again error rates were extremely low, and no significant main effects or interaction effects were found.

Number-quantity

Mean response time scores indicated that participants took longer to respond to the incongruent stimuli than both the baseline and congruent stimuli. Low-ability children also generally took longer to respond to stimulus presentations particularly in the incongruent condition (see Table 5.1.5.).

Table 5.1.5. Mean RT scores and standard deviations (ms) for low-, average- and high-ability mathematicians.

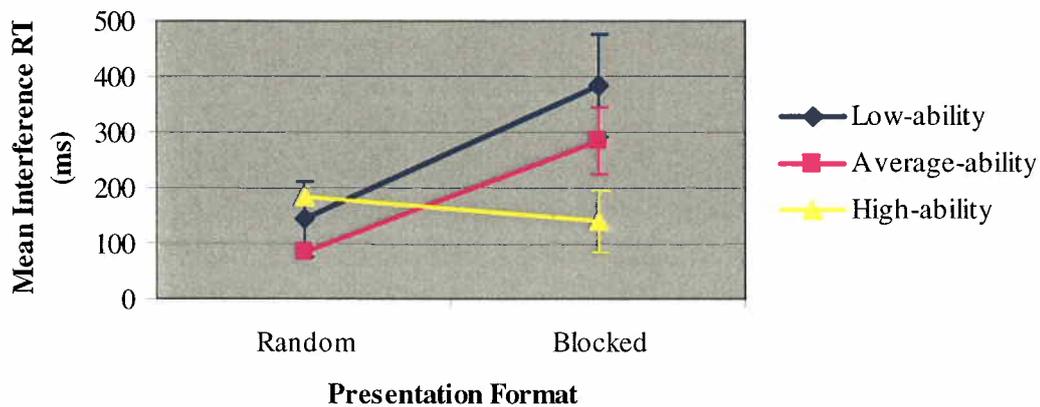
Ability	Measure	Random			Blocked		
		Baseline	Congruent	Incongruent	Baseline	Congruent	Incongruent
Low	Mean	1619.61	1575.89	1763.94	1414.09	1530.14	1797.37
	SD	319.48	491.84	330.51	288.57	395.38	361.26
Average	Mean	1498.24	1413.85	1580.91	1402.62	1333.79	1687.1
	SD	218.95	311.47	222.44	304.38	226.4	381.98
High	Mean	1424.79	1449.19	1608.42	1364.74	1406.39	1503.2
	SD	274.61	351.63	375.82	234.72	315.21	238.54
Overall	Mean	1514.57	1481.14	1652.68	1393.62	1425.48	1662.00
	SD	281.11	391.55	321.23	271.15	324.7	347.16

A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed only a significant main effect of condition, $F(2,82) = 33.29, p < 0.01$. Once again, the predicted Stroop-like interference effect was reproduced: RT scores were significantly longer in the incongruent condition compared with the baseline condition under both Random ($t = 4.1, df = 43, p < 0.01$) and Blocked ($t = 6.24, df = 43, p < 0.01$) presentation formats.

Interference scores

A 2 (presentation format) x 3 (ability level) analysis of variance on interference scores was calculated and revealed a significant main effect of presentation format ($F(1,41) = 6.38, p < 0.05$) and a near significant interaction effect between presentation format and ability level ($F(2,41) = 2.97, p = 0.063$ (see Fig. 5.1.3.).

Fig. 5.1.3. Mean interference under blocked & random presentation



In general, more interference was experienced under blocked presentation format than under random presentation, supporting the proposal that blocked presentation introduces an additional switching/inhibition requirement, which in turn places further demands on the executive system. From Fig. 5.1.3. it is clear that only the low- and average-ability children experience greater interference under blocked compared with random presentation format. Paired t-tests confirmed a significant effect of presentation format for the average-ability children ($t = 3.24$, $df = 13$, $p < 0.01$) and a near significant impact of presentation format for the low-ability children ($t = 1.94$, $df = 14$, $p = 0.07$).

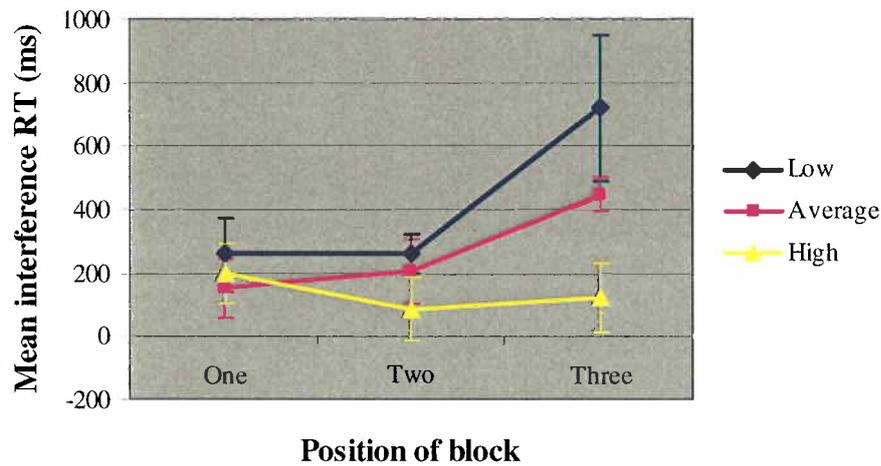
There was no significant main effect of ability; however the near significant interaction between presentation format and ability level and inspection of the data suggests a simple effect of ability level under blocked presentation format (see Fig. 5.1.3.). Further independent t-tests revealed that, under blocked presentation format, low-ability children experienced significantly more interference than high-ability children, $t = 2.29$, $df = 28$, $p < 0.05$. This provides further support to Bull *et*

al.'s (2000) research which also found that low-ability mathematicians experienced greater interference under blocked presentation format than high-ability mathematicians. As mathematics ability correlated well with IQ ($r = .328^*$) and reading ability ($r = .511^{**}$), an analysis of covariance (ANCOVA) was conducted controlling for these factors. This did not remove the significant main effect of presentation format ($F(1,37) = 4.13, p < 0.05$), however, the interaction between presentation format and ability level no longer approached significance. This suggests that the relationship between mathematical ability and presentation format is not particularly due to variations in mathematical ability, but rather is a facet of intelligence in general.

It was proposed that the increased interference under blocked presentation format may be related to the block position of each condition (i.e. baseline, congruent, incongruent). Hence, interference scores were also examined in relation to the position of each condition. 3(block position) x 3(ability level) ANOVAs on blocked interference scores were conducted for each condition. These revealed no significant main effects or interaction effects for the baseline and congruent conditions. However, in the incongruent condition, significant main effects of block position, $F(2,35) = 3.82, p < 0.05$ and ability level, $F(2,35) = 4.63, p < 0.05$ (see Fig. 5.1.4.) were revealed. There was no significant interaction effect².

² Splitting the sample up in relation to both the block position and ability level reduced the group sizes considerably. An interaction effect may have arisen with a larger sample.

Fig. 5.1.4. Mean 'blocked' interference in relation to the incongruent block position



As anticipated interference scores were highest when the incongruent condition was in position three. Planned comparisons confirmed that significantly more interference was experienced with the incongruent in position 3 compared with both positions one ($t = 2.39, df = 30, p < 0.05$) and two ($t = 2.57, df=21, p < 0.05$). In addition the low-ability children experienced greater interference than the average- and high-ability children, particularly when the incongruent block was in position 3.

Bull and colleagues (i.e. Bull & Scerif, 2001; Bull *et al.*, 2000) proposed that greater interference was experienced under blocked presentation format due to the opportunity to establish a temporary strategy in the congruent block. It was anticipated therefore that greater interference would be experienced when required to switch from the congruent block to the incongruent block. This proposal was further explored in order to determine whether switching to the incongruent block from congruent block resulted in greater interference than when switching from the baseline block. Table 5.1.6. contains the mean interference scores for those orders

of presentation format where the incongruent block follows the baseline block and where the incongruent block follows congruent block.

Table 5.1.6. Mean blocked interference scores (ms) in relation to the order of block presentation

Measure	Order of presentation	
	Congruent – Incongruent	Baseline - Incongruent
Mean Interference	297.61	327.49
SD	385.56	239.84
N	12	14

There was little difference in terms of interference scores when the incongruent block followed the baseline block in comparison to when it followed the congruent block. A 2(order of presentation) x 3(ability) ANOVA on blocked interference scores confirmed that there was no significant impact of order of presentation and no significant interaction effect between order of presentation and ability level.

Facilitation scores

Facilitation scores were modest and as expected a 2 x 3 analysis of variance on facilitation scores revealed no significant main effects or interaction effects.

Correlational analyses

Correlational analyses were conducted to discover whether there was any significant relationship between interference and facilitation scores and any of the screening measures. These revealed the predicted significant relationship between mathematical ability and IQ ($r = .31, p < 0.05$) and reading ability ($r = .47, p < 0.01$)

and between IQ and reading ability ($r = .5, p < 0.01$). There was no significant correlation between interference or facilitation scores and any of the three screening measures under both presentation formats. The lack of any predicted correlation between mathematical ability and blocked interference is likely due to the similar level of performance between the low- and average-ability children.

It is possible that the increased interference scores of the low-ability mathematicians under blocked presentation format may be the result of greater automatic activation of the irrelevant dimension (see Salthouse & Meinz, 1995). The facilitation scores however should reveal any benefits of this automatic activation. Correlational analyses revealed negative correlations between facilitation and interference scores under both blocked ($r = -.21, df = 44, p = ns$) and random ($r = -.492, df = 44, p < 0.01$) presentation formats. Thus, as interference scores increased, facilitation scores decreased, hence no support is provided for this proposal. Correlation coefficients were also calculated for the low-ability children only to ensure that this negative relationship between interference and facilitation scores held. These revealed a highly significant negative relationship between interference and facilitation scores under random presentation format ($r = -.65, df = 15, p < 0.01$) and although non-significant a negative relationship between blocked interference and facilitation scores.

Errors

Mean error scores for each ability level across conditions are displayed in Table 5.1.7. below:

Table 5.1.7. Mean error scores and standard deviations for low-, average- and high-ability mathematicians.

Ability	Measure	Random			Blocked		
		Baseline	Congruent	Incongruent	Baseline	Congruent	Incongruent
Low	Mean	.33	.13	1.2	.13	.13	1.2
	SD	.72	.52	1.15	.52	.52	1.21
Average	Mean	.07	.0	.36	.07	.0	.86
	SD	.27	.0	.75	.27	.0	.95
High	Mean	.13	.2	.47	0.0	.07	.47
	SD	.52	.41	.64	.0	.26	.52
Overall	Mean	.18	.11	.68	.07	.07	.84
	SD	.54	.39	.93	.33	.33	.96

The low-ability children generally made the most errors across all conditions under both presentation formats. A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed a significant main effect of condition, $F(2,82) = 33.79$, $p < 0.01$ and a significant interaction between condition and ability, $F(4,82) = 3.15$, $p < 0.05$, reflecting higher error scores in the incongruent conditions, particularly for the low-ability children. Hence, Stroop-like interference was also supported by the error scores with significantly more errors being made in the incongruent condition than the baseline condition under both random ($t = 4.1$, $df = 43$, $p < 0.01$) and blocked ($t = 6.24$, $df = 43$, $p < 0.01$) presentation formats. Planned comparisons also revealed that in the incongruent conditions the low-ability mathematicians made significantly more errors than both the average- ($t = 2.33$, $df = 27$, $p < 0.05$) and high-ability ($t = 2.16$, $df = 28$, $p < 0.05$) children under random presentation format and more than the high-ability children ($t = 2.16$, $df = 28$, $p < 0.05$) under blocked presentation format.

Interference error scores were calculated and a 2 (presentation) x 3 (ability) mixed design ANOVA revealed no significant main effects or interaction effects.

Comparisons between the three Stroop variants

The mean interference and facilitation RT scores for each of the three variants are presented below in Table 5.1.8.

Table 5.1.8. Mean interference & facilitation RT scores for each of the three Stroop variants

Stroop Variant	Measure	Random		Blocked	
		Interference	Facilitation	Interference	Facilitation
Colour-word	Mean	117.29	83.96	271.84	32.97
	SD	257.62	274.47	382.72	240.86
Global-local shapes	Mean	112.49	-13.58	114.23	0.28
	SD	248.19	248.06	340.84	270.17
Number-quantity	Mean	130.38	55.56	285.79	-17.97
	SD	226.68	339.64	305.35	274.24

Under random presentation format levels of interference were highly comparable across the three Stroop variants. There was a significant effect of presentation format for the colour-word and number-quantity variants, but not for the global-local shape variant. In addition, under blocked presentation format there was significantly less interference experienced in the global-local shapes variant than either the colour-word ($t = 1.89$, $df = 45$, $p = 0.065$ (approaching significance)) or number-quantity ($t = 2.26$, $df = 43$, $p < 0.05$). Thus, it seems that the opportunity to establish an alternative strategy under blocked presentation format has less impact on the inhibition requirements of the global-local shapes variant to the colour-word

and number-quantity variants. Finally, there was little variation between facilitation scores under both blocked and random presentation format.

Correlational analyses were conducted in order to determine whether there was any significant relationship between the interference scores across the three Stroop variants. These correlations revealed the general trend for the interference scores in each variant to correlate negatively with the facilitation scores in that variant.

However, there was no significant relationship found between interference scores across variants indicating that high interference in one variant was not necessarily associated with high levels of interference in another variant. This provides further support to the domain-specificity hypothesis as it suggests that those children experiencing increased interference in the numerical Stroop variant did not display a global inhibition efficiency deficit.

STUDY 2

Study 2 further explored the domain-specificity proposal and inhibition efficiency in relation to mathematical ability using a further three variants of the Stroop task: the reverse Stroop effect variant, the highest number variant and the colour-picture variant.

METHOD

Participants

In order to increase the sample size, children from another school in the same area were recruited. A total of 71 children participated, mean age 8 years 8 months (SD = 6.83 months, range of 7;08 - 9;08). The sample consisted of 38 girls and 33 boys. Each participant completed three Stroop task variants in a single session.

Once again, the total number of participants included in the analysis of each of the three Stroop task variants employed varies slightly as a consequence of some children being excluded in the analysis of one or more variants due to their failure to achieve a sufficient level of accuracy.

The performance characteristics of each mathematical ability level across the three screening tasks are shown in Table 5.2.1. below:

Table 5.2.1: Mean IQ, mathematics and reading standard scores (& standard deviations) for low, average and high ability mathematics groups

Ability	Screening Measures		
	IQ	Mathematics	Reading
Low (N = 26)	88.04 (10.18)	84.78 (6.72)	87.13 (8.8)
Average (N = 21)	95.85 (11.11)	99.7 (3.15)	97.25 (11.55)
High (N = 24)	104.38 (9.57)	113.83 (6.6)	106.38 (11.55)

The children were split into three mathematical ability groups according to their performance on the mathematical screening test. This resulted in 26 low-ability, 21 average-ability and 24 high-ability children.

The computer keys were labelled with stickers appropriate to each variant. There were 3 rows of labelled keys (i.e. one for each variant) and the surrounding buttons had plain white stickers in them to remove any potential distractions. In addition those rows which were not required for the task had plain white card placed over them. A description of each variant follows below:

Variant 1: Reverse Stroop Effect

Participants

The final sample consisted of 64 participants (mean age = 8 years 9 months, SD = 6.69, range of 7;08 – 9;08). The mathematical ability groups comprised of, 24 low-ability, 20 average-ability and 20 high-ability children. 34 girls and 30 boys participated.

Stimulus Materials

Participants were instructed to *read* the word and respond by pressing one of 4 keys labelled with the colour words red, blue, green and yellow. The font used was Arial Black, point size 48. Each condition consisted of the following:

Baseline Condition

Colour words, white outlined in black ink: 

Congruent Condition

Colour words coloured in the appropriate colour of ink: **RED**

Incongruent Condition

Colour words coloured in an inappropriate colour of ink: **RED**

(In each case the correct response was 'red'.)

Variant 2: Highest Number

Participants

The final sample consisted of 63 participants (mean age = 8;09, SD = 6.55, range of 7;08 – 9;08). The mathematical ability groups comprised of 23 low-ability, 18 average-ability and 22 high-ability children. There were 34 girls and 29 boys.

Materials

Participants were presented with two numbers and were asked to select the *numerically* larger number. They were asked to respond by pressing one of two keys. The keys had black stickers placed over them – one on the left and one on the right. There was a gap consisting of four keys between the two response keys and these and the surrounding keys were labelled with white stickers. Participants were asked to respond by pressing the key which was on the same side (i.e. left or right) as the larger number. Every combination of numerals from 1 to 9 was used, excluding ties. This resulted in 72 combinations and these were divided amongst the baseline, congruent and incongruent conditions resulting in 24 stimuli

presentations in each. These 24 combinations were further divided into two, resulting in 12 combinations for each condition for the Random presentation format and 12 for each condition for the Blocked presentation format.

Consideration was also taken of the 'Distance Effect' (see p. 76) by ensuring that the mean difference between the two numerals (i.e. for the combination 2 7, the difference is 5) remained approximately equal across the three conditions.

The font employed was Arial Black, point sizes 36 and 72.

The three conditions took the following format:

Baseline Condition:

Both numbers were physically equal in size: **7 3**

Congruent Condition:

The numerically larger number was also physically larger: **7 3**

Incongruent Condition:

The numerically larger number was physically smaller: **7 3**

(In each case the correct response was the left button.)

Care was taken to ensure that there were roughly equal numbers of responses from the left and right-hand sides (i.e. the numerically larger number was placed on the left and right sides of the screen in an equal number of trials).

Variant 3: Colour-picture

Participants

The data from 67 children (mean age = 8;09, SD = 6.69, range of 7;08 – 9;08) was included in the analysis. The mathematical ability groups consisted of 23 low-ability, 20 average-ability and 24 high-ability children. There were 36 girls and 31 boys.

Materials

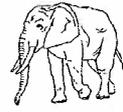
Participants were presented with pictures of familiar objects and animals and instructed to *prescribe* the typical colour of these objects³. Responses were made by pressing one of 6 coloured keys. The children were asked to name each of the coloured stickers prior to testing to ensure that they were very familiar with the colours employed. Every object was also presented during the practice session to ensure that the child was familiar with the objects and their typical colours.

³ All pictures were taken from Snodgrass & Vanderwart (1980)

The following six pictures and their corresponding characteristic colours were as follows:



= pink



= grey



= red



= orange



= yellow



= green

In the incongruent condition, the object was presented in one of the other 5 colours employed in the study. All of these colours were non-characteristic, and although on occasion possible, they are far more unusual than the characteristic colours (e.g. tropical frogs can be orange and strawberries are green before ripening).

Each condition comprised of the following:

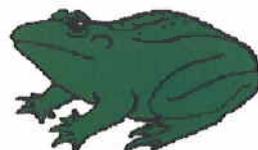
Baseline Condition:

The picture consisted of an achromatic outline drawing:



Congruent Condition:

The picture was coloured in its typical colour:



Incongruent Condition:

The picture was coloured in a non-typical colour:



(In each case the correct response was 'green'.)

The baseline and congruent conditions each contained 2 cycles of the 6 pictures.

Within the incongruent condition there were a total of 30 possibilities. 24 of these were randomly selected for the test trials and 6 for the practice trial. Of the 24 selected for the test trials, they were divided in two resulting in 12 for the Blocked and 12 for the Random presentations formats. Within each selection of 12 steps were taken to ensure that there were two presentations of each object/animal and two presentations of each colour.

Procedure

The children were tested individually. They completed the three variants in one testing session lasting approximately 15 minutes. The variants were presented in a randomised order and the presentation of the conditions within each variant was also randomised.

In each variant, the children initially completed a practice session, which consisted of 6 stimuli presentations. In the testing phase, they were presented with 36 stimuli presentations in both the blocked and random presentation formats. In the blocked format, blocks of 12 baseline, 12 congruent and 12 incongruent stimuli were

presented. The presentation order of these blocks was randomised across participants. In the random format, a random mix of 12 baseline, 12 congruent and 12 incongruent were presented. Half of the children completed the blocked format first then the random, for the other half this order was reversed.

Analysis

Mean RT scores were calculated for each condition under both presentation formats. From these, interference and facilitation scores were calculated using the traditional equations detailed on p. 64

Post-hoc comparisons were again conducted in order to explore the impact of block position on interference scores. There are three 'condition' blocks in the blocked presentation format. These are presented in a randomised fashion thus resulting in six potential orders of presentation. Each condition is presented in either block position one, two or three and the impact of the block position of each condition on interference scores is examined.

RESULTS

Reverse Stroop Effect

The mean stimulus response scores and standard deviations for each ability level across conditions are displayed in Table 5.2.2. below:

Table 5.2.2. Mean RT scores (& standard deviations) for low-, average- and high-ability mathematicians

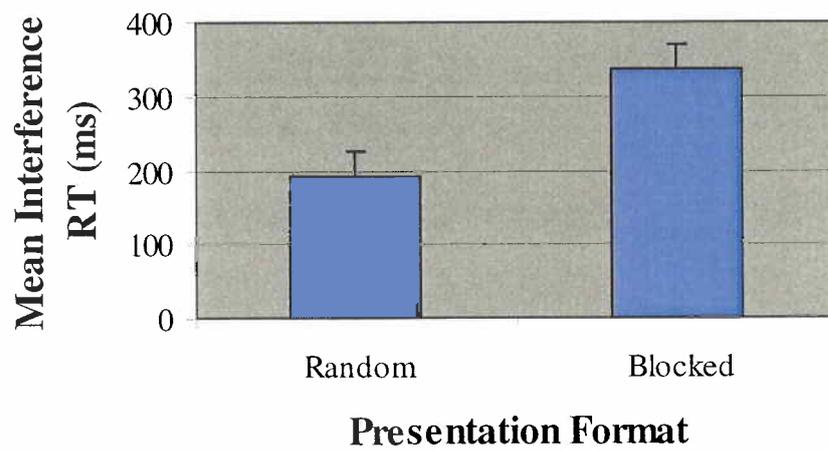
Ability	Measure	Random			Blocked		
		Baseline	Congruent	Incongruent	Baseline	Congruent	Incongruent
Low	Mean	1304.02	1254.08	1558.42	1302.19	1213.46	1683.79
	SD	223.00	255.57	292.75	268.48	323.85	373.91
Average	Mean	1274.79	1241.85	1454.95	1193.24	1180.71	1488.74
	SD	277.9	234.7	260.53	194.24	344.15	318.25
High	Mean	1232.48	1210.74	1363.79	1189.65	1154.26	1509.09
	SD	200.77	213.95	320.99	197.75	190.36	320.98
Overall	Mean	1272.55	1236.58	1465.14	1233.37	1184.7	1569.1
	SD	232.91	233.76	299.81	229.37	291.75	348.05

A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed a significant main effect of condition, $F(2,126) = 82.08, p < 0.01$ and a significant interaction between presentation format and condition, $F(2,126) = 11.64, p < 0.01$. RT scores were higher in the incongruent condition in comparison to the baseline and congruent conditions, particularly under blocked presentation format. So, this study was also successful in replicating Stroop-like interference, with the children taking significantly longer to respond to the incongruent stimuli compared with the baseline stimuli under both blocked ($t = 9.64, df = 65, p < 0.01$) and random ($t = 6.01, df = 65, p < 0.01$) presentation formats. Hence, this study was successful in producing a reverse Stroop effect where the ink colour interfered with word reading. Baseline and congruent RT scores were highly comparable indicating little facilitation effect.

Interference scores

A 2 (presentation format) x 3(ability) mixed design ANOVA on interference scores revealed a significant main effect of presentation format only, $F(1,63) = 12.5$, $p < 0.01$ (see Fig. 5.2.1.).

Fig. 5.2.1. Mean Interference under blocked & random presentation



More interference was experienced under blocked presentation format suggesting that the additional demand of switching had a negative impact on the executive system.

There were no significant main effects of ability level indicating that the degree of interference experienced on the RSE was not related to mathematical ability.

Interference scores were higher under blocked presentation format compared with random presentation format. It was proposed that the position of the blocks may exert a significant impact on interference scores. Hence, interference scores were also examined in relation to the position of each condition. 3(block position) x 3(ability level) ANOVAs on blocked interference scores were conducted for each

condition. These revealed no significant main effects or interaction effects for each condition. Nevertheless, the mean interference scores of the incongruent block increased from position one (230.34 ms) to position three (455.84ms), hence following the predicted pattern.

Correlational analyses

A correlational analysis was conducted to determine whether any of the screening measures were significantly correlated to interference or facilitation scores. These revealed the anticipated highly significant relationships between IQ and mathematical ability ($r = .68, p < 0.01$), IQ and reading ability ($r = .63, p < 0.01$) and reading ability and mathematical ability ($r = .7, p < 0.01$). A significant positive correlation between blocked interference and random interference scores was also found ($r = .28, p < 0.05$). Indicating that increased interference scores under random presentation was associated with increased interference scores under blocked presentation. A negative correlation was found between the random interference and facilitation scores, ($r = -.33, p < 0.01$) indicating that a higher amount of interference was associated with a lower degree of facilitation. Finally, it was anticipated that the strength of the RSE would be related to reading ability however the present data offers no support to this proposal as no significant relationship was found.

Errors

The error scores were once again low, however a 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed a significant main effect of condition, $F(2,126) = 16.25, p < 0.01$. Significantly more errors were made in the incongruent condition than the baseline condition under both blocked ($t = -4.52, df = 65, p <$

0.001) and random ($t = -4.98$, $df = 65$, $p < 0.001$) presentation formats (see Table 5.2.3.).

Table 5.2.3. Mean error scores (& standard deviations) under blocked and random presentation format

Condition	Measure	Presentation Format	
		Blocked	Random
Baseline	Mean	0.11	0.18
	SD	0.36	0.55
Congruent	Mean	0.11	0.14
	SD	0.36	0.43
Incongruent	Mean	0.61	0.88
	SD	0.89	1.06

Thus, the error data combined with the RT data clearly indicate the presence of Stroop-like interference.

Interference errors were low and a 2(presentation) x 3(ability) mixed design ANOVA revealed no significant main effects or interaction effects.

Highest Number

The mean stimulus response scores and standard deviations for each ability level across conditions are displayed in Table 5.2.4. Participants in every ability group took longer to respond to the incongruent stimuli compared with both the baseline and congruent stimuli and the RT scores of the low-ability children were generally longer than those of the average- and high-ability children.

Table 5.2.4. Mean RT scores (& standard deviations) for low-, average- and high-ability mathematicians

Ability	Measure	Random			Blocked		
		Baseline	Congruent	Incongruent	Baseline	Congruent	Incongruent
Low	Mean	1391.47	1320.49	1688.43	1554.46	1472.31	1662.66
	SD	316.3	301.01	366.75	344.05	316.96	367.34
Average	Mean	1385.1	1267.57	1472.33	1363.29	1290.9	1447.25
	SD	355.54	271.92	337.45	251.23	267.81	249.93
High	Mean	1215.05	1105.49	1322.19	1307.44	1218.63	1356.22
	SD	290.75	261.95	320.91	323.33	326.49	356.47
Overall	Mean	1329.66	1230.6	1494.67	1409.12	1327.87	1489.36
	SD	326.71	289.58	369.68	322.9	319.32	349.83

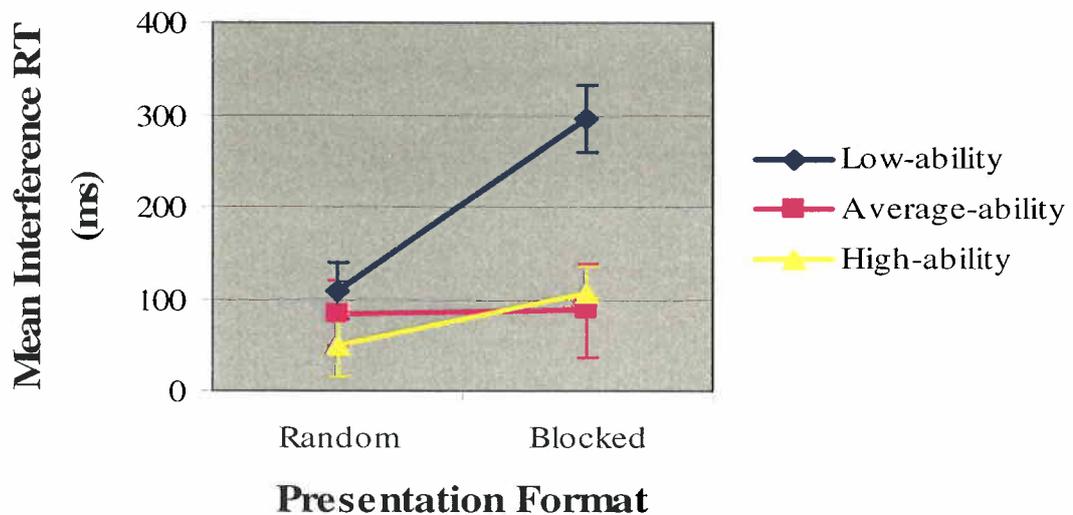
A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed significant main effects of presentation format, $F(1,59) = 6.38, p < 0.05$, condition, $F(2,118) = 66.56, p < 0.01$ and ability level, $F(2,59) = 4.52, p < 0.05$ and significant interactions between condition and ability level, $F(4,118) = 2.77, p < 0.05$ and presentation and condition, $F(4,118) = 5.64, p < 0.01$.

RT scores were once again significantly higher in the incongruent condition compared with the baseline condition under both blocked ($t = 6.55, df = 61, p < 0.001$) and random ($t = 4.19, df = 61, p < 0.01$) presentation formats, indicating the presence of Stroop-like interference. A significant facilitation effect was also revealed as the children were quicker to respond to the congruent stimuli compared with the baseline stimuli under blocked ($t = 3.74, df = 61, p < 0.01$) and random ($t = 3.85, df = 61, p < 0.01$) presentation formats.

Interference scores

A 2 (presentation format) x 3 (ability level) mixed design analysis of variance revealed significant main effects of presentation format, $F(1,59) = 10.39$, $p < 0.01$, ability level $F(2,59) = 6.1$, $p < 0.01$ and a significant interaction between presentation format and ability level, $F(2,59) = 4.51$, $p < 0.05$. See Figure 5.2.3.

Fig. 5.2.3. Mean interference under blocked & random presentation



The children in the low-ability mathematic group displayed greater interference under blocked presentation in comparison with random presentation format.

Planned comparisons revealed that under blocked presentation format, low-ability participants experienced significantly more interference than both average ($t = 3.4$, $df = 39$, $p < 0.01$) and high-ability participants ($t = 3.87$, $df = 40$, $p < 0.01$). Under random presentation format there was no difference in interference scores between ability levels.

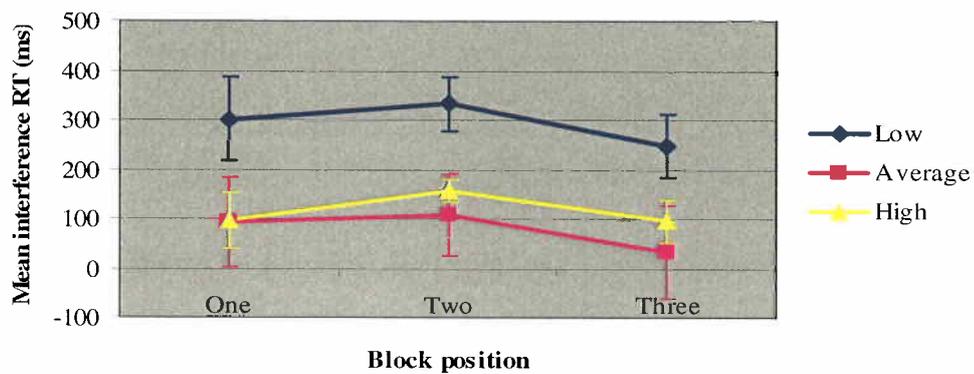
Mathematics ability correlated significantly with both IQ ($r = .68, p < 0.01$) and reading ability ($r = .64, p < 0.01$), so in order to be certain that the differences found between the ability groups is an element of mathematics ability and not simply an element of general intelligence an analysis of covariance was carried out to control for the differences between the groups in terms of reading ability and IQ. A 2 x 3 ANCOVA removed the significant main effects of ability ($p = 0.068$) and presentation format, however the significant interaction between presentation format and ability level remained, $F(2,57) = 3.81, p < 0.05$.

The results clearly indicate that low-ability mathematicians experience more interference under blocked presentation format. From past research this supports the proposal that low-ability mathematicians experience increased interference due to difficulty switching strategy. For instance, Bull *et al.* (2000) proposed that greater interference was experienced under blocked presentation format as this introduced an additional inhibition requirement: during the recurrent presentation of the congruent stimuli. This enables an alternative strategy to be put in place and it is proposed that following this opportunity the children will experience difficulty inhibiting this strategy and switching to a new strategy.

3(block position) x 3(ability level) ANOVAs were conducted on blocked interference scores for each condition in order to determine whether the position of this condition (i.e. first, second or third block) had a significant impact on interference scores. These revealed a significant main effect of ability level for the baseline, $F(2,53) = 7.54, p < 0.01$ (see Fig. 5.2.4.), congruent, $F(2,53) = 7.21, p < 0.01$ (see Fig. 5.2.5.) and incongruent, $F(2,53) = 8.25, p < 0.01$ conditions, reflecting

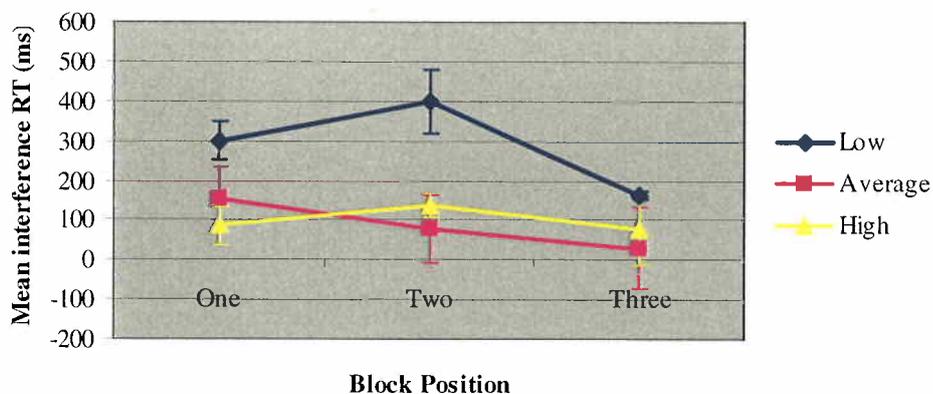
a general trend where the low-ability mathematicians experienced greater interference in comparison to the average- and high-ability children. The analyses also revealed a significant main effect of block position in the incongruent condition only, $F(2,53) = 3.41, p < 0.05$ (see Fig. 5.2.6.).

Fig. 5.2.4. Mean 'blocked' interference in relation to the baseline block position



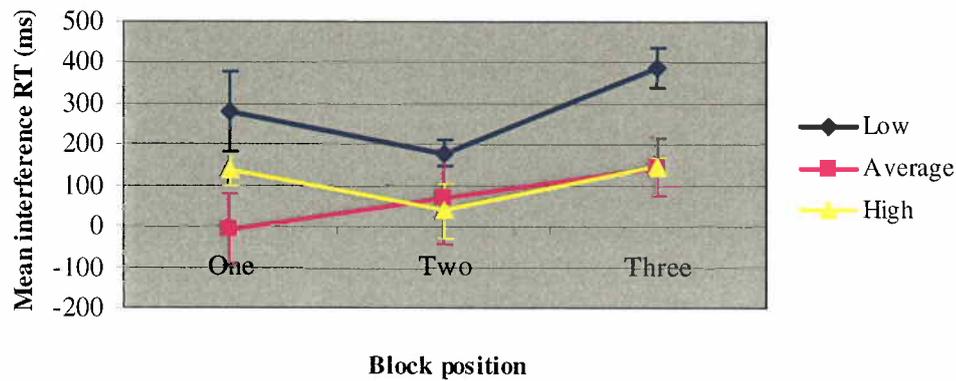
The low-ability children experienced greater interference than the average- and high-ability children when the baseline condition was presented in every position.

Fig. 5.2.5. Mean 'blocked' interference in relation to the congruent block position



Again, the low-ability children again experienced greater interference when the congruent block was presented in each of the three conditions.

Fig. 5.2.6. Mean 'blocked' interference in relation to the incongruent block position



Finally, in the incongruent condition the low-ability children experienced greater interference than the average- and high-ability children across block positions.

In addition, interference scores were significantly higher when the incongruent condition was in position three compared with both positions one ($t = 1.2.6, df = 41, p < 0.05$) and two ($t = 2.36, df = 44, p < 0.05$).

Interference scores were further examined in order to determine whether greater interference was experienced when the incongruent block followed the baseline or congruent block (see Table 5.2.5). However, no significant difference was found between these two alternative orders of presentation.

Table 5.2.5. Mean blocked interference scores (ms) in relation to the order of block presentation

Measure	Order of presentation	
	Congruent – Incongruent	Baseline - Incongruent
Mean Interference	180.28	176.24
SD	176.08	223.95
N	20	26

Table 5.2.5. suggests that switching from a congruent block to an incongruent block exerts similar demands on the executive system as switching from a baseline block to an incongruent block.

Facilitation scores

Analysis of the facilitation scores revealed no significant main effects or interaction effects.

Correlational analyses

Correlational analyses were conducted in order to discover whether there existed a significant relationship between performance on the screening measures and interference and/or facilitation scores.

Table 5.2.6. Correlation coefficients between the screening measures and interference and facilitation scores (above principal diagonal) and partial correlation coefficients controlling for reading ability and IQ (below principal diagonal).

	2.	3.	4.	5.	6.	7.
1. IQ	.63**	.68**	-.22	-.02	-.33	-.05
2. Reading ability		.64**	-.16	.08	-.24	-.06
3. Mathematical ability	—		-.24	-.02	-.4**	.07
4. Random Interference	—	-.12		-.24	.26*	-.22
5. Random Facilitation	—	-.06	-.24		-.01	.11
6. Blocked Interference	—	-.26*	.21	-.14		-.22
7. Blocked Facilitation	—	.17	-.24	.12	-.23	

Note: in all cases df = 62

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.5 level (2-tailed)

Correlational analyses revealed a significant relationship between mathematical ability and blocked interference ($r = -0.4$, $p < 0.01$) and a near significant correlation between mathematical ability and random interference ($r = -.24$, $p = 0.06$) indicating that as mathematical ability increased, interference scores decreased. Mathematical ability correlated highly with IQ ($r = 0.68$, $p < 0.01$) and reading ability ($r = 0.64$, $p < 0.01$), hence partial correlation coefficients were calculated controlling for IQ and reading ability. This removed the near significant relationship between mathematical ability and random interference, however the significant correlation

between mathematical ability and blocked interference remained ($r = -.26, p < 0.05$), suggesting that inhibition efficiency may be specifically related to mathematical ability.

If the increased interference scores of the low-ability children was the result of greater automatic activation of the physical size dimension then this should be evident in increased facilitation scores. However, there existed a negative relationship between interference and facilitation scores under both blocked ($r = -.2$) and random ($r = -.24$) presentation formats indicating that as interference scores increased, facilitation scores decreased. Correlation coefficients were also calculated for the low-ability children to ensure that this negative relationship existed for this subgroup alone. These also revealed that an increase in interference scores was indeed associated with a decrease in facilitation scores.

Error scores

A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed a significant main effect of condition only (see Table 5.2.7.).

Table 5.2.7. Mean error scores (& standard deviations) under blocked and random presentation formats

Condition	Presentation Format	
	Blocked	Random
Baseline	0.23 (0.49)	0.18 (0.43)
Congruent	0.1 (0.3)	0.11 (0.37)
Incongruent	0.58 (0.9)	0.74 (0.92)

Significantly more errors were made with the incongruent versus baseline stimuli under both blocked ($t = 2.75$, $df = 63$, $p < 0.01$) and random ($t = 4.68$, $df = 63$, $p < 0.01$) presentation format, indicating the presence of Stroop-like interference. There were no significant effects of ability level or presentation format on interference error scores.

Colour-picture results

Mean response time scores of each ability level for every condition under both blocked and random presentation format are displayed in Table 5.2.8.

Table 5.2.8. Mean RT scores and standard deviations (ms) for low-, average- and high-ability mathematicians

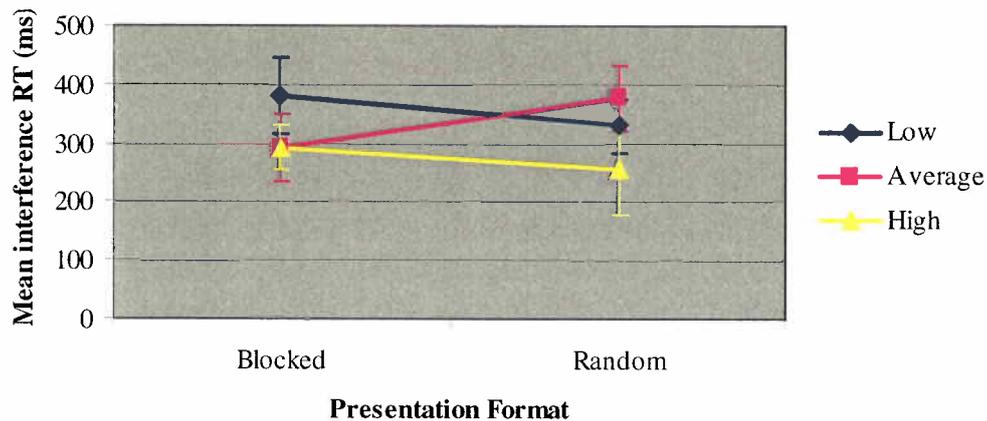
Ability	Measure	Random			Blocked		
		Baseline	Congruent	Incongruent	Baseline	Congruent	Incongruent
Low	Mean	1460.35	1401.64	1841.95	1492.85	1428.54	1822.48
	SD	320.29	245.77	416.04	360.96	413.12	497.52
Average	Mean	1355.82	1349.12	1647.56	1382.32	1477.39	1759.35
	SD	312.09	307.84	342.71	188.71	342.25	327.89
High	Mean	1383.09	1392.06	1675.79	1464.35	1431.29	1717.52
	SD	328.28	333.07	398.87	359.83	318.54	480.56
Overall	Mean	1401.47	1382.53	1724.4	1449.65	1444.11	1766.04
	SD	318.98	294.23	392.96	317.66	355.6	442.63

A 2(presentation) x 3(condition) x 3(ability) revealed significant main effects of condition $F(2,128) = 87.49, p < 0.01$. Once again Stroop-like interference was found: participants took longer to respond to the incongruent stimuli than the baseline stimuli under blocked ($t = 10.31, df = 66, p < 0.001$) and random ($t = 9.02, df = 66, p < 0.001$) presentation formats. There was no significant facilitation effect.

Interference scores

Every ability level experienced a substantial amount of interference however there was little difference between ability levels in terms of interference RT scores, indicating no relationship between mathematical ability and inhibition efficiency on this Stroop variant (see Fig, 5.2.7.).

Fig. 5.2.7. Mean interference RT under blocked & random presentation format.



In addition, the interference scores were highly similar under both blocked and random presentation formats revealing no significant impact of presentation format.

Error data

The error scores for each condition under blocked and random presentation formats are presented in Table 5.2.9. below:

Table 5.2.9. Mean error scores (& standard deviations) under blocked and random presentation formats

Condition	Measure	Presentation Format	
		Blocked	Random
Baseline	Mean	0.07	0.12
	SD	0.32	0.33
Congruent	Mean	0.09	0.03
	SD	0.42	0.17
Incongruent	Mean	0.43	0.09
	SD	0.8	0.42

A 2(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed a significant main effect of condition, $F(2,128) = 38.22, p < 0.01$ and a significant interaction between presentation format and condition, $F(2,128) = 4.74, p < 0.01$. As expected, significantly more errors were made with the incongruent stimuli than the baseline stimuli under blocked ($t = 3.46, df = 66, p < 0.01$) and random ($t = 6.17, df = 66, p < 0.01$) presentation formats supporting the proposal that the children experienced Stroop-like interference. Error scores were also highest in the incongruent condition under blocked presentation format.

Interference error scores were also calculated and again no significant main effects or interaction effects were found.

Correlational analyses

A correlational analysis was conducted to determine whether there existed a significant relationship between interference and facilitation scores and any of the screening measures (see Table 5.2.10.).

Table 5.2.10. Correlation coefficients between the screening measures and interference and facilitation RT scores

	2.	3.	4.	5.	6.	7.
1. IQ	.63**	.68**	-.26*	.02	.00	-.31*
2. Reading ability		.71**	-.24	-.12	-.17	-.23
3. Mathematical ability			-.07	-.02	-.09	-.09
4. Random Interference				-.51**	.3*	.16
5. Random Facilitation					-.02	.15
6. Blocked Interference						-.19
7. Blocked Facilitation						

Note: in all cases $df = 67$

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

These correlation coefficients revealed the anticipated highly significant positive relationships between each of the screening measures. A significant negative relationship was also found between IQ and interference scores under both blocked and random presentation formats, indicating that a decrease in interference scores was associated with an increase in IQ. A significant negative correlation was also found between interference and facilitation scores under random presentation format suggesting that any interference experienced was not due to more automatic activation of the irrelevant dimension as this would also have resulted in increased facilitation scores. Finally, a significant positive relationship between interference scores under blocked and random presentation format was found indicating that increased interference under one presentation format was associated with increased scores under the other.

Comparisons between the three variants

Correlational analyses were conducted in order to determine whether there was any significant relationship between the Stroop variants. These revealed no significant correlations between the interference or facilitation scores across these three Stroop task variants.

Comparisons of interference and facilitation scores across the three variants are shown in Table 5.2.11. below:

Table 5.2.11. Mean interference and facilitation RT scores for each Stroop variant

Stroop Variant	Measure	Random		Blocked	
		Interference	Facilitation	Interference	Facilitation
RSE	Mean	192.59	36.07	335.73	36.07
	SD	260.15	165.84	283	165.84
Highest-Number	Mean	80.26	99.06	165.01	81.25
	SD	150.97	166.17	198.34	210.76
Colour-picture	Mean	316.85	5.54	322.93	18.38
	SD	287.19	259.25	256.44	291.49

There was a significant impact of presentation format on interference scores in the RSE and Highest Number variants. This was not replicated in the Colour-Picture variant indicating that the children did not experience increased difficulty under blocked presentation format in this variant.

Under random presentation, interference scores in the colour-picture variant were significantly higher than those in the highest number ($t = 6.13$, $df = 58$, $p < 0.01$) and RSE ($t = 2.78$, $df = 62$, $p < 0.01$) variants. In addition, under blocked

presentation, interference scores were significantly lower in the Highest Number variant than the RSE ($t = 3.9$, $df = 58$, $p < 0.01$) and colour-picture ($t = 4.55$, $df = 58$, $p < 0.01$). Similarly, under random presentation format interference scores were lower in the Highest Number variant than the RSE ($t = 2.8$, $df = 58$, $p < 0.01$) and colour-picture ($t = 6.13$, $df = 58$, $p < 0.01$).

Facilitation scores were significantly higher in the Highest Number than the colour-picture variant under both blocked ($t = 2.36$, $df = 58$, $p < 0.05$) and random ($t = 2.37$, $df = 58$, $p < 0.05$) presentation formats.

DISCUSSION

The goals of studies 1 and 2 were: 1) to determine whether each of the six variants employed could successfully produce a Stroop-like interference effect; 2) to examine the hypothesis that low-ability mathematicians have a domain-specific problem with the inhibition of irrelevant numerical information; 3) to examine whether low-ability mathematicians possess less efficient inhibition mechanisms; and 4) examine the impact of presentation format. The results will be discussed in relation to these goals throughout the following discussion:

Stroop Interference

Each of the six variants of the Stroop task employed successfully reproduced the well-documented Stroop interference effect, indicating that they are all valid

measures of interference and that each of the incongruent dimensions place a strain on the central executive due to its inhibitory demands. The error scores in the Number-quantity, RSE, Highest Number and Colour-picture variants (i.e. numerical and verbal variants) also revealed significant Stroop-like interference. This indicates that, on occasion, the children were unable to successfully inhibit the irrelevant dimension in the incongruent condition.

Domain-specific problem?

Past research indicated that low-ability mathematicians displayed problems with executive functioning, in particular with inhibition (Bull, Johnston & Roy, 1999). Bull & Scerif (2001) also found evidence to support this, however they found that levels of interference were only related to mathematical ability on a numerical variant of the Stroop task. The present study aimed to provide further justification for this proposal that low-ability mathematicians may have a domain-specific problem with the inhibition of irrelevant numerical information (see Swanson, 1993) or a reduced domain specific working memory capacity (see Dark & Benbow, 1994) by examining their performance across a wider range of Stroop variants. Indeed, the achieved results provide further support to the proposal that low-ability mathematicians have a reduced capacity for the inhibition of numerical information as they demonstrated reduced inhibition efficiency in both of the numerical Stroop variants. There was no significant impact of ability level on interference scores in any of the four non-numerical Stroop variants. So, the more extensive range of tasks employed in the present study provides further validation of the hypothesised domain-specific difficulty experienced by low-ability mathematicians. Nevertheless, it is possible that these differences between the

numerical and non-numerical variants may be due to some other factor we have failed to consider here. Yet, despite this possibility, for the purposes of this thesis, the apparent inhibitory problem experienced by these low-ability mathematicians when dealing with numerical information is paramount. If this inhibitory deficit contributes to their poor performance in mathematics then we can use this knowledge to aid the development of teaching materials and strategies to help these children overcome these problems.

The impact of presentation format

A preliminary study by Bull *et al.* (2000) employed a numerical variant of the Stroop task. The results revealed that the low-ability children experienced greater interference under blocked presentation format. In each variant of Studies 1 and 2, the children were instructed to employ a specific strategy (e.g. state the quantity not the number; state the colour not the word). It was proposed that under blocked presentation format the children can evaluate the effectiveness of this strategy and that they have the opportunity to adopt a more appropriate strategy (see Shallice & Burgess, 1996). The results from both the numerical and verbal variants support the preliminary findings of Bull *et al.* (2000) that under blocked presentation the recurrent presentation of the congruent stimuli enables the establishment of a temporary schema and that this introduces an additional inhibition requirement. So, for example, in the Number-quantity variant, the repeated presentation of stimuli where the number presented and the quantity of the numerals matched (e.g. 333) may have encouraged the children to adopt the strategy of simply stating the number presented. Consequently, when presented with the incongruent block a switch in strategy would be required. Nevertheless, before accepting Bull *et al.*'s

(2001) reasoning behind the impact of presentation format on interference scores, a closer examination of the requirements of this presentation format and the strategies adopted by the children is required.

Thus, attempts were made here to gain a clearer picture of the source of this enhanced difficulty under blocked presentation format. The order of presentation of the three blocks was randomised across participants hence there were six possible orders of presentation. Consequently, Bull et al's proposal that blocked interference presents an additional inhibition requirement (i.e. due to the strategy switch requirement when switching from the congruent to incongruent conditions) is not entirely accurate for every participant, since some may begin with the incongruent condition and for others the incongruent condition follows the baseline condition. Clearly, an alternative and more encompassing explanation is required.

In an attempt to provide a more appropriate explanation, the data were analysed in order to ascertain whether greater interference was experienced when the incongruent block followed a congruent or baseline block. However, in those variants which revealed significant presentation effects (i.e. verbal and numerical variants), there was no difference in interference scores between those orders of presentation where the incongruent block followed the baseline block and where the incongruent block followed the congruent block. So, similar levels of interference are experienced when switching to an incongruent block from a baseline block and when switching from a congruent block. Consequently, a more plausible explanation is that the switching difficulty stems from switching between blocks which can be differentiated in terms of their inhibition requirements and as such, the

consequent demands they exert upon the executive system. For example, in both the baseline and congruent conditions, there was no need to inhibit an irrelevant dimension and the repeated presentation of these 'easy' stimuli may have enhanced performance. In the incongruent condition, however, inhibitory demands are introduced and subsequently the difficulty level rises. It is proposed that when switching from the 'easy' blocks (i.e. baseline and congruent) to the 'difficult', and more demanding, incongruent block the children experience difficulty due to the switch in strategy required. This 'switch' consists of employing a more appropriate strategy with no inhibitory components (i.e. baseline, congruent) to adopting a strategy clearly requiring inhibitory mechanisms (i.e. incongruent). As a result of the repeated presentation of the non-conflict baseline or congruent stimuli, the children are not prepared for this switch and subsequently they must generate a more appropriate strategy including an inhibitory feature to cope with the 'conflict' stimuli. Thus, as proposed by Bull *et al.* (2000), the introduction of switching demands places greater strain on the executive system. The difficulty experienced by the low-ability children under blocked presentation format suggests that they have fewer resources available to cope with these increased demands. As a result, the irrelevant dimension in the incongruent condition gains greater access to working memory and is thus able to interfere more with the processing of the relevant dimension.

Under random presentation format there was no opportunity to establish a strategy with no inhibition component, hence the children had to adopt a continual strategy which included an inhibitory component. As a result, the children were always, in a

sense, prepared for the incongruent stimuli and consequently, there was less opportunity for the conflict dimension to interfere.

Interference scores were also examined in relation to the position of each block in the order of presentation (i.e. position one, two, or three). These analyses revealed that the position of the baseline and congruent blocks had no significant impact on interference scores in the verbal and numerical variants. However, interference scores were found to be significantly higher when the incongruent block came third in terms of order of presentation⁴. This supports the above proposal that the children experience difficulty switching from the 'easy' conditions (i.e. no inhibition) to the 'difficult' conditions (i.e. inhibition required). So, after completing a substantial amount (i.e. two blocks) of easy tasks, increased interference is experienced when a switch has to be made from conditions requiring no inhibition to those requiring a high level of inhibition.

It must be noted that the above analyses regarding presentation order under blocked presentation format were exploratory in nature and future studies should fully explore the impact of the six different presentation formats in order to gain a clearer understanding of the inhibition and switching requirements of each presentation order. In addition, no significant interaction between ability level and presentation order was revealed here. This may be related to the distribution of the orders of presentation which was completely randomised across ability groups, which resulted in uneven and in some cases comparatively small subgroups. Clearly,

⁴ This effect failed to achieve significance in the RSE variant. However, the pattern of results did follow this pattern of increased interference when the incongruent block was presented last.

further research is required to validate these proposals and to further examine specifically which, if any, order of presentation exacerbates the interference levels⁵.

Nevertheless, the data clearly suggests that greater interference is experienced under blocked presentation format and that when the incongruent condition is presented *after* the baseline and congruent conditions, interference scores increase.

Consequently, support is provided for Bull et al's (2000) proposal that low-ability mathematicians experience greater difficulty switching between strategies.

However, the precise nature of this proposed strategy switch differs. Nonetheless, the available data here offers more support to the proposal that difficulty is experienced switching between schemas which do not require inhibition to those which do require an inhibitory component.

Discussion of the verbal, numerical & pictorial variants

The results of the verbal (i.e. colour-word, reverse Stroop effect), numerical (i.e. number-quantity, highest number) and pictorial (i.e. global-local shape, colour-picture) variants in relation to the main goals of these two studies stated at the beginning of this section are discussed below:

Verbal Variants

A similar pattern of results was achieved in both of the verbal variants. Greater interference was experienced under blocked compared with random presentation format in both the colour-word and RSE variants. Hence, in line with the

⁵ It was not practical to fully explore these proposals in the present study as dividing the sample as a function of presentation order resulted in small subgroups. In addition, only the low-ability participants were affected by the blocked presentation format, hence statistical analyses were not practical due to the extremely small number of low-ability participants receiving each presentation order.

suggestions of Bull and colleagues (Bull & Scerif, 2001; Bull *et al.*, 2000), and the proposals outlined above, the switching requirements introduced under blocked presentation format increases the degree of interference experienced.

There was no significant main effect of mathematical ability level or any interaction found between presentation format and ability level indicating that each ability level was performing in a similar fashion in these variants. Thus, the low-ability mathematicians did not experience a particular difficulty inhibiting the irrelevant dimension in these verbal variants providing further support to the proposed domain-specific problem with the inhibition of numerical information. However, mathematical ability was highly correlated with reading ability and this may have affected the levels of interference experienced. For instance, theoretical models of the Stroop phenomenon typically assert that interference is experienced due to more automatic/stronger processing of the word reading dimension compared with the slower and less automatic processing of naming of colours. Hence, for the poor readers (who also tended to be low-ability mathematicians) it is possible that any potential interference effects are *reduced* due to their less well established reading skills (i.e. less automatic).

The introduction of the RSE variant attempted to control for this factor by exploring whether conflicting ink colours could interfere with word reading. It was anticipated that interference scores would be higher for the poor readers (and hence, the low-ability mathematicians)⁶ on account of their less automatic reading

⁶ Mathematical ability and reading ability were highly significantly correlated in Studies 1 and 2.

processes which, it was proposed, would enable greater interference from the irrelevant dimension. However, no significant relationship between reading ability or mathematical ability and interference scores was revealed suggesting that the level of interference experienced was not directly associated with reading or mathematical ability.

A RSE was successfully reproduced with this group of children without any serious manipulations of the experimental design or extensive practice which previous studies have found necessary when dealing with adults (e.g. Gumenik and Glass, 1970; Dyer and Severance, 1972). This successful reproduction of the RSE may be easier with children as word reading is a less automatic process for them than adults and as a consequence there is greater opportunity for the conflicting ink colour to interfere with word reading.

Pritchatt (1968) also found that keys labelled with colour patches were more likely to produce interference. In the present variant the keys were actually labelled with the colour word, indicating that interference can also be produced with this labelling method. Of course, future studies would need to investigate the effect of different labelling on the interference levels experienced by children.

Numerical variants

In both of the numerical Stroop variants, the low-ability mathematicians experienced greater interference than the high-ability mathematicians under blocked presentation format. However, there was no significant effect of ability level under random presentation. These results mirror those of Bull *et al.* (2000) and support

their proposal that the increased inhibition demands of blocked presentation format place increased strain on the executive system. The interaction between presentation format and ability level only approached significance in the Number-quantity variant and after controlling for IQ and reading ability this effect diminished further, suggesting that this interaction is not specifically related to mathematical ability. On the other hand, in the Highest Number variant, the significant interaction between presentation format and mathematical ability remained after controlling for IQ and reading ability suggesting that the ability to inhibit strategies for dealing with a task may be a specific element of mathematical ability rather than simply a facet of general intelligence. Thus, the development of the executive function inhibition may play a specific role in the development of mathematical ability.

The increased interference scores of the low-ability children in these variants may be due to reduced attentional focus towards the relevant dimension or to differences in counting speed (Pansky & Algom, 1999). However, this has been controlled for to some extent by taking the performance in the baseline condition into account in order to calculate the interference and facilitation scores. An alternative explanation is that greater interference is linked with more automatic activation of the irrelevant element. However, the negative correlations between interference and facilitation scores ruled out the possibility that the increased interference scores of the low-ability mathematicians was due to greater automatic activation of the irrelevant dimension as this would have facilitated performance in the congruent condition and hence increased facilitation scores. A remaining feasible explanation is that poorer inhibition of the irrelevant information enables this information to gain

greater access to working memory, for the low-ability mathematicians. Hasher and Zacks (1988) proposed that such a breakdown of inhibitory mechanisms also allows this information to remain active in working memory for a longer period of time, hence exerting a more detrimental impact on working memory. This supports earlier research which showed that less-skilled readers experienced no difficulty activating relevant information yet they do experience problems when required to suppress the activation of irrelevant information (De Beni, Palladino, Pazzaglia, & Cornoldi, 1998).

This interpretation may be sufficient for the numerical variants however it does not explain why the low-ability mathematicians did not experience greater interference in the non-numerical variants. A remaining viable explanation is that low-ability mathematicians may have a domain-specific problem inhibiting irrelevant numerical information (see Swanson, 1993). The adoption of more varied stimuli in the present study also strengthens this proposal.

The correlational analyses also revealed a significant interaction between mathematical ability and 'blocked interference' (i.e. interference scores under blocked presentation format) in the Highest Number variant. This correlation held even after controlling for reading ability and IQ suggesting that inhibition efficiency may be specifically related to mathematical ability. There was no significant correlation between mathematical ability and blocked interference in the Number-quantity variant. This may be attributed to the similar level of performance of the low- and average-ability children, whereas in the Highest Number variant the performance of the average-ability children was more comparable to the high-ability

children. The significant correlation between mathematical ability and blocked interference failed to hold after controlling for reading ability and IQ in Bull *et al.*'s (2000) study, hence the present results alone provide support for the proposal that inhibition efficiency may be specifically related to mathematical ability.

So, the results of the numerical variants support Bull *et al.*'s finding that low-ability mathematicians display less efficient inhibition mechanisms when both inhibition and switching demands are present. The present results also suggest that a specific relationship may exist between mathematical ability and inhibition efficiency.

However, at present it is impossible to ascertain whether the enhanced interference scores of the low-ability children under blocked presentation format derive from the additional switching demands alone or the combined switching and inhibition demands.

Pictorial Variants

Stroop interference was also found in the global-local shape and colour-picture variants, however, there was no significant effect of presentation format or ability level. The interference levels experienced in these variants were comparable to those in the numerical and verbal variants and in the Colour-picture variant significantly more interference was experienced under random presentation format than in the Highest Number and RSE variants. This increase in interference perhaps reflects the fact that the required response in this variant must be extracted from memory, hence perhaps providing the irrelevant dimension with greater opportunity to interfere with processing. Nevertheless, there was no significant impact of presentation format on interference scores. This suggests that the anticipated

switching demands introduced here placed no additional demands on the executive system.

Error scores

Participants, had to achieve 80% accuracy in order to be included in the analysis, hence error scores were low overall. Nonetheless, the errors in the Number-quantity, RSE, Highest Number and Colour-picture variants supported the presence of Stroop-like interference effects revealed in the RT scores. The lack of any interference in the error score data in the colour-word and Global-local shape variant may be attributed to the particularly low error scores in these variants.

Facilitation scores

Across each of the six Stroop variants there was no significant impact of ability level on facilitation scores.

Comparisons between the Stroop variants

In both Studies 1 and 2 there was no significant relationship between the interference scores of the Stroop variants. Thus, increased interference scores in one variant did not correspond with increased interference in another. This further supports the hypothesised domain-specific problem with the inhibition of numerical information, as increased interference scores in the numerical variants was not associated with increased interference scores in the verbal and pictorial variants. Hence, this suggests that the increased interference experienced by the low-ability children in the numerical variants cannot be attributed to a global inhibition deficit.

In addition, the interference scores of the verbal and pictorial variants were similar to or indeed higher than the interference scores of the numerical variants. This suggests that the verbal and pictorial variants placed sufficient demands on the executive system and consequently, the lack of any main effects of ability level cannot be attributed to a failure to place sufficient strain on the executive system.

Relation to theoretical models of the Stroop phenomenon

Some of the main theories surrounding the Stroop phenomenon were discussed in Chapter 1. The results obtained from these variants of the Stroop task provide further evidence against the speed of processing theories for Stroop phenomenon as following this theory there should be no RSE. The speed of processing model explained the levels of interference found in the colour-word variant by declaring that as word reading is a faster process than colour naming the irrelevant colour-word arrives at the response buffer first and hence interferes with the colour-naming process. The children in every ability level showed significant RSE, indicating that the speed of processing model should be rejected. The automaticity theories also fail to sufficiently explain these results, as they do not assign enough credit to the role of learning and attention. The presentation effects which were evident in the verbal and numerical variants suggest that learning, attention and indeed practice has some role to play. Thus, at present the parallel-distributed processing model appears to be the best available explanation for Stroop interference as this model accounts takes account of practice effects.

Concluding points

Each of these variants appear to be valid measures of Stroop-like interference and the results support the proposal that low-ability mathematicians may have a domain-specific problem with the inhibition of numerical information. Of course, as noted above, further exploration employing a wider range of stimuli is required before this statement can be justified. Support was also provided for the hypothesised increased strain a blocked presentation format places on the executive system in comparison to a random presentation format⁷. This suggests that when switching demands are introduced the strain placed on the executive system increases, hence, leaving fewer resources available to inhibit the irrelevant information. Finally, and most importantly for the purpose of this thesis, further support was provided to the research suggesting that low-ability mathematicians possess less efficient inhibition mechanisms and that the development of inhibition mechanisms may play a specific role in the development of mathematical skills. In the numerical variants the poorer performance of the low-ability mathematicians under blocked presentation format suggests that they experience a particular difficulty when a strategy switching requirement is introduced. It is proposed, however, that this switching stems from switching between schemas requiring no inhibitory component and those which do require inhibition. However, from the results of the present study it is impossible to determine whether the increased interference scores are due to the combined inhibition and switching requirements of blocked presentation format or due to the switching requirements alone.

⁷ Support was only provided for this goal from the verbal and numerical variants. There was no main effect of presentation format revealed in either of the pictorial variants.

In the present study the switching demands were hypothetical and reliant on participants developing a continual strategy during random presentation format and employing more appropriate strategies where possible during blocked presentation format. In the following study (Study 3), clear switching requirements are introduced as the children are required to switch between arithmetical operations. They have all received extensive practice with addition and subtraction hence they will possess established strategies for dealing with these operations, consequently when switching between these arithmetical operations they will have to inhibit one strategy in favour of another.

Chapter 6

Study 3: An arithmetic Stroop variant

Overview

The following series of experiments were based on the premise that given the specific inhibitory deficit, exhibited in the numerical Stroop variants generalises to all cognitive tasks requiring the inhibition of numerical information, it should be possible to replicate these findings in a more naturalistic task, such as mental arithmetic. Hence, the aim was to examine whether low-ability mathematicians exhibit an inhibitory deficit when they are *actually* dealing with mathematics. If the results suggest otherwise, then the proposal that children's difficulty with mathematics is related to an inhibitory deficit will be thrown into question. However, if the results mirror those of the numerical Stroop task variants, then this will suggest that the results from these relatively artificial tasks can be generalised to a more natural skill, with direct applicability and obvious educational significance.

At present there is no agreed list of executive functions (EFs), however inhibition and switching are two of the most commonly proposed EFs (Miyake *et al.*, 2000) and these are explored throughout this entire body of work. These component processes of EF were chosen following the findings of earlier research (i.e. Bull & Scerif, 2001, Bull *et al.*, 2000) and the successful replication of these results in Studies 1 & 2, suggesting that low-ability mathematicians possess less efficient inhibition mechanisms. Research exploring EF typically employs a number of common executive tasks (e.g. Stroop, Continuous Performance Test, Tower of Hanoi). However, how applicable are these findings to more naturalistic tasks which also tap executive resources? It is proposed that examining the impact of manipulating 'executive' demands, whilst performing mental arithmetic will

provide a more valid assessment of the relationship between EF performance and arithmetical ability as the cognitive demands of arithmetic are considered. Thus, one of the main aims of this research is to provide a more naturalistic and appropriate exploration of the relationship between mathematical ability and the executive functions *inhibition* and *switching*.

INTRODUCTION

Zbrodoff & Logan (1986) employed an arithmetic variant of the Stroop task to determine the degree to which the processes underlying simple mental arithmetic are autonomous¹. If simple arithmetic processing is at least partially autonomous then participants should take longer to respond to *associative lures*, which are equations which would be true if an alternative operation is employed (e.g. $4 + 3 = 1$; $4 - 3 = 7$), than *nonassociative lures*, which are equations which would remain false regardless of the operation employed (e.g. $3 + 4 = 9$). The associative lures should ‘confuse’ participants by encouraging them to provide an incorrect ‘true’ response. No such tendencies should be initiated with the nonassociative lures, hence participants should respond more quickly to these equations.

¹ Stroop tasks cannot determine whether processes are completely autonomous as it is possible that an unintentional process is *evoked to the same extent or with equal strength* but the output is inhibited or suppressed intentionally, which in turn weakens the associative confusion effect or interference (cf. Logan, 1980; Seidenberg, Waters, Sanders & Langer, 1984). Zbrodoff & Logan (1986) also employed a stop signal task to determine whether mental arithmetic processes are partially autonomous or completely autonomous. They concluded that simple arithmetic processes can begin unintentionally; however, they can be inhibited once they have begun and thus require intention in order for processing to be completed. So, simple arithmetic processes appear to be partially autonomous.

Winkelman and Schmidt (1974) were the first to report such an *associative confusion effect*² in a group of well-practised subjects. This effect was calculated by subtracting the response time to the *nonassociative lures*, from the response time to the *associative lures*. It was proposed that the associative lures produced ‘interference’ as they evoked a tendency to say the equation was true, which in turn increased response time. Further studies also found an associative confusion effect in grade school children between addition and multiplication (Zbrodoff, 1979, cited in Zbrodoff & Logan, 1986) and between addition and subtraction (Findlay, 1978)³.

Mental arithmetic was employed by Zbrodoff and Logan (1986) not only because it is a well-practised and everyday activity, but also because a number of contradictory theories regarding the underlying mental processes for mental arithmetic have been proposed. For example, Thorndike (1922) asserted that simple arithmetic is atomic in the sense that the answer is retrieved directly from memory (see also, Winkelman & Schmidt, 1974). Others have proposed that simple arithmetic operations are non-atomic since they can be split up into simpler steps such as counting (Groen & Parkman, 1972; Parkman & Groen, 1971), or because since a sequential memory search is employed (Ashcraft & Battaglia, 1978; Ashcraft & Stazyk, 1981). It is more likely that atomic processes will be autonomous than nonatomic processes, which seem to require more intentional processing.

² In the Stroop literature, associative confusion effects are typically called *interference effects*. The terminology employed here is simply to remain consistent with that introduced by Winkelman & Schmidt (1974), Zbrodoff & Logan (1986) and subsequent related researchers.

³ However, it must be noted that the associative confusion effect reported by Findlay (1978) was calculated from error scores rather than response time scores. This measurement may have exaggerated the associative confusion effect as it is possible that the errors made with the associative lures were common ‘operation confusion’ errors. Operation confusion errors may also have been made with the nonassociative lures, however, this would have resulted in a correct response of ‘false’ (see pp. 169-170 for further discussion).

So, Zbrodoff and Logan (1986) aimed to replicate the associative confusion effect. Furthermore, in order to determine whether arithmetic processing is completely or only partially autonomous, they manipulated participants' intentions to process the irrelevant arithmetic operation. This manipulation was achieved by presenting the equations in unmixed and mixed presentation formats. In the unmixed presentation format, a single arithmetic operation was relevant for the entire testing block, thus participants should never intend to employ the irrelevant operation. In the mixed presentation format, two arithmetical operations were relevant to intentions.

Their results revealed that an arithmetic variant of the Stroop task could produce a Stroop-like associative confusion effect. They also indicated that arithmetic processes are *partially* autonomous, since the associative confusion effect was greater in the mixed presentation format than the unmixed presentation format, which suggests that arithmetic processes can be suppressed when they are less relevant to intentions. They proposed that, like the continuum of automaticity, autonomy should also be seen as a continuous dimension rather than as a dichotomy. Thus, in relation to arithmetic processes, their results suggest that it is likely that there are direct associations between pairs of single digits and their sums. But, any unintentional activation is not strong enough for mental arithmetic and hence, requires deliberate activation in order to function accurately. On the other hand, it is also possible that the direct associations are supplemented by counting or memory search strategies in order to reach the required level of accuracy (Zbrodoff & Logan, 1986).

The present study

The present study employs a similar methodology to Zbrodoff and Logan (1986). The children are asked to verify a series of individually presented simple arithmetical equations of the form $a + b = c$ and $a - b = c$. Half of the equations are true (e.g. $5 + 4 = 9$) and the other half are false. Half of these false equations are labelled *false-confusing*⁴ as they could be true if the participant employs another arithmetic operation other than the one which is presented (e.g. $5 + 4 = 1$; $5 - 4 = 9$). The remaining false equations are labelled *false-neutral*⁵ equations, which could not be true using any alternative standard arithmetical operation (e.g. $5 + 4 = 7$).

Participants will complete three presentation formats. The unmixed and mixed presentation formats used by Zbrodoff & Logan (1986) are employed here and an additional *mixed blocked* (i.e. 8 addition, 8 subtraction, 8 addition, 8 subtraction) presentation format is included. Again, in the unmixed presentation format, only one operation is relevant to intentions. Hence, providing arithmetic processing is only *partially autonomous*, the irrelevant operations should be easily suppressed. However, in the mixed presentation formats, both operations are relevant to intentions, thus increasing the potential for ‘confusion’.

So, this study aims to replicate the Stroop-like associative confusion effect in primary school children and examine the impact of manipulating the children’s intentions to employ an irrelevant arithmetical operation. However, in order to

⁴ The term *false-confusing* replaced *associative lures*.

⁵ *False-neutral* was employed rather than *non-associative lures*.

experience associative confusion, the children's arithmetic processing will have to possess some degree of autonomy. From earlier observations of the children (during administration of the WOND and the time spent in class) it was clear that they were employing a mix of strategies, with many continuing to rely on overt counting strategies (i.e. finger counting). Thus, it seems that for this age group arithmetic processing is definitely only partially autonomous. Thus, replication of the associative confusion effect and the level of confusion experienced will be dependent upon the degree of automatisisation of these basic arithmetical facts.

Nevertheless, even if this experiment fails to replicate the Stroop-like associative confusion effect, a number of other important experimental aims will be explored. For instance, if the children's arithmetic processing does not contain a sufficient degree of autonomy, there may be a greater need for the development of temporary schemas (i.e. counting strategies), thus the switching requirements of the mixed presentation format may have a detrimental impact on performance. Bull and Scerif (2001) suggested that *"...once children are able to retrieve well-practiced strategies or arithmetic facts directly from long-term memory, there may be less need for the establishment of temporary new schemas, and so executive processing may not play such an important role once a skill becomes more automatic."* (p. 289). Thus, in regards to exploring the impact of presentation format on performance, this lack of automatisisation may be beneficial as the children may experience greater difficulty switching between the required counting strategies. Hence, it is predicted that the children will experience greater difficulty verifying equations in the mixed presentation format compared with the unmixed presentation format, due to the anticipated difficulty of switching between two arithmetical

processes which are both highly relevant to intentions. In addition, it is expected that the low-ability mathematicians will experience greater disturbance in the mixed formats than their peers. This is predicted due to previous findings suggesting that low-ability mathematicians possess less efficient inhibition mechanisms. Hence, it is likely that they will experience greater difficulty switching between arithmetical operations (i.e. inhibiting one strategy in favour of another).

Two mixed presentation formats are included in the present study: blocked and random. The numerical Stroop variants included in Studies 1 and 2 revealed that greater *interference* was experienced under blocked presentation format compared with random. It was proposed that under blocked presentation format, difficulty is experienced when switching between those conditions requiring no inhibition (i.e. baseline and congruent) to those conditions which do require inhibition (i.e. incongruent). In the present study, the switching requirement consists of switching between the arithmetical operations of addition and subtraction. The children already possess relatively well-established strategies for dealing with addition and subtraction. Thus, both blocked and random mixed presentation formats require switching between these calculation strategies. Random presentation format requires greater switching between operations than blocked presentation, thus it is proposed that the children may experience greater difficulty in the mixed random presentation format than in the mixed blocked presentation format.

The purpose of this experiment was to explore whether low-ability mathematicians also experience difficulty inhibiting irrelevant information and/or switching between strategies when dealing with arithmetic. If the results of the present

experiments reveal that the presence of irrelevant information and/or increased switching requirements has a negative impact on arithmetic performance then these factors can be taken into consideration when designing teaching materials. For example, reducing the amount of irrelevant information and/or the amount of switching between tasks/strategies required may improve performance. Basically, the goal of the present experiments was to examine whether the findings of the numerical Stroop variants are directly applicable to children's experiences and difficulties when performing arithmetic.

Also, this arithmetic variant of the Stroop task may prove a useful complement to existing tasks for assessing inhibition (e.g. Stroop, Stop/Go task) and, subject to satisfactory evidence regarding its reliability it may also provide a more accurate indication of inhibition efficiency in relation to children's performance in mathematics. In addition, these tasks are attractive resources for educational establishments as they may serve as useful early indicators of potential difficulties in the development of mathematical skills and they are quick and easy to administer.

METHOD

Participants

86 children participated in this study. 12 children were removed from the analysis due to poor performance levels, thus the final sample contained 74 children. The mean age of the children was 8 years 7 months (SD = 9.57 months, range 7;01 to 10;00). The sample consisted of 42 girls and 32 boys.

The children were split into 3 mathematical ability groups according to their performance on a standardised mathematics test (see Chapter 4, pp. 59-60). This resulted in 22 low-ability, 25 average-ability and 27 high-ability. Table 6.1. contains the performance characteristics of each ability level.

Table 6.1. Mean standardised scores (& standard deviations) for each screening tests for low, average and high ability participants

Ability	Screening Measures		
	Mathematics ability	IQ	Reading ability
Low (N = 22)	85.59 (7.5)	88.41 (9.9)	87.45 (10.37)
Average (N = 25)	100.16(2.93)	98.68 (10.71)	99.6 (10.53)
High (N = 27)	113.67 (6.56)	103.19 (10.23)	106.44 (12.13)

Materials

The stimuli were presented in black font (Times New Roman point size = 36) on a white background in the centre of a laptop computer screen. The computer program E-Prime (version 1.0) was again used to present the stimuli. The stimuli were equations of the form $a*b = c$ where a and b are single digits ranging from 2 to 9 and $*$ is either + or -. All possible pairs of digits from 2 through 9 were used, however, only those equations containing a smaller addend or subtrahend were used (e.g. $4 * 3$ was employed, but $3*4$ was not, so as to avoid negative numbers for subtraction problems). All ties were also removed (e.g. $2*2$). This resulted in 36 combinations of numerals. 36 true equations were formed where c is the correct answer of the equation $a*b$, 36 false-confusing equations were constructed where c is the correct answer for equation $a*b$ when an action other than the one presented is

taken (e.g. $4 + 3 = 1$, where 1 would be the correct answer for $4 - 3$) and 36 false-neutral equations were formed where c could not be correct for $a*b$ using any conventional arithmetic procedure.

Consideration of the counting procedures employed by children was also taken when assigning the equations to subgroups (i.e. true, false-neutral and false-confusing). For example, two common strategies employed by children and documented in numerous research studies are: 1) the *counting all* strategy: where each set is counted separately starting from one. For example for $3 + 2$: 1, 2, 3...1, 2, before counting 1, 2, 3, 4, 5 altogether; 2) the *counting on* strategy – counting starts from the first number irrespective of its size. For example $2 + 4$: 2...3, 4, 5, 6 (from Aubrey, 1999, p. 60). Obviously when adopting these counting procedures RT scores would increase in relation to the magnitude of the equations. For example, it would take longer to respond to $5 + 4$ than $2 + 1$. So, care was taken to ensure that the magnitude of the equations was distributed fairly amongst the conditions (i.e. true, false-confusing and false-neutral).

The c terms of the equations in the true and false-confusing conditions were set according to the numerals and operator symbol involved. However, for the false-neutral equations (e.g. $5 + 2 = 10$), the value of c had to be constructed. Thus, consideration was also taken of Ashcraft & Battaglia's (1978) finding that response times to *reasonably* incorrect (± 1 or 2) equations were significantly slower than response times to *unreasonably* incorrect (± 4 or 5) equations, whilst constructing these c values (see also Moyer & Landauer, 1967; Restle, 1970). So, in order to overcome this potential confounding variable, the c terms of the false-neutral

equations were chosen to match the difference between the right and left-hand sides of the false-confusing equations. For example, for the equation $4 + 3 = 1$, the difference between the left and right-hand sides was six. Thus, within each presentation format the mean difference between the two sides of the equation in the false-neutral condition was equal to the mean difference between these sides in the false-confusing condition. The mean difference for each trial was approximately 6 and the difference ranged from ± 2 to ± 16 .

Procedure

The children initially completed a practice session of 12 trials, which enabled them to become familiar with the testing format. 80% accuracy was required in the practice session before the children could proceed to the ‘test’ trials. If they failed to achieve 80% accuracy on a second attempt, testing was terminated.

The testing phase consisted of 108 trials, divided into three test presentation formats (i.e. mixed blocked, mixed random and unmixed) each containing 36 equations. The stimuli were presented within 3 blocks: *unmixed*, *mixed random* and *mixed blocked*. Each presentation format contained 18 true equations, 9 false-neutral equations (e.g. $4 + 3 = 9$) and 9 false-confusing equations ($4 + 3 = 1$). The *unmixed* block contained 36 subtraction **or** addition problems only, the *mixed random* block contained a random mix of 18 addition and 18 subtraction and the *mixed blocked* block also contained 18 addition and 18 subtraction equations presented in blocks of, for example, 9 +, 9 -, 9 +, and 9 -.

Within each presentation format, the order of stimuli was randomised and the order of presentation itself (i.e. unmixed, random and blocked) was randomised across participants. In the unmixed presentation format, half of the children were required to use addition and the other half employed subtraction.

Instructions were given at the start of each new presentation format. For the unmixed presentation format, half of the children were told that they would see addition problems only and the other half were told that they would see subtraction problems only. For the mixed presentation format they were told they would see both addition **and** subtraction problems. They were asked to respond as quickly as possible, but to avoid sacrificing accuracy for speed. They were encouraged to pretend that they were the 'teacher' and that they had to mark some addition and subtraction problems by giving them a 'tick' if correct or a 'cross' if incorrect. The children responded by pressing one of two computer keys marked with the familiar tick (✓) and cross (×) symbols denoting correct and incorrect respectively. Half of the children pressed a key on the right hand side of the computer keyboard to indicate that the equation was true and a key on the left hand side to indicate it was false. This order was reversed for the other half of the group.

Analysis

The computer program calculated mean RT scores for each condition under each presentation format. These RT scores are initially examined in order to assess whether this arithmetic variant of the Stroop task has been successful in replicating Stroop-like interference. In order to examine any differences between ability levels,

it was necessary to calculate a within-participant interference score. Interference scores were calculated using the following equation:

$$\text{INTERFERENCE RT / ERROR} = \text{FALSE-CONFUSING} - \text{FALSE-NEUTRAL}$$

Error scores were also recorded for each condition in each presentation format. From these, it was necessary to calculate proportional error scores to enable valid comparisons between conditions as there were 18 stimuli presentations in the true condition compared with only 9 in both the false-confusing and false-neutral conditions. Consequently, there was twice the opportunity to make an error in the true condition.

The impact of intending to perform more than one operation in comparison to intending to perform only one operation on performance was also examined by calculating a ‘presentation effect’ score:

$$\text{PRESENTATION EFFECT} = \text{MIXED RT} - \text{UNMIXED RT}^6$$

These scores were also calculated for both the mixed blocked and mixed random presentation formats.

⁶ Mean RT/error scores for each presentation format were initially calculated (i.e. (false-confusing RT + false-neutral RT + true RT) / 3)

RESULTS

Mean response times (RT) and interference scores for each presentation format are displayed in Table 6.2. RT scores were highly comparable across conditions and surprisingly they were actually generally lower in the false-confusing condition.

Hence, the associative confusion effect (Zbrodoff & Logan, 1986) was not replicated as indicated by the negative interference effect scores.

Table 6.2. Mean RT scores for each condition across the three presentation formats

Condition	Measure	Presentation Format		
		Mixed Blocked	Mixed Random	Unmixed
False-confusing	RT	4510.99	4422.95	4033.67
	SD	1979.96	1788.36	1508.79
False-neutral	RT	4572.4	4539.19	4176.00
	SD	1897.33	1865.84	1802.11
True	RT	4507.96	4546.64	4147.2
	SD	2014.47	1815.11	1740.51
Interference	RT	-61.41	-116.25	-142.33
	SD	1029.41	1092.94	1074.07
Total	RT	4530.45	4502.93	4118.95
	SD	1871.96	1718.64	1588.89

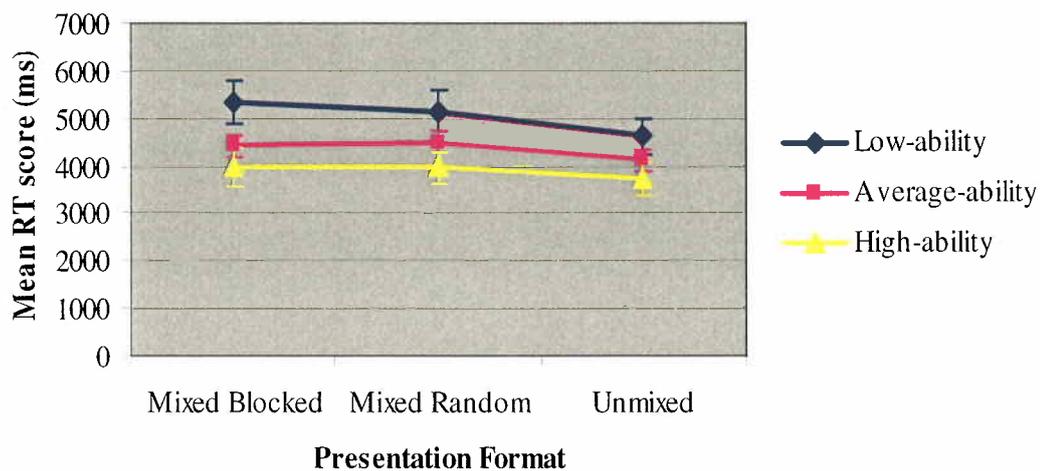
A 3 (presentation format) x 3 (condition) x 3 (ability) repeated measures ANOVA on mean RT scores revealed a significant main effect of presentation format ($F(2,142)^7 = 14.117, p < 0.01$). Intending to perform only one operation (i.e. unmixed) reduced the mean RT for every condition. There was no main effect of

⁷ Sphericity assumptions were violated, the Greenhouse-Geisser corrected values were $F(1.7, 120.66) = 14.15$.

condition or any significant interaction effects, however there was a near significant main effect of ability level, $F(1,71) = 2.93$, $p < 0.06$ reflecting the predicted trend of RT scores decreasing with increasing mathematical proficiency⁸. Figure 6.1.

displays the mean RT scores for each presentation format across ability levels.

Fig. 6.1. Mean RT scores under mixed blocked, mixed random & unmixed presentation formats



RT scores were higher in the mixed blocked and mixed random presentation formats than the unmixed format, indicating that intending to perform more than one operation had a detrimental impact on performance. Planned comparisons confirmed the expectation that the unmixed presentation format would be easier than both the mixed blocked ($t = 5.04$, $df = 73$, $p < 0.01$) and the mixed random ($t = 4.97$, $df = 73$, $p < 0.01$) presentation formats. Figure 6.1. shows that RT scores declined with increasing mathematical proficiency and independent t-tests revealed a significant difference in RT scores between low- and high-ability children in the

⁸ This result is believed to derive from the increasing automatization of counting strategies with increasing proficiency.

mixed blocked ($t = 2.26$, $df = 47$, $p < 0.05$) and mixed random ($t = 2.21$, $df = 47$, $p < 0.05$) conditions.

In the unmixed condition, 39 children were presented with addition equations, whilst the remaining 35 were presented with only subtraction equations. In order to ensure that the lower RT scores in the unmixed conditions was not due to the children finding one of these operations significantly easier than the other a 3(condition) x 2(operation) mixed design ANOVA was conducted on the RT scores in the unmixed condition. This revealed no significant main effect of operation type.

Interference scores

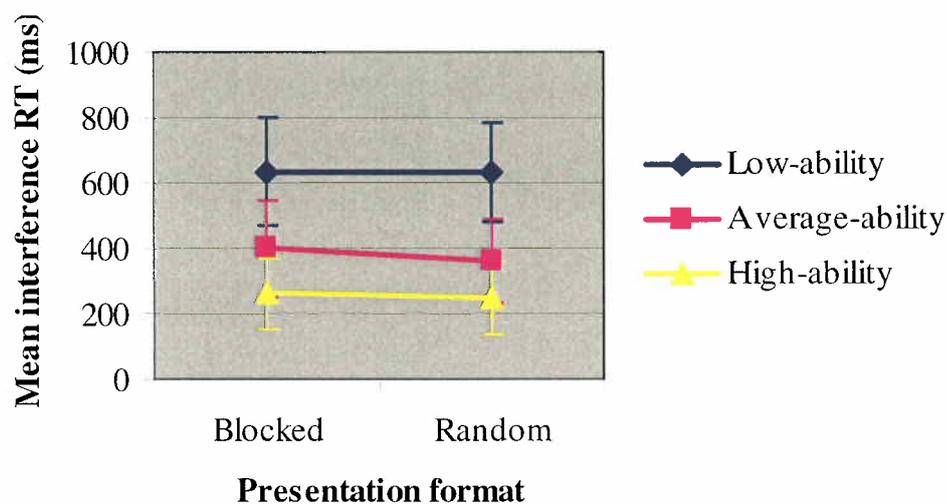
The negligible interference scores demonstrate that Stroop-like interference was not replicated in the present study and a 3(presentation) x 3(ability) mixed design ANOVA on interference scores revealed no significant main effects or interaction effects. In order to experience confusion from the irrelevant information in the false-confusing condition arithmetic processing would have to be partially autonomous. Hence, this data provides evidence against autonomy as they suggest that counting procedures were being employed rather than direct memory retrieval.

Presentation effect scores

A 2(presentation) x 3(ability) mixed design ANOVA on 'presentation effect' scores revealed significant main effects of ability, $F(2,71) = 3.93$, $p < 0.05$. This indicates that the lower ability children experienced greater difficulty in the mixed presentation formats in comparison to the unmixed presentation format than the

average- and high-ability children (See Fig. 6.1). Mathematical ability correlated highly with reading ability ($r=0.59$) and IQ ($r = 0.6$). Hence, in order to ensure that any differences found between ability levels was specific to mathematical ability, a 2(presentation) x 3(ability) analysis of covariance (ANCOVA) was calculated controlling for IQ and reading ability. The ANCOVA did not remove the significant main effects of ability ($F(2,69) = 3.82, p < 0.05$).

Fig. 6.2. Presentation interference scores across ability levels



Presentation effects increased with decreasing mathematical proficiency, indicating that the switching requirements of the mixed presentation formats (i.e. mixed blocked and mixed random) placed greater strain on the executive resources of the lower ability children.

Correlational analyses

Correlation coefficient scores were calculated to discover whether presentation effect scores correlated significantly with any of the screening measures. These revealed that mathematical ability correlated significantly with both the blocked ($r =$

-.3, $df = 74$, $p < 0.01$) and random ($r = -.25$, $df = 74$, $p < 0.05$) presentation effect scores, indicating that as mathematical ability increased, the level of presentation effect experienced decreased. Mathematical ability correlated highly with both IQ ($r = .6$, $df = 74$, $p < 0.01$) and reading ability ($r = .59$, $df = 74$, $p < 0.01$). Hence, partial correlation coefficients controlling for IQ and reading ability were calculated. The significant correlation between mathematical ability and blocked presentation effects remained ($r = -.33$, $df = 70$, $p < 0.01$), but the correlation between mathematical ability and random presentation effects only approached significance ($r = -.22$, $df = 70$, $p = 0.066$). So, these results indicate that intending to perform more than one arithmetical operation has a detrimental impact on performance, particularly the performance of the low-ability children.

Error Data

Error scores were low overall and the three ability groups made a comparable amount of errors.

Mean proportional error scores were calculated for each condition across the three presentation formats and are contained below in Table 6.3.

Table 6.3. Mean proportional error scores for each condition across the three presentation formats

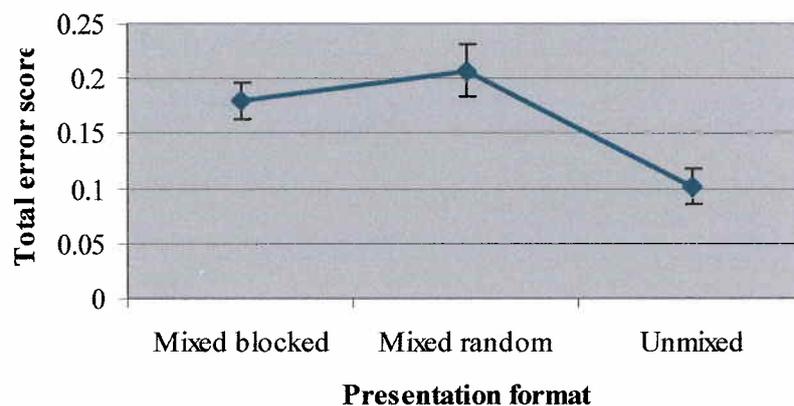
Condition	Measure	Presentation Format		
		Mixed Blocked	Mixed Random	Unmixed
False-confusing	P(E)	0.078	0.105	0.035
	SD	0.095	0.12	0.069
False-neutral	P(E)	0.027	0.014	0.023
	SD	0.054	0.041	0.055
True	P(E)	0.074	0.089	0.045
	SD	0.079	0.1	0.072

A 3(presentation) x 3(condition) x 3(ability) mixed design ANOVA revealed significant main effects of presentation format, $F(2,142) = 10.1, p < 0.01$, condition $F(2,142) = 27.16, p < 0.01$ and a significant interaction between presentation format and condition, $F(4,284)^9 = 7.62, p < 0.01$. Error scores were higher in both of the mixed presentation formats than the unmixed presentation format and lower in the false-neutral condition in comparison to the false-confusing and true conditions. Planned comparisons further explored these effects and revealed Stroop-like associative confusion (i.e. greater errors in the false-confusing condition than the false-neutral condition) in the mixed blocked ($t = 3.86, df = 73, p < 0.01$) and mixed random ($t = 6.58, df = 73, p < 0.01$) presentation formats. There were no such significant effects of condition in the unmixed presentation format. Similarly significantly more errors were made with the true stimuli than the false-neutral stimuli in the mixed blocked ($t = 4.43, df = 73, p < 0.01$) and mixed random ($t = 7.15, p < 0.01$) presentation formats. However, these results may be simply due to the fact that there is more scope for making errors in the true and false-confusing conditions (see pp. 169-170 in Discussion).

⁹ Greenhouse Geisser, $F(3.4, 241.05) = 7.62, p < 0.01$.

Total proportional error scores were also calculated for each presentation format. These were higher in the both of the mixed presentation formats compared with the unmixed presentation format. A 3(presentation) x 3(ability) mixed design ANOVA revealed a significant main effect of presentation format only $F(2,142) = 10.1, p < 0.01$ (see Fig. 6.3).

Fig. 6.3. Total error scores under mixed & unmixed presentation formats



Planned comparisons confirmed that significantly fewer errors were made in the unmixed presentation format than both the mixed blocked ($t = 3.84, df = 73, p < 0.01$) and mixed random ($t = 3.98, df = 73, p < 0.01$) presentation formats.

Thus intending to perform only one operation has a strong effect on performance; both the mean RT and error scores were reduced.

Interference error scores

A 3(presentation format) x 3(ability level) mixed design ANOVA conducted in the interference error scores also revealed a significant main effect of presentation format, $F(1,71) = 12.46, p < 0.01$ (see Fig. 6.2). There was no significant impact of ability level.

Fig. 6.4. Interference error scores under mixed and unmixed presentation formats

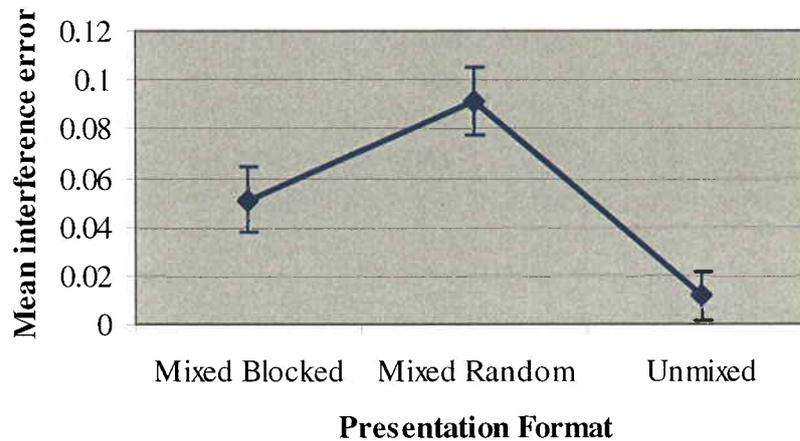


Figure 6.4. shows that the children experienced less interference in the unmixed presentation format than the mixed blocked ($t = 2.62$, $df = 73$, $p < 0.05$) and mixed random ($t = 5.34$, $df = 73$, $p < 0.01$) presentation formats. This confirmed the expectation that, as both operations were relevant to intentions in the mixed presentation formats, this would increase the likelihood that the children would fail to inhibit the ‘irrelevant’ operation in the false-confusing condition. In addition, interference error scores were significantly higher in the mixed random presentation than the mixed blocked presentation format ($t = 2.31$, $df = 73$, $p < 0.05$). Hence, it appears that the frequent switching between arithmetical operations required in the mixed random presentation format increases the likelihood that the alternative arithmetical operation will be employed.

Presentation Effect error scores

Presentation effect error scores were also calculated, however no significant main effects or interaction effects were found.

DISCUSSION

The latency data of this arithmetic variant of the Stroop task failed to replicate the Stroop-like associative confusion effect found in previous studies (Winkelman & Schmidt, 1974; Zbrodoff, 1979; Zbrodoff & Logan, 1986). A pre-requisite for producing this Stroop-like interference was that arithmetic processing was at least partially autonomous. If simple arithmetic processing is at least partially autonomous then the false-confusing stimuli should confuse the participant by encouraging them to incorrectly respond 'true'. However, the response time scores (and observations) indicated that the children were generally employing overt counting strategies (e.g. finger counting, verbal counting) rather than direct fact retrieval, which is necessary in order to experience associative confusion.

Nevertheless, the results supported Zbrodoff & Logan's (1986) proposals regarding presentation format. Intending to perform only one operation (i.e. unmixed presentation) had strong effects; response time scores were significantly quicker in comparison to when two operations were relevant to intentions (i.e. mixed presentation). In the mixed presentation formats the children had to maintain two operations in working memory. In addition, in order to determine which operation is relevant for each stimulus presentation, they have to firstly encode the operator symbol (+ or -). When more than one operation is relevant, they are also required to switch between the relevant counting strategies and thus inhibit one strategy in favour of another. In the unmixed presentation format, the children are aware that only one operation is required, so there is no necessity to encode the operator symbols, switch between counting strategies, or inhibit one strategy in favour of

another. Finally, in the mixed presentation formats two schemas are equally activated in working memory, thus placing greater strain on the executive under mixed presentation format compared to unmixed. Consequently, it is not surprising that this increased strain results in increased RT and error scores in the mixed presentation formats.

In order to explore the relationship between mathematical ability and the switching demands of the two mixed presentation formats, within-participant 'Presentation effect'¹⁰ scores were calculated. These demonstrated that the increased switching requirements of the mixed presentation formats placed greater strain on executive resources than the unmixed presentation format. Presentation effects increased with decreasing mathematical competency indicating that the less proficient mathematicians possess fewer executive resources to deal effectively with the increased switching demands in the mixed presentation formats. These results also support the proposal that lower ability children experience difficulty inhibiting strategies for dealing with a task (Bull *et al.*, 2000), since in both of the mixed presentation formats the children were required to switch between their established strategies for addition and subtraction equations. Similarly, and in addition to this switching requirement, the intention to perform more than one operation results in two schemas (i.e. addition and subtraction) being activated in working memory, which in turn, drains the available resources.

The numerical Stroop variants (Studies 1 and 2) and previous research (Bull *et al.*, 2000) revealed that when given the opportunity to establish a strategy (i.e. blocked

¹⁰ This was calculated by subtracting the mean unmixed RT score from the mean mixed RT score for both blocked and random presentation format.

presentation), Stroop-like interference scores revealed that low-ability children experienced difficulty inhibiting strategies for dealing with a task. But, they do not appear to experience increased interference inhibiting a prepotent response (i.e. random presentation)¹¹. An important distinction between the ‘switching requirements’ of Studies 1 and 2 and those of the present study must be made. In Studies 1 and 2, the children had to switch between the *congruent* and *incongruent* stimuli, whilst simultaneously inhibiting the irrelevant information when dealing with the incongruent stimuli. In the present study, the ‘switching’ requirement consisted of switching between the arithmetical operations of *addition* and *subtraction*¹² and there was no (or little) concurrent inhibition of irrelevant information required (due to the apparent lack of automaticity). Consequently, under mixed random presentation, the children were required to switch frequently between their established strategies for addition and subtraction, whereas under mixed blocked presentation they had to switch less frequently between addition and subtraction strategies. Thus, it was hypothesised that the children would take longer to respond under mixed random presentation due to the high switching requirement.

The results clearly indicated that both mixed blocked and mixed random presentation format placed increased demands on the executive system in comparison to the unmixed presentation format. However, there was no difference found between the ‘presentation effect’ scores of blocked and random presentation

¹¹ In studies 1 and 2 it was possible to establish a strategy under blocked presentation format through the recurrent presentation of the congruent stimuli. There was no such opportunity under random presentation format hence no switching between strategies was required.

¹² The goal here was to explore the impact of varying the presentation format of the arithmetical operations. Switching between arithmetical operations is a typical requirement of a mathematics lesson hence from an educational point of view it was important to determine whether the presentation format of teaching materials can have a significant impact on performance.

formats suggesting that the frequent switching demands failed to sufficiently increase the demands on the executive. The increased switching demands may have failed to sufficiently stretch the executive as the children possess well-established strategies for dealing with addition and subtraction and they also have experience switching between these strategies. However, if greater strain was placed on the executive by introducing inhibition demands, the impact of these increased switching demands may become more apparent. Thus, it is possible that the respective demands of blocked and random presentation format in the present study fail to sufficiently stretch executive resources. The following studies, further explore the differential impact of blocked and random presentation formats on arithmetical performance, when clear inhibition requirements are also present.

In addition, it is possible that under blocked presentation format the children are less attentive due to the less frequent switching requirement. Consequently, RT scores increase due to the more complacent attitude. Under random presentation format, the children must remain vigilant throughout due to the high switching demands.

Error Data

In contrast to the RT scores, the error scores of the mixed presentation formats suggest that the children experienced associative confusion as more errors were made in the false-confusing condition. Findlay (1978) achieved a similar pattern of results where the error scores argued for an associative confusion effect whereas the latency data did not. He proposed that the children were employing a mix of strategies. For instance, with the associative lures (false-confusing) it is possible to state that the sum $7 + 5 = 4$ is false without any specific knowledge regarding the

correct answer, by simply observing that the sum (4) is smaller than either addend. This magnitude comparison strategy is plausibly fairly efficient, hence latency scores would be quicker when this strategy was employed and any associative confusion effect in the RT scores would be reduced. However, as the error scores indicated an associative confusion effect, it is clear that this strategy was not employed exclusively. Findlay (1978) proposed that during the process of development children are “...initially making heavy use of the counting algorithm, but gradually developing to become effectively autonomous associations.” (Findlay, 1978, p. 450). Thus, suggesting that the increased errors with the associative lures were due to the autonomous associations held between *some* pairs of single digits and their sums.

However, if the potential for errors in each condition in the present study is considered, an alternative conclusion can be reached. The increased error score with the false-confusing stimuli was plausibly simply due to the fact that there was more scope for making errors in this condition in comparison to the false-neutral stimuli¹³. For example, ‘operation confusion’, where an operation other than the one presented is employed to solve an equation, is a common error that children make (Ashcraft, 1992; Baroody, 1989). So, for example, if the children experience operation confusion with the false-confusing stimuli (e.g. $4 + 2 = 2$), they will incorrectly respond ‘true’. However, even if the children experienced operation confusion with the false-neutral stimuli, they would correctly respond ‘false’ (e.g. $4 + 2 = 7$). Thus, the apparent associative confusion effect revealed through the error scores may simply be the result of common counting errors. The counting errors

¹³ It was unlikely that any of the common errors would have resulted in the children incorrectly responding ‘true’ to the nonassociative lures. For instance operation confusion, near misses and wild guesses would most likely have resulted in a correct ‘false’ response.

result in an amplified level of apparent associative confusion as they produce more errors in the false-confusing condition than in the false-neutral condition.

Error scores were highly comparable between the false-confusing and true conditions, which further supports this proposal that the associative confusion effect was simply the result of common counting errors. The potential scope for errors was even higher in the true condition than in the false-confusing condition as an incorrect 'false' response would occur if any of the common errors (e.g. wild guesses, near misses and operation confusion) identified by Ashcraft (1992) and Baroody (1989) were made (see Chapter 2, p. 29). Also, if the children were truly experiencing associative confusion then this should also have been evident in the latency data.

Finally, the size of the latency scores and observations indicate that the children were employing counting based strategies as opposed to direct fact retrieval. This provides further support to the proposal that counting-based errors contributed to the increased error scores in the false-confusing and true conditions. A production task (i.e. where the children provide the answer) as opposed to a verification task, would provide a clearer insight into the types of errors that the children are making.

As with the RT scores, the error scores were also higher in the mixed presentation format (blocked and random) compared with the unmixed presentation format, signifying that it is the switching requirement that increases the prevalence of these operation confusions. Maintaining two schemas in working memory and switching between these schemas places an increased strain on the executive system, hence

increasing RT scores and the likelihood of counting errors being made.

Interference error scores were also significantly higher in the mixed random condition compared with the mixed blocked condition, supporting the proposal that the increased switching requirements of random presentation format increases the demands placed on the executive system. However, as described above the increase in error scores in the false-confusing condition is more likely to reflect ‘operation confusion’ than ‘associative confusion’. It seems highly plausible that, when required to frequently switch between arithmetical operations, the likelihood of employing an irrelevant operation and hence incorrectly responding ‘true’ in the false-confusing condition increases. Nevertheless, the results support the proposal that the high switching demands in the mixed random condition places greater strain on the executive and reduces the ability to inhibit the irrelevant operation.

There was no main effect of ability level on the error scores. Error scores were very low and in order to be included in the analysis the children had to achieve at least 80% accuracy. Thus, this may have obscured any effects of mathematical ability. It is also possible that the lower ability participants approached the task with less confidence and as a result took more care over their responses.

Concluding comments

One aim of this experiment was to examine whether the Stroop interference produced in Studies 1 and 2 could be replicated in an arithmetic variant of the Stroop task. This goal was not achieved as there was no replication of the Stroop-like associative confusion effect found in previous studies (e.g. Zbrodoff & Logan, 1986). It is proposed that a fundamental flaw of Study 3 is the fact that the children

could not experience Stroop-like interference if the ‘incongruent’ stimuli (i.e. associative lures) failed to interfere with processing. The most obvious, and most likely, explanation for this is that the children were lacking in the experience and proficiency required in order for arithmetical processes to become at least partially automatic. Nevertheless, the presentation format of the equations had a significant impact on performance and the RT scores revealed that lower ability mathematicians experienced greater difficulty when more than one operation was relevant to intentions. This suggests that the additional working memory and switching requirements present under mixed presentation format was more taxing on the executive system and that the resources available to cope with these additional demands are to some extent dependant upon mathematical ability.

Finally, an additional major shortcoming of the present study was its failure to fulfil a number of task requirements in order to be considered a true measure of executive functioning. For instance, Phillips (1997), declared that executive tasks should be novel in both content and form (in order to tap goal identification and strategy use); they should require a degree of effort, for example by requiring inhibition and online monitoring, and they should place demands on the working memory system. Thus, measures of executive functioning typically place demands on working memory as well as requiring the inhibition of irrelevant responses “... *executive tasks share a common requirement to represent the task requirements or goals, coupled with a need to inhibit inappropriate responses* (Cohen & Servan-Schreiber, 1992; Diamond, 1990; Roberts *et al.*, 1994; Roberts & Pennington, 1996, cited in Beveridge, Jarrold, & Pettit, 2002). The arithmetic Stroop variant employed in Study 3 clearly failed to meet these requirements as: 1) it was not novel in content

(the children are presented with arithmetic equations on a daily basis); 2) no or little inhibition was necessary (due to the lack of autonomy); and 3) there was no need to maintain task demands in memory whilst simultaneously inhibiting irrelevant information.

The following study (Study 4) aims to overcome a number of the shortcomings identified with this study and, in addition, more adequately fulfil the requirements of executive functioning tasks by introducing novel elements, rules and inhibitory demands.

Chapter 7

Study 4: A successful reproduction of Stroop-like interference in an arithmetical Stroop task

Overview

The results from the arithmetic Stroop variant employed in Study 3 failed to replicate the Stroop-like interference effect found by Zbrodoff and Logan (1986). This was attributed to a lack of automatised basic arithmetical skills. Consequently, it is impossible to determine whether the findings from the numerical variants of the Stroop task in Studies 1 and 2 (see also Bull & Scerif, 2000; Bull *et al.*, 2000) can be generalised to the more naturalistic task of arithmetic.

Thus, the aim of the present study was to overcome some of the identified shortcomings of Study 3 and in turn design an arithmetic Stroop variant which successfully reproduces Stroop-like interference in children.

In Study 3, the ‘conflict dimension’ of the incongruent condition (i.e. false-confusing: $4 + 3 = 1$) failed to sufficiently interfere with arithmetical processing as it was dependent upon a high level of arithmetical proficiency. Consequently, the present study introduces more ‘typical’ incongruent stimuli where there is a clear conflict between the two dimensions. This study also aims to be more consistent with other measures of executive functioning. Thus, in accordance with the assertions of Phillips (1997) and Diamond (1990) (see Chapter 6, p.172) novel elements are introduced and the children are required to maintain rules, relating to these elements, in working memory whilst completing the task.

INTRODUCTION

In this study, the children are again invited to verify simple arithmetical equations. The equations are presented within a two-dimensional shape and the children are instructed to employ the specific arithmetical operation defined by the 'shape' (e.g. circle = addition; square = subtraction) regardless of the arithmetic symbol presented. In the congruent condition, the arithmetical operation is in accordance with the shape and in the incongruent condition the operation and shape conflict. Hence, in the incongruent condition the children are required to inhibit the conflicting irrelevant arithmetical operation. It is hypothesised that the presence of the irrelevant arithmetic operation will activate counting strategies which are specific to that operation and that this unintentional activation of the irrelevant operation should interfere with the execution of the relevant arithmetical process, as these must be inhibited in favour of the relevant strategy.

The stimuli are presented in two presentation formats: Blocked and Random. Under Blocked presentation, the stimuli are presented in 'arithmetic' blocks (i.e. 8 trials) requiring addition (circles) or subtraction (squares)¹. Under Random presentation format a randomised mix of addition and subtraction equations are presented. Consequently, the switching requirements of the present study are similar to those in Study 3: participants are required to switch between addition and subtraction under both presentation formats. The congruent and incongruent stimuli were presented in a randomised fashion across both presentation formats.

¹ For example blocked presentation format would consist of the following format, 8 addition, 8 subtraction, 8 addition, 8 subtraction.

So, there was no opportunity to establish temporary strategies related to the repeated presentation of the conditions. From an educational point of view, it was deemed more important to examine the demands placed on the executive when switching between arithmetical operations. In particular, the aim was to explore whether one presentation format placed greater strain on the executive system than another.

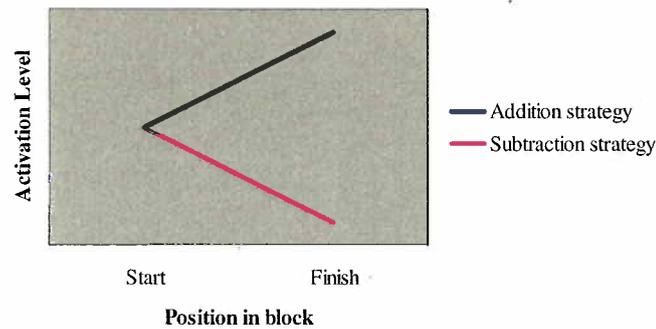
In Study 3, the RT and error scores revealed that the children experienced greater difficulty when required to switch between arithmetical operations than when only one arithmetical operation was relevant to intentions. The interference error scores also indicated greater difficulty when switching demands were high (i.e. in the mixed random presentation format). This suggests that the children experience greater difficulty inhibiting one arithmetical operation in favour of another when required to switch frequently between these operations.

In Study 3, the error scores did not reveal any significant impact of ability level. This may be accounted for by the low inhibition requirements of Study 3² which failed to sufficiently stretch the executive system. For example, Bull *et al.* (2000) and the results of the numerical Stroop variants in Studies 1 and 2, revealed that low-ability children experienced increased interference scores only when *both* inhibition and switching requirements were present (i.e. under blocked presentation). This implies that these combined demands were required before the executive system was stretched sufficiently.

² The inhibition requirement was related to the level of automatization of basic arithmetical facts.

In the present study, the inhibition demands were consequently increased by ensuring that there was a clear conflict between the two dimensions in the incongruent condition. Each stimulus presentation requires the children to firstly encode the 'rule' in order to determine which operation is relevant and in the incongruent trials the irrelevant arithmetical operation must be inhibited simultaneously. It is predicted that under random presentation format this irrelevant dimension will gain greater access to working memory and hence interfere more with processing compared with blocked presentation format due to the required frequent switching between these arithmetical operations. As a consequence of this frequent switching, both addition and subtraction schemas are equally activated in working memory and highly relevant to intentions throughout random presentation format. Both addition and subtraction schemas are also activated in working memory under blocked presentation format, however, it is proposed that during a block, the activation of these strategies vary in strength. For example, during a block of addition, addition strategies become increasingly activated and relevant to intentions whilst the activation of and the intention to perform subtraction decreases. Thus, during a block it is likely that it becomes increasingly easy to inhibit the irrelevant operation as its activation and the consequent intention to employ it decreases. Figure 7.1 below provides a graphical illustration of this proposal.

Fig 7.1: Level of activation during addition block



These proposals regarding the impact of intentions are in accordance with recent proposals which have suggested that executive functioning and intentionality are closely linked (Frye & Zelazo, 2003, cited in Zelazo *et al.*, 2003). Executive functioning research has acknowledged the distinction between non-automatic, controlled processes and automatic, stimulus-driven processes for a considerable time (e.g. Hasher & Zacks, 1984; Logan, 1988; Norman & Shallice, 1986; Posner & Snyder, 1975; Shiffrin & Schneider, 1977). However, researchers have only recently begun to consider the role of intentionality. For example, Allport & Wylie (2000) found that when adults were required to switch from one task (e.g. stating the ink colour of a word in a Stroop task) to another (e.g. reading the word; Reverse Stroop Effect) response times increased following the switch. In order to account for “...these switch costs researchers have suggested that intentional, goal-directed processes formed on the basis of an experimenter’s instructions interact with automatic, involuntary response tendencies to produce goal-directed behaviour.” (Zelazo, Muller, Frye, & Marcovitch, 2003, p.109). Hence, in order to fully understand executive functions we must also take into account a person’s intentional state (e.g. goals, beliefs, desires, intentions)

Hypotheses

The aim of this study is to produce Stroop-like interference in an arithmetic variant of the Stroop task and consequently extend the earlier findings from the numerical Stroop variants to a more naturalistic task. Providing the task successfully produces Stroop-like interference, it is predicted following the earlier studies, that low-ability mathematicians will experience greater interference than the average- and high-ability children. It is also anticipated that the level of interference experienced will be dependent upon the extent to which the presentation format enhances the saliency of the irrelevant information, making it more relevant to intentions. Consequently, for reasons outlined above it is hypothesised that greater interference will be experienced under random presentation where both addition and subtraction schemas are highly relevant to intentions and equally activated throughout.

METHOD

Participants

44 children participated in this study. 6 children were removed from the analysis due to poor performance levels, thus the analysis contained 38 children. The mean age of the children was 9 years 4 months (SD = 6.6 months, range 8;04 to 10;03). The sample consisted of 24 girls and 14 boys.

The children were split into three mathematical ability groups according to their performance on a mathematics screening test. This resulted in 12 low-ability, 12

average-ability and 14 high-ability children. The performance characteristics of the three ability levels on each of the screening tests are contained in Table 7.1 below.

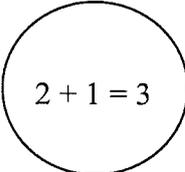
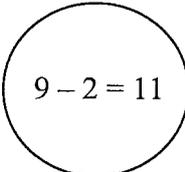
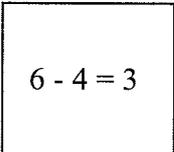
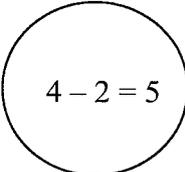
Table 7.1. Mean mathematics, IQ and reading standardised scores (& standard deviations) for low, average and high ability mathematicians

Ability	Screening Measures		
	IQ	Mathematics ability	Reading ability
Low (N = 12)	95 (13.11)	88.67 (6.62)	91.25 (11.34)
Average (N=13)	99.15 (9.49)	99.15 (3.26)	102.23 (9.94)
High (N = 13)	100 (7.85)	111.15 (3.46)	101.23 (11.31)

Materials & Procedure

The stimuli consisted of simple arithmetical equations of the form $a*b = c$, where $*$ is either + or -, and a and b were digits ranging from 2 to 10. All possible combinations of 2 to 10 were employed. All ties were removed and only those combinations with the larger first addend/subtrahend were employed in order to avoid negative numbers (e.g. 2 - 1, but not 1 - 2). This resulted in 45 possible combinations of numerals. The children were instructed to determine whether the equation was 'true' or 'false' by pressing one of two computer keys, labelled respectively with a tick symbol (\surd) or a cross symbol (\times). Half of the children pressed the key under their right hand to indicate that the equation was true and their left hand to indicate that the equation was false and for the other half this was reversed. The stimuli were presented in black font (Times New Roman point size = 36) on a white background in the centre of the computer screen.

The arithmetical equations were presented within one of two shapes. If the equation was inside a **circle** the children were instructed to use **addition**, whereas if it was inside a **square** they were instructed to employ **subtraction**. In the congruent condition, the operation presented matched the shape and in the incongruent condition, the operation and shape conflicted. See examples below:

True congruent (TC):		True Incongruent (TI):	
False congruent (FC):		False incongruent (FI):	

Within each condition (i.e. congruent or incongruent), half of the equations were false and the other half were true. The difference between the left and right hand sides of the equation in the TI condition ranged from ± 2 to ± 9 . This range was also adopted when constructing the *c* terms of the false equations (FC and FI). This control was introduced in consideration of research revealing that response times to *reasonably* incorrect (± 1 or 2) were significantly slower than response times to *unreasonably* incorrect (± 4 or 5) (Ashcraft & Battaglia; Moyer & Landauer, 1967; Restle, 1970).

Procedure

Each participant completed a total of 80 test trials and 10 practice trials. The test trials were presented in two presentation formats each containing 40 trials. Under

random presentation format a random mix of 20 equations requiring addition (i.e. circles) and 20 requiring subtraction (i.e. squares) were presented, whereas under blocked presentation format the stimuli were presented in blocks of addition and subtraction, for example, 10 addition (i.e. circles), 10 subtraction (i.e. squares), 10 addition, 10 subtraction. Within each presentation format there were 20 congruent stimuli and 20 incongruent stimuli³. The incongruent and congruent stimuli were presented in a randomised fashion within both random and blocked presentation formats. Half of the children were presented with random presentation format followed by blocked presentation format and for the other half this order of presentation was reversed. The children were invited to take a break in between each presentation format and to resume testing when they were ready.

The task was completed within one session, which lasted approximately 20 minutes. They were instructed to respond as quickly as possible but to avoid sacrificing speed for accuracy. They were asked to pretend that they were a teacher marking a student's work by awarding 'ticks' and 'crosses'.

Analysis

Mean RT scores were initially examined in order to assess whether this arithmetic variant of the Stroop task had been successful in replicating Stroop-like interference. In order to examine any differences between ability levels it was necessary to calculate within-participant interference scores. These were calculated

³ Under blocked presentation format each block comprised of the following: 2 TC, 3 TI, 3 FC, 2 FI OR 3 TC, 2 TI, 3 FC, 2 FI. So, each block contained 5 congruent and 5 incongruent stimuli, which were presented in a randomised fashion.

using the standard Stroop interference calculation (i.e. Interference = incongruent - congruent).

RESULTS

Mean response time scores for the congruent and incongruent stimuli were calculated for each presentation format and are shown in Table 7.2.

Table 7.2. Mean RT scores (& standard deviations) under blocked & random presentation format

Ability Level	Measure	Random		Blocked	
		Congruent	Incongruent	Congruent	Incongruent
Low	Mean	6635.09	7607.38	6827.59	7229.61
	SD	1163.63	1415.12	872.84	1623.5
Average	Mean	6259.58	6429.22	6079.63	6481.61
	SD	1383.75	1496.29	1627.48	1519.65
High	Mean	6636.55	6758.26	6255.8	6664.62
	SD	2176.27	1950.37	2082.88	1773.94

As expected, the children took longer to respond to the incongruent stimuli than the congruent stimuli. Similarly, RT scores were higher in the random presentation format than in the blocked presentation format.

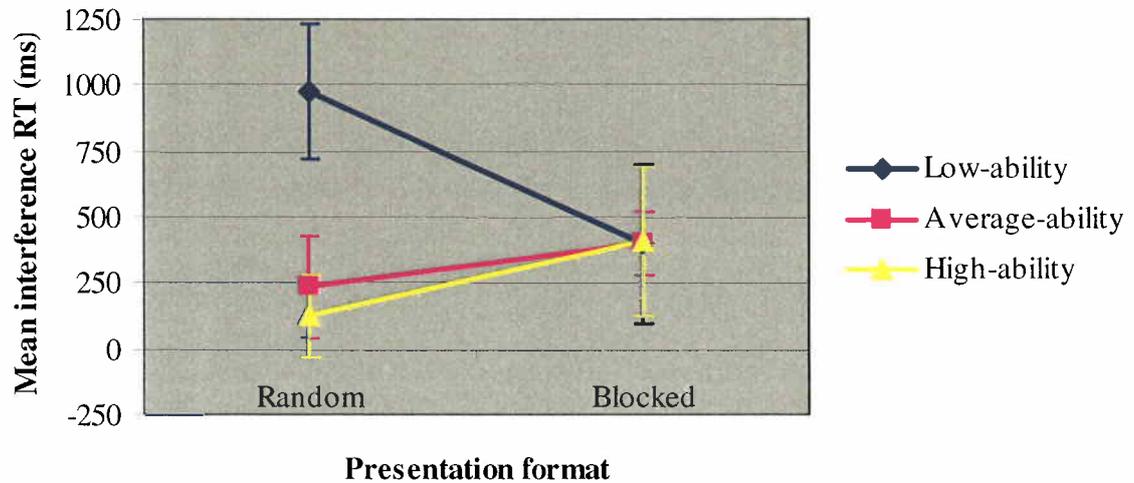
A 2(presentation) x 2(condition) x 3(ability) repeated measures ANOVA conducted on the mean RT scores revealed a main effect of condition only, $F(1,35) = 19.21$, $p < 0.01$ indicating the presence of Stroop-like interference; the inhibitory demands of

the incongruent condition significantly increased RT. Paired t-tests confirmed the presence of this Stroop-like interference under both random ($t = 3.32$, $df = 37$, $p < 0.01$) and blocked ($t = 2.93$, $df = 37$, $p < 0.01$) presentation formats. There was no significant main effect of presentation format, although the RT scores followed the predicted trend of increased RT scores under random presentation format. In addition, as expected, the low-ability children were generally slowest to respond to the stimuli, particularly the incongruent condition under random presentation format (see Table 7.2.). The average-ability children were actually slightly quicker to respond than the high-ability children, however, analyses revealed no significant main effect of ability level.

Interference scores

A 2(presentation) x 3(ability) mixed design ANOVA on interference scores revealed no significant main effects or interaction effects. However, observation of the data suggested a simple effect of ability under random presentation format: the low-ability participants experienced greater interference than both the average- and high-ability children (see Figure 7.2).

Fig. 7.2. Mean interference under blocked & random presentation



A one-way ANOVA confirmed this significant impact of ability on interference scores under random presentation format, $F(2,37) = 5.1$, $p < 0.05$. However, mathematics ability correlated significantly with both IQ ($r = .39$, $p < 0.05$) and reading ability ($r = 0.48$, $p < 0.01$). So, to be certain that the main effect of ability was specifically due to mathematics ability alone, an analysis of covariance (ANCOVA) controlling for IQ and reading ability was calculated. The ANCOVA did not remove this significant effect of ability level ($F(2,33) = 4.58$, $p < 0.05$), suggesting that mathematics ability is specifically related to inhibition efficiency under certain conditions. There was no main effect of presentation format. The data shows that the low-ability children experienced greater interference under random presentation compared with blocked presentation format, however a paired t-test on the low-ability children's interference scores revealed that this failed to approach significance ($t = 1.72$, $df = 11$, $p = 0.0113$ (2-tailed)).

Error data

The error data for the congruent and incongruent stimuli under blocked and random presentation format are contained in Table 7.3. The error scores also supported expectations; they were higher in the incongruent compared with the congruent condition and they were also higher in the random presentation format compared with blocked presentation format.

Table 7.3. Mean error scores (& standard deviations) under blocked & random presentation format

Ability Level	Measure	Random		Blocked	
		Congruent	Incongruent	Congruent	Incongruent
Low	Mean	0.75	1.17	0.83	1.42
	SD	1.14	1.34	1.11	1.24
Average	Mean	1.08	1.31	0.46	0.54
	SD	0.76	1.03	0.66	0.52
High	Mean	0.77	1.46	0.23	0.46
	SD	1.36	1.33	0.6	0.66

A 2(presentation) x 2(condition) x 3(ability) repeated measures ANOVA confirmed that the children experienced greater difficulty under random compared with blocked presentation format, $F(1,37) = 13.2$, $p < 0.01$, and similarly with the incongruent stimuli compared with the congruent stimuli, $F(1,37) = 8.77$, $p < 0.01$. A significant interaction between presentation format and ability level was also revealed, $F(2,35) = 6.21$, $p < 0.01$, reflecting a reduction in error scores under blocked presentation format compared with random presentation format for the average- and high-ability children. The error scores of the average- and high-ability children were lower under blocked presentation format compared with random presentation format. Paired t-tests confirmed that presentation format had a

significant impact on the error scores of the average-ability children in both the congruent ($t = 2.31$, $df = 12$, $p < 0.05$) and the incongruent ($t = 3.83$, $df = 12$, $p < 0.01$) conditions. Similarly, for the high-ability children, significantly more errors were made under random compared with blocked presentation in the congruent ($t = 2.21$, $df = 12$, $p < 0.05$) and incongruent ($t = 3.12$, $df = 12$, $p < 0.01$) conditions. The low-ability children, however, made similar levels of errors under both presentation formats. Under blocked presentation format the low-ability children made significantly more errors in the incongruent condition than both the average- $t = 2.34$, $df = 23$, $p < 0.01$ and high-ability $t = 2.43$, $df = 23$, $p < 0.05$.

Interference error scores

Interference error scores were also calculated, however these were low and a 2(presentation) x 3 (ability) mixed design ANOVA revealed no significant main effects of presentation format, ability level or interaction effects.

Correlational analyses

As expected these analyses confirmed that mathematical ability was related to IQ ($r = .373$, $df = 38$, $p < 0.05$), and reading ability ($r = .48$, $p < 0.01$). There was no significant relationship found between either of these screening measures and the levels of interference (RT or errors) experienced under blocked or random presentation format.

DISCUSSION

Stroop-like interference

This arithmetical variant of the Stroop task successfully elicited Stroop-like interference, with both the latency and error scores revealing poorer performance with the incongruent stimuli compared to the congruent stimuli. Consequently, these results clearly indicate that the irrelevant arithmetic operation sufficiently interferes with the processing of the relevant dimension, hampering the execution of the relevant arithmetic process.

Interference Scores

Stroop-like interference was replicated and as anticipated, the low-ability participants experienced significantly greater interference than both the average- and high-ability children under random presentation format. These findings support the proposal that the low-ability children have fewer executive resources available to cope with the enhanced switching required under random presentation format. It is proposed that these increased demands reduce the efficiency of the executive system allowing the irrelevant information to gain greater access to working memory and disturb processing⁴.

The results of random presentation format suggest that the low-ability mathematicians experience greater difficulty suppressing the activation of irrelevant information. Following Hasher & Zacks' (1988) 'Inhibition Theory' the results also support their proposal that less efficient inhibitory mechanisms not only allows

⁴It is possible that the low-ability children were simply experiencing difficulty with the incongruent stimuli due to problems switching between mathematical operations. However, this has been controlled for by taking congruent performance into account when calculating interference scores.

irrelevant information to enter working memory, but that they also enable this information to remain active for longer. Consequently, the potential for the irrelevant information to interfere with the processing of the relevant information is increased.

There was no significant impact of mathematical ability level on the interference scores under blocked presentation format. The children had to switch less frequently between arithmetical operations under blocked presentation format hence it is proposed that fewer demands were placed on the executive system. The performance of the low-ability children suggests that they possess sufficient executive resources to cope with the infrequent switching required under blocked presentation format. Moreover, blocked presentation format makes the appropriate rule more relevant to intentions and therefore it becomes increasingly easy to inhibit the irrelevant dimension. For example, when presented with a block requiring addition (i.e. circle), the intention to employ subtraction would decrease. Consequently, the irrelevant subtraction operator symbol in the incongruent conditions would be easier to inhibit, as it would be less relevant to intentions. It was anticipated, therefore, that interference scores would be higher under random presentation format, as the frequent switching between addition and subtraction resulted in both schemas being equally activated in working memory and relevant to intentions. Consequently, it was more difficult to inhibit any unintentional activation of the irrelevant operator symbol. The performance of the low-ability mathematicians supported this hypothesis, as greater interference was experienced

under random compared with blocked presentation format⁵⁶. Also, they experienced significantly more interference than children of higher mathematical ability, under random presentation format, indicating that the frequent switching between schemas placed greater demands on the executive systems of these low-ability children.

Furthermore, Bull & Scerif (2000) proposed that the role played by the executive system may diminish in relation to how automatic a process is. The children have a substantial amount of experience with addition and subtraction hence these processes are likely to contain a degree of autonomy⁷. Consequently, the infrequent switching between these established strategies under blocked presentation format is possibly less taxing on the executive system than the frequent switching between strategies required under random presentation format. Hence, the absence of any differences between ability levels under blocked presentation format may be due to the failure of this presentation format to sufficiently stretch the executive.

Error data

The error scores were, as predicted, higher under random presentation compared with blocked presentation format. Thus, this supports the proposal that the frequent switching required under random presentation format increases the demands placed on the executive system. This significant effect of presentation format, however, was only evident in the error scores of the average- and high-ability children. The

⁵ The pattern of results followed the hypothesised trend, but they failed to achieve significance.

⁶ A larger sample size may have revealed a significant impact of presentation format (Low-ability children, N = 12).

⁷ The concept of autonomy adopted here is that a process can begin without intention triggered by the presence of a relevant stimulus. Some processes may be more autonomous than others. Autonomy is considered to be a continuum along which processes may differ rather than a strict dichotomy.

‘Interference error’ scores also revealed no significant impact of ability level. Hence, contrary to the interference RT data, the low-ability children do not appear to experience greater difficulty under random compared with blocked presentation format.

However, the response method employed may have masked any differences between ability levels as the potential for making errors was considerably reduced for the false stimuli in comparison to the true stimuli. For example, if the children experienced ‘complete’ interference and employed the irrelevant operation when dealing with the incongruent false stimuli, they would proceed to ‘correctly’ respond ‘false’ despite having incorrectly employed the irrelevant operation⁸. On the other hand, if they experienced such interference with the true stimuli they would incorrectly respond ‘false’. In addition, if the children made any of the other common counting errors identified by Ashcraft (1992) (see also Baroody, 1989) (e.g. operation confusion, near misses, wild guesses) they would incorrectly respond ‘false’ to the true stimuli, whereas they would correctly respond ‘false’ to the false stimuli. Consequently, it is highly likely that the children actually made more errors than suggested by the reported scores. Thus, a study requiring prescription of the answer as opposed to simple verification would be more informative of both the amount (i.e. counting error versus interference error) and amount of errors that the children are actually making.

⁸ For example, if presented with the equation $4 + 3 = 5$ contained within a square (i.e. subtraction) if the children employed addition or subtraction they would reach the same correct conclusion, ‘false’.

Concluding comments

In conclusion, this arithmetic variant of the Stroop task has successfully reproduced Stroop-like interference effects. In addition, the interference RT scores revealed that the low-ability children experienced greater interference than both the average- and high-ability children under random presentation format where the switching requirements were high. It is proposed that the frequent switching between arithmetical operations results in both operations being highly activated in working memory and equally relevant to intentions. As a result, additional demands are placed on the executive system and this enables more irrelevant information to gain access to working memory.

The following study employs a similar arithmetic Stroop variant, however the children are required to prescribe the answer. The working memory demands are also increased from two to three rules with the expectation that this will increase the demands on the central executive and in turn raise interference levels. In addition, a larger sample of children is recruited in order to overcome any problems associated with small groups of children, particularly when dealing with RT scores.

Chapter 8

***Study 5: An exploration of switching demands
in an arithmetic Stroop task.***

Overview

Study 4 revealed that low-ability mathematicians experienced higher levels of interference than the average- and high-ability children under random presentation format. It was suggested that the increased switching demands of random compared with blocked presentation places increased demands on the executive system. This finding also supports previous research (e.g. Bull *et al.*, 2000), indicating that children of lower mathematical ability have fewer resources available to cope with increased executive demands.

In the arithmetic variant employed in Study 4, the children were instructed to employ the operation defined by the shape. Under both random and blocked presentation format, the presentation of the incongruent and congruent conditions was completely randomised, so there was no opportunity to establish temporary strategies relating to these conditions. Blocked presentation format in Studies 1 and 2, however, provided an opportunity to develop a more appropriate strategy containing no inhibitory component during the congruent and baseline blocks. Then, when required to switch to the incongruent block the children had to inhibit this strategy and switch to a new strategy containing an inhibitory component.

So, Study 4 examined the impact of presentation format on interference scores when switching between established addition and subtraction strategies. Studies 1 and 2, however, explored switching between the baseline, congruent and incongruent conditions. Despite these methodological differences, the results of the numerical Stroop variants (Studies 1 and 2) and the arithmetic Stroop variant (Study 4) all correspond with the proposal that manipulating the presentation format of stimuli

can exert a direct influence on children's ability to inhibit the irrelevant dimension and that it can enhance the demands placed upon the executive system. In addition, the results from these studies support the proposal that increasing and/or introducing switching demands has a more detrimental impact on the performance of low-ability mathematicians in comparison to the average- and high-ability mathematicians.

INTRODUCTION

The present study aims to develop an arithmetical Stroop variant which is more comparable, in terms of switching demands, with Studies 1 and 2. In addition, in order to overcome the problems associated with simply verifying the equations, the children will be required to prescribe the answer. This will enable greater distinction to be made between 'interference' and 'counting' errors as well as reducing the opportunity to 'guess'.

The children are once again presented with arithmetical equations contained within a shape and asked to employ the arithmetical operation defined by the 'rules'. Both blocked and random presentation formats are again employed. However, as in Studies 1 and 2, blocked presentation format consists of blocks of congruent and incongruent stimuli (i.e. 10 congruent, 10 incongruent, 10 congruent, 10 incongruent) rather than blocks of addition and subtraction. So, like the Stroop variants employed in Studies 1 and 2, blocked presentation format will provide the children with an opportunity to establish a more appropriate temporary strategy, requiring no inhibition, through the recurrent presentation of the congruent stimuli.

This temporary schema is only viable in the congruent condition, thus blocked presentation introduces the additional requirement of inhibiting this temporary strategy and switching to a new one when presented with the incongruent block. So, in the present study **both** blocked and random presentation format require participants to switch frequently between arithmetic operations. Each ‘rule’ (i.e. shape) is presented as frequently as the other hence they should all be equally relevant to intentions and equally activated throughout each presentation format.

Examining children’s ability to switch between newly established temporary strategies, whilst performing mental arithmetic, will further enable us to determine whether the findings from the relatively artificial Stroop tasks (Studies 1 and 2) can be generalised to this more natural skill.

In comparison with Study 4, the working memory demands of the present study are also increased from two to three rules. This modification was based on the impressive volume of empirical evidence suggesting that our capacity for executive control is limited¹ and it is also supported by a number of theoretical accounts of executive control (Baddeley, 1986; Duncan, 1986; Engle *et al.*, 1999; Norman & Shallice, 1986; Pennington, 1994). Thus, it is anticipated that the increased working memory demands will place greater strain on executive resources, which in turn will have an adverse effect on inhibition efficiency.

¹ This evidence stems from research on typical development e.g. Case, 1995; Welsh *et al.*, 1991; Zelazo *et al.*, 1996; atypical development e.g. Barkeley *et al.*, 1992; Pennington & Ozonoff, 1996; Swanson, 1993; typical functioning in adults e.g. Allport *et al.*, 1994; Morris *et al.*, 1988; Ward & Allport, 1997; adult neuropsychological cases e.g. Baddeley *et al.*, 1986; Shallice & Burgess, 1992; Van der Linden *et al.*, 1992)

Hypotheses

Following the results of Study 4, it is expected that the irrelevant arithmetic operator symbol will interfere with the arithmetic process required by the ‘rule’. It is also anticipated that the low-ability mathematicians will experience greater interference than the average- and high-ability children under random presentation format due to its high switching demands. Similarly, following the results of Studies 1 and 2 and Bull *et al.*’s (2000) preliminary findings, it is hypothesised that the low-ability children will also experience significantly more interference under blocked presentation, due to the switching required between temporary strategies.

Furthermore, more interference is anticipated under blocked compared with random presentation format, as blocked requires two types of switching (i.e. switching between arithmetical operations *and* switching between temporary schemas) whereas random requires only one switching requirement (i.e. switching between arithmetical operations).

METHOD

Participants

83 children participated in this experiment². However, 13 children failed to achieve the required 80% accuracy level. This resulted in a final sample of 70 children. All children were in Primary 4 and Primary 5 classes from 2 schools. 39 girls and 31 boys participated in the study. The mean age of the children ranged was 9 years 8 months (SD = 6.59 months, range 8;07 to 10;07).

² This group of children were not involved in Study 4.

The performance characteristics of the three ability groups are shown below in Table 8.1. The children were separated into three mathematical ability groups, according to their performance on a standardised mathematics test (WOND). This resulted in 25 low-ability, 22 average-ability and 23 high-ability participants.

Table 8.1. Mean mathematics, IQ and reading standardised scores (& standard deviations) for low, average and high ability mathematicians

Ability	Measure	Screening Measure		
		IQ	Math Ability	Reading Ability
Low (N = 25)	Mean	90.16	86.68	90.92
	SD	10.13	6.56	10.08
Average (N = 22)	Mean	97.59	100.05	100.23
	SD	10.58	2.72	9.55
High (N = 23)	Mean	105.26	113.48	108.17
	SD	9.48	7.01	12.21

Materials & procedure

The stimuli were equations of the form $a*b = ?$, where $*$ was either $+$, $-$ or \times . a were single digits ranging from 1 to 8 and b were single digits ranging from 1 to 3 and $?$ indicated that the children were required to provide the answer to this equation by pressing the appropriate button on the computer keyboard. In order to avoid negative numbers, only those combinations where the first digit was higher than the second were employed (e.g. $3*2$ was included but $2*3$ was excluded) and 2) only those combinations where when multiplied, the sum of the two digits was less than 25 were included. This constraint was introduced in order to keep the difficulty level relatively low and on a more practical level there was a limit to the

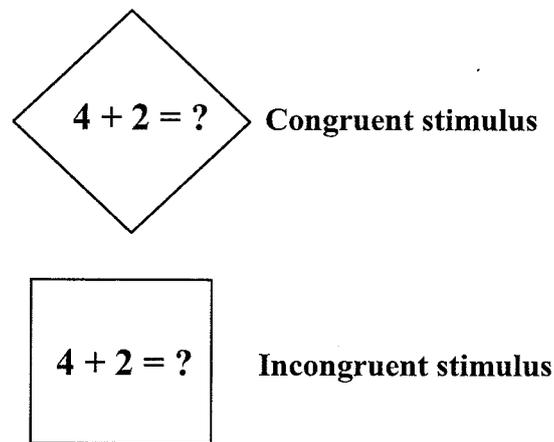
amount of computer keys, which could be classified as response keys within the E-Prime (v.1.1) software package. These constraints resulted in 18 possible combinations of numerals.

The stimuli were presented in black font (Times New Roman, point size = 36) and were contained within a 2-dimensional shape. The children responded to each stimulus presentation by pressing the appropriate key on the computer keyboard. The keys were numbered 1 to 30 and the surrounding keys had white stickers placed over them to avoid any distractions.

The children were instructed to provide the answer to each equation whilst maintaining three rules in working memory. These rules consisted of the following:

- 1) *If the equation is contained within a diamond you must use addition*
- 2) *If the equation is contained within a circle you must use subtraction*
- 3) *If the equation is contained within a square you must use multiplication*

In the *congruent* condition each equation was contained within the appropriate shape. For example, all of the addition stimuli were contained within a diamond. However, in the *incongruent* condition the stimuli were contained within an inappropriate shape. For example, the addition stimuli were presented within a square or diamond. See examples below:



The stimuli were presented in both blocked and random presentation formats. Blocked presentation format consisted of 4 blocks of 9 congruent or incongruent equations (e.g. 9 congruent, 9 incongruent, 9 congruent, 9 incongruent). Random presentation consisted of a randomised mix of 18 congruent and 18 incongruent equations. Within each presentation format there was an equal mix of addition, subtraction and multiplication stimuli. The children initially completed a practice session consisting of 12 trials followed by two presentation formats each containing 36 trials. Under random presentation format the order of the trials was completely randomised and under blocked presentation format the trials were presented randomly *within* each block. In order to ensure that the difficulty level remained constant across blocks, each block contained 3 addition, 3 subtraction and 3 multiplication equations. Half of the children completed blocked presentation format first followed with random presentation format and this order was reversed for the remaining half.

The children were instructed to provide the answers to a series of single digit addition, subtraction or multiplication equations and again they were instructed to

employ the operation defined by the 'rule' rather than simply employing the presented operation.

As the children prescribed the answer to each stimulus presentation it was possible to examine and code any errors. These incorrect responses were placed into one of the four following categories:

- 1) *Interference error*: the presented irrelevant operation was employed. For example, using subtraction for an equation presented within a square.
- 2) *Operation error*: an operation other than the one requested from the shape or the presented irrelevant operation was employed. For example, using multiplication when presented with the equation $5 - 2 = ?$ contained within a diamond.
- 3) *Calculation error*: these consisted of responses which were + or - 1 away from the correct answer.
- 4) *Random error*: these errors could not be attributed to any of the above.

'Interference errors' could only occur in the incongruent condition hence category one was not included when coding errors in the congruent condition. Interference errors and operational errors are also conceptually very similar and thus difficult to completely disentangle. This complication is discussed further in the Discussion section (p. 216).

RESULTS

Response time data

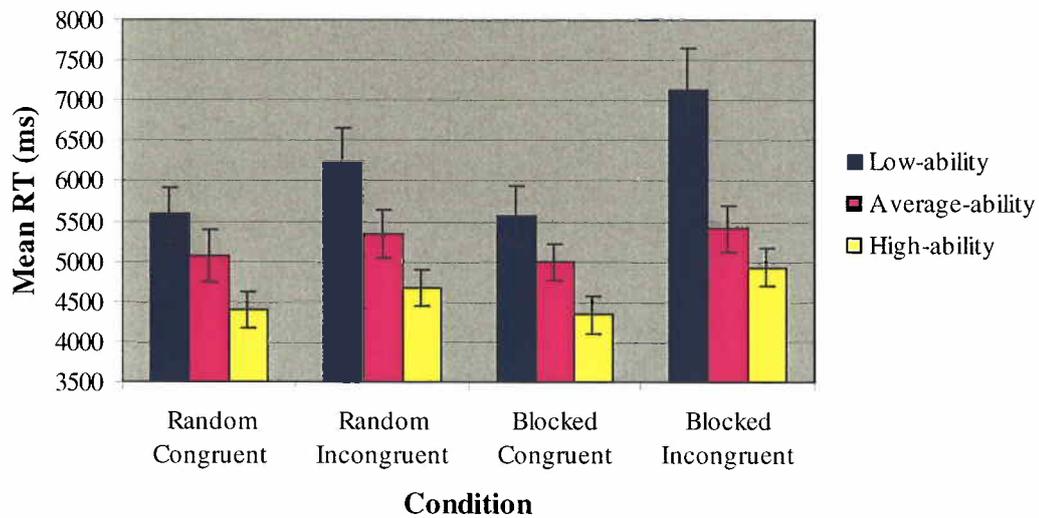
Mean response time and standard deviations scores were calculated and are presented in Table 8.2. below:

Table 8.2. Mean RT scores (& standard deviations) under blocked and random presentation formats

Condition	Measure	Presentation Format	
		Random	Blocked
Congruent	RT	5026.55	4976.97
	SD	1503.02	1478.59
Incongruent	RT	5439.24	5861.61
	SD	1726.33	2055.35

Once again, RT scores were higher in the incongruent condition than the congruent condition indicating the presence of Stroop-like interference. A 2(presentation) x 2(condition) x 3(ability) mixed design ANOVA on RT scores revealed significant main effects of condition, $F(1,67) = 75.76$, $p < 0.001$ and ability level, $F(2,67) = 6.59$, $p < 0.01$, and significant interaction effects between presentation and condition, $F(1,67) = 15.95$, $p < 0.001$, condition and ability, $F(2,67) = 11.85$, $p < 0.01$ and a 3-way interaction between presentation, condition and ability level, $F(2,67) = 4.19$, $p < 0.05$. Response time scores increased with increased inhibitory demands and they were greatest when inhibitory demands and switching requirements were both high (i.e. Blocked-Incongruent). In addition, the low-ability children were particularly affected by the increased inhibition and switching demands (see Fig. 8.1).

Fig. 8.1. Mean RT scores across conditions for low-, average- and high-ability children .

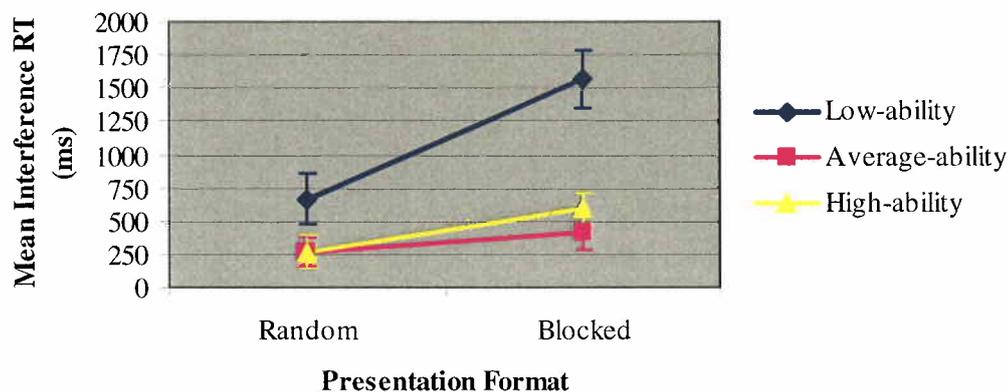


From Fig. 8.1. it is clear that, once again as expected, RT scores decreased with increasing mathematical ability and that RT scores were highest in the blocked-incongruent condition.

Interference scores

The mean interference scores for each ability level under both presentation formats are presented in Figure 8.2 below. As anticipated the low-ability children experienced greater interference under both presentation formats than both the average- and high-ability children (although the difference between ability levels was considerably smaller under random compared with blocked presentation format). In addition, interference scores were higher under blocked presentation format in comparison to random presentation format, particularly for the low-ability children.

Fig. 8.2. Mean interference under random & blocked presentation



A 2 (presentation format) x 3 (ability level) analysis of variance on interference scores revealed significant main effects of presentation format ($F(1,67) = 15.95, p < 0.01$), and ability ($F(2,67) = 11.85, p < 0.01$) and a significant interaction between presentation format and ability ($F(2,67) = 4.19 < 0.05$). See Fig. 8.2.

Figure 8.2. illustrates that under random presentation format the low-ability children experienced slightly more interference than the average- and high-ability children. Nevertheless, independent t-tests revealed no significant differences between the ability groups under random presentation format³. Under blocked presentation however, low-ability mathematicians experienced greater interference than both average- ($t = 4.42, df = 45, p < 0.01$) and high- ($t = 3.89, df = 46, p < 0.01$) ability children. In addition, for the low-ability participants, presentation format had a significant impact on interference scores, $t = 4.75, df = 24, p < 0.001$; greater interference was experienced under Blocked compared with Random presentation format. Thus, low-ability participants experienced greater interference when an additional switching requirement was included.

³ low vs. average, $t = 1.71, df = 45, p = 0.095$ (2-tailed)
low vs. high, $t = 1.69, df = 45, p = 0.099$ (2-tailed)

Mathematics ability correlated significantly with both IQ ($r = .64$, $df = 70$, $p < 0.01$) and reading ability ($r = .61$, $df = 70$, $p < 0.01$), so in order to be certain that these differences between ability levels were specifically related to mathematics ability, an analysis of covariance was also conducted controlling for IQ and reading ability. The 2(presentation format) x 3(ability) ANCOVA removed the significant main effect of presentation format, but the significant main effect of ability, $F(2,65) = 9.48$, $p < 0.01$, and the significant interaction between presentation format and ability remained, $F(2,65) = 3.2$, $p < 0.05$.

Correlational analyses

Correlational analyses were conducted in order to determine whether Stroop-like interference was significantly related to mathematical ability.

Table 8.3. Correlation coefficients between screening measures and arithmetical Stroop performance (above principal diagonal) and partial correlation coefficients controlling reading ability and IQ (below principal diagonal)

	Reading Ability	Mathematical ability	Random Interference	Blocked Interference
IQ	.63**	.64**	-.12	-.24*
Reading ability		.61**	-.08	-.21
Mathematical ability	--		-.18	-.43**
Random interference	--	-.14		.33**
Blocked interference	--	-.37**	.31*	

Note. For all correlations, $df = 70$. For partial correlations, $df = 66$.

* $p < 0.05$. ** $p < 0.01$

Table 8.3. displays the expected highly significant positive relationships between IQ, reading ability and mathematical ability. It also reveals a significant positive correlation between blocked interference and random interference scores – high interference under one presentation format was associated with high interference under the other. The most interesting result, however, was the significant negative correlation between mathematical ability and interference scores under blocked presentation format ($r = -.43$) indicating that lower mathematical ability is associated with increased interference for irrelevant information. There also existed a significant negative correlation between IQ and ‘blocked interference’, thus suggesting that efficiency of inhibition may be an element of intellectual ability in general. However, partial correlations coefficients controlling for IQ and reading ability revealed that the significant relationship between mathematical ability and blocked interference remained ($r = -.37$) indicating that efficiency of inhibition may be specifically related to mathematical ability.

Error Scores

The children had to achieve at least 75% accuracy in every condition in order to be included in the analysis hence error scores were understandably low.

As expected, however, the error scores were higher in the incongruent condition than the congruent condition and they were also higher under blocked presentation compared with random presentation format (see Table 8.3.).

Table 8.3. Mean error scores & standard deviations under blocked & random presentation formats

Ability level	Measure	Random		Blocked	
		Congruent	Incongruent	Congruent	Incongruent
Low	Mean	0.53	1.26	0.61	1.43
	SD	0.97	0.96	1.24	1.24
Average	Mean	0.5	0.68	0.69	0.91
	SD	0.67	0.84	0.63	1.08
High	Mean	0.58	1	0.5	1.28
	SD	0.65	0.96	0.57	1.2

A 2(presentation) x 2(condition) x 3(ability) repeated measures ANOVA revealed a significant main effect of condition, $F(1,67) = 25.89$, $p < 0.01$. Error scores were higher in the incongruent conditions than in the congruent conditions under both blocked ($t = 3.48$, $df = 68$, $p < 0.01$) and random ($t = 3.75$, $df = 68$, $p < 0.01$) presentation formats. As expected significantly more errors were made with the incongruent stimuli compared with the congruent stimuli, hence the error scores support the existence of Stroop-like interference. The errors were slightly higher under random presentation format compared with blocked, however, this difference did not even approach significance. There was also no significant impact of ability level on error scores.

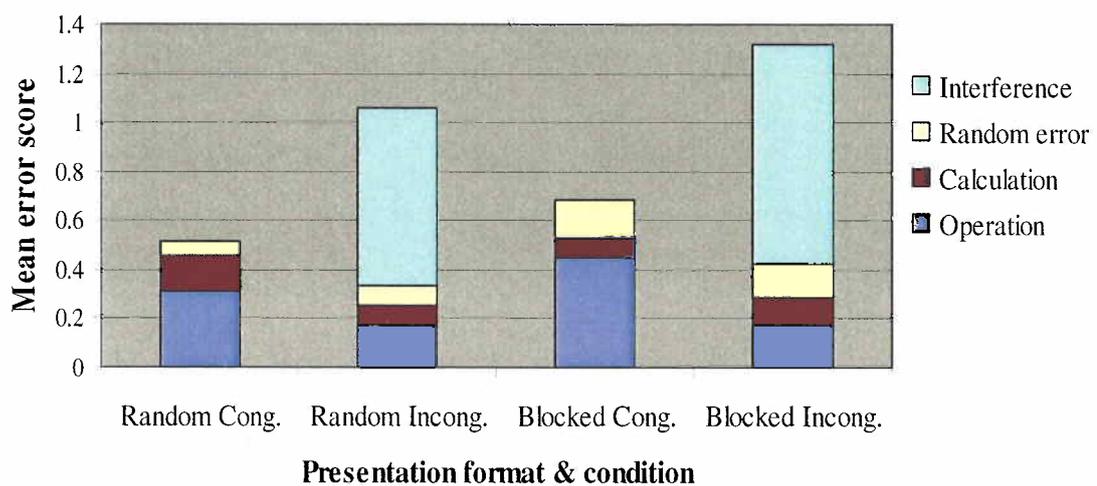
Interference errors

A 2(presentation) x 3(ability) mixed design ANOVA on interference error scores revealed no significant main effects or interaction effects.

Error Categories

Each individual error response was inspected and coded according to the apparent source of the error. The proportions of errors attributed to the categories described in the Method section were computed and are displayed in Fig. 8.2.

Fig. 8.2. Mean error score & proportional error categories



In the congruent conditions the majority of the errors could be attributed to operation confusion errors and in the incongruent condition, the majority of the errors were categorised as interference errors. Planned comparisons of these error categories were conducted for the congruent and incongruent stimuli under both presentation formats and the results of these paired t-tests are contained in Table 8.4.

Table 8.4. Paired t-test results of planned comparisons of error categories

Pres. Format & Condition	Planned Comparisons of error categories				
	Interference* calculation	Interference* operation	Interference* random	Operation* random	Operation* calculation
Random Congruent	--	--	--	t = 4.08** (df = 25)	t = 1.94, df = 25, p = 0.064
Random Incongruent	t = 7.02** df = 44	t = 5.09** df = 44	t = 6.89** df = 44	--	--
Blocked Congruent	--	--	--	t = 2.87** df = 30	t = 4.52** df = 30
Blocked Incongruent	t = 7.59** df = 44	t = 5.96** df = 44	t = 6.45** df = 44	--	--

* $p < 0.05$. ** $p < 0.01$

In the incongruent condition under both random and blocked presentation formats ‘interference errors’ occurred significantly more frequently than any of the other three categories of errors. Similarly, in the congruent condition ‘operation errors’ generally⁴ occurred significantly more frequently than the remaining two error categories.

For each error condition, under both presentation formats, one-way ANOVAs were conducted in order to determine whether there was any significant impact of ability level on the types of errors made. These analyses revealed no significant impact of ability level on the types of errors made.

⁴ In the congruent condition under random presentation format the comparison between operation and calculation errors only approached significance, $p = 0.064$.

DISCUSSION

Stroop interference

Once again both the RT and error scores were significantly higher for the incongruent stimuli in comparison with the congruent stimuli, indicating the presence of Stroop-like interference. The RT results also revealed a significant interaction between presentation format and condition, reflecting a tendency for RT scores to be highest for the incongruent stimuli under blocked presentation format. This supports the hypothesis that blocked presentation format places increased demands on the executive system due to the additional switching requirement introduced from the opportunity to establish a temporary strategy. This temporary strategy contains no inhibitory component which in turn, enhances the saliency of the irrelevant dimension (i.e. the operator symbol). Thus, when a switch is required to the incongruent condition, this irrelevant dimension gains greater access to working memory and interferes with the processing of the relevant dimension (i.e. the shape).

Interference scores

The pattern of the interference scores mirror those of the numerical variants of the Stroop task (Studies 1 and 2; see also Bull *et al.*, 2000), with the low-ability mathematicians experiencing greatest interference under blocked presentation format. These results support the proposal that low-ability mathematicians have fewer resources available to cope with the increased switching demands⁵ present under blocked presentation format. The significant main effect of ability level on

⁵ i.e. switching between temporary schemas.

interference scores under blocked presentation format persisted even after controlling for reading ability and IQ. This suggests that inhibition efficiency may be specifically related to mathematics ability rather than simply being an element of general intelligence. In addition, the increased interference scores under blocked presentation also support the proposal that low-ability mathematicians experience a particular difficulty inhibiting strategies for dealing with a task (Bull *et al.*, 2000). However, it cannot be determined whether the increased interference under blocked presentation format is due to the *type* of switching required (i.e. switching between temporary schemas is introduced under blocked presentation) or the *amount* of inhibition required (i.e. inhibiting the irrelevant dimension, inhibiting one operation in favour of another *and* inhibiting the temporary strategy).

In addition, following the results of study 4, it was anticipated that the low-ability mathematicians would experience greater interference under random presentation, due to the required frequent switching between established arithmetic strategies. It was proposed that this frequent switching resulted in the relevant arithmetical schemas (i.e. addition or subtraction) being equally activated in working memory. Hence, when presented with an incongruent equation, the unintentional activation of any strategies associated with the irrelevant operation gains greater access to working memory (e.g. + operator symbol = addition strategy). The present results follow the predicted pattern, with the low-ability children experiencing greater 'random' interference than both the average- and high-ability children however this failed to achieve significance. This was unexpected, as random presentation, in this study, contained essentially the same inhibition requirements as random presentation in Study 4 (i.e. inhibiting the irrelevant operation and switching

frequently between arithmetical operations). One, perhaps crucial, difference however, between these two studies was the inclusion of an additional rule (i.e. multiplication) in the present study. It was anticipated that this would place greater demands on working memory, and further enhance the switching demands (i.e. switching between three versus switching between two arithmetical operations) which in turn would result in increased interference levels. Clearly, this additional rule failed to have the anticipated impact on the levels of interference experienced. Consequently, little support is provided here for Roberts and Pennington's (1996) model which suggests that working memory and inhibition demands place competing demands on a single limited capacity executive system (see Chapter 9, p. 221-224 for further discussion).

So, given these expectations and the results of Study 4, why did the children not experience more interference under random presentation format? It is possible that the irrelevant multiplication operator symbol may interfere less with the processing of the relevant dimension, as the execution of multiplication may be a less autonomous process⁶ than that of addition and subtraction. For instance, multiplication is typically introduced at a later stage of a child's schooling. Thus, it is likely that for some of the children, and in particular the low-ability children, their counting/derived fact strategies are likely to be less well-established for multiplication. Consequently, the unintentional activation of these strategies is less automatic than those of addition and subtraction. So, even though the introduction of the additional multiplication rule may place additional demands on working memory, it may be easier to inhibit the irrelevant operator symbol when it is

⁶ The concept of autonomy adopted here is that a process can begin without intention triggered by the presence of a relevant stimulus. Some processes may be more autonomous than others. Autonomy is considered to be a continuum along which processes may differ rather than a strict dichotomy.

multiplication rather than addition/subtraction due to its reduced level of autonomy. For example, when presented with an equation of the format $a \times b = ?$ within a circle (i.e. addition) or square (i.e. subtraction), the irrelevant multiplication symbol will interfere less with processing, as multiplication is a less autonomous process. Thus, the presence of the irrelevant multiplication operator symbol in the incongruent conditions is less efficient at initiating counting procedures/strategies and hence easier to inhibit. Zbrodoff and Logan (1986) found evidence to support the proposal that addition is a more autonomous process than multiplication as the associative confusion effect (see Chapter 6, pp. 145-147 for description) was reduced with the addition stimuli compared with the multiplication stimuli⁷. For example, their results indicated that addition interferes more with the execution of multiplication processes than vice versa (see Zbrodoff & Logan, 1986, p. 128).

By the same token, more interference may be experienced when switching only between addition and subtraction (i.e. Study 4), than when switching between addition, subtraction *and* multiplication, as similar counting strategies are often employed to solve addition and subtraction equations. For example, counting is regularly employed to solve simple subtraction: $8 - 3$ can be solved by counting up (i.e. ...4, 5, 6, 7, 8) whilst keeping track by counting on fingers (Aubrey, 1999). Carpenter and Moser (1982) suggested that children often employ counting up (e.g. 2, 3, 4..) rather than counting down (e.g. 6, 5, 4,..) to solve subtraction as counting backwards and keeping track of counting is difficult. Thus, as similar strategies are employed this may increase the potential for interference when dealing with

⁷ Adult students participated in Zbrodoff & Logan's (1986) study.

addition and subtraction. Finally, as the children are less familiar with multiplication, the introduction of this rule may cause the children to take more care over their responding and this may reduce any potential interference effects.

So, in order to experience interference from the irrelevant dimension, the activation of cognitive processes and/or strategies appropriate to this dimension must possess a sufficient degree of autonomy, to interfere with the processing of the relevant dimension.

Correlational analyses

There was a significant correlation between mathematical ability and interference under blocked presentation format, with children of lower mathematical ability experiencing greater interference. This significant relationship held even after controlling for reading ability and IQ, suggesting that there exists a specific relationship between mathematical ability and inhibition efficiency. An alternative explanation could be that children who display greater interference do so because of greater unintentional activation of the arithmetic processes related to the irrelevant operator symbol. This unintentional activation should have enhanced the performance of these children in the congruent condition. However, the RT scores do not support this proposal as those children who took longest to respond (i.e. low-ability) to the incongruent stimuli also took longer to respond to the congruent stimuli (see Fig. 8.1.). The slower performance of the low-ability mathematicians in the incongruent condition may also be due to reduced attentional focus toward the relevant dimension or to differences in calculation speed. Attempts have been taken to control for any such differences in performance by taking performance in

the congruent condition into account when calculating interference scores. Thus, a remaining viable explanation of the relationship between mathematical ability and interference scores is reduced inhibition efficiency in children of lower mathematical ability.

Error categories

As the children had to prescribe the answer, as opposed to simply verifying the equation, it was possible to explore the type of errors the children were making. For instance, did the children employ the irrelevant operation in their solution and was this the root source of their error? In the congruent condition, under both presentation formats, the majority of errors were due to ‘operation confusion’ (i.e. one of the alternative operations was employed) and in the incongruent condition the majority of errors were the result of ‘interference errors’ (i.e. the presented irrelevant operation was employed). However, as interference errors and operation errors are conceptually very similar, it cannot be ruled out that some of the interference errors were simply operation errors. For example, operation errors in the congruent condition are most likely to be caused by confusing the ‘rules’ and/or a careless mistake. Similarly, interference errors may also be the result of ‘rule’ confusion, careless mistakes and of course through employing the irrelevant arithmetical symbol. Nevertheless, as the error scores were significantly higher in the incongruent compared with the congruent condition, and as these errors generally appeared to be the result of employing the irrelevant operation, the error data strongly suggests that the children experienced difficulty inhibiting the irrelevant information.

There was no main effect of ability level on the error scores. However, this may be attributed to the fact that error scores were low overall and that the children were required to achieve a high level of accuracy in order to be included in the analysis.

Summary

This study has also revealed that Stroop-like interference can be successfully reproduced in an arithmetic variant of the Stroop task. In addition, a similar pattern of interference as the numerical Stroop variants employed in Studies 1 and 2 and by Bull and colleagues (e.g. Bull & Scerif, 2001; Bull *et al.*, 2000) was achieved, indicating that it is a valid measure of Stroop interference. In addition, it appears that low-ability mathematicians experience a particular difficulty performing a task when required to inhibit strategies for dealing with a task. This difficulty appears to be specific to mathematical ability as the relationship between inhibition efficiency and mathematical ability remained significant even after controlling for the potential confounding variable of IQ and reading ability.

However, the present results do not enable us to determine whether the increased interference experienced by the low-ability children, under blocked presentation format, is due to the increased inhibition demands (i.e. two types of switching required) or the introduction of the novel inhibition requirement (i.e. switching between temporary strategies) present only under blocked presentation format.

The following study (Study 6) aims, by systematically and orthogonally varying inhibition and switching demands, to determine whether it is the type or amount of inhibition which results in increased interference scores.

Finally, subject to satisfactory evidence regarding its reliability, this arithmetic variant may also provide a more accurate and reliable indicator of inhibition efficiency in relation to children's performance in mathematics. These tasks are particularly attractive for educational establishments as they may serve as useful early indicators of potential difficulties in the development of mathematical skills and they are quick and easy to administer.

Chapter 9

Study 6: Is it the type or amount of inhibition demands that increases interference scores?

Overview

Studies 1 to 5 revealed that the performance of low-ability mathematicians is more susceptible to disruption from the presence of irrelevant information than that of average- and high-ability mathematicians. However, these differences in performance are typically only evident under particular conditions. For instance, both the preceding studies and Bull *et al.*'s (2000) preliminary study revealed that low-ability mathematicians experience a particular difficulty under those conditions which require the inhibition of established strategies for dealing with a task *in addition* to the inhibition of the irrelevant dimension. When the sole inhibition requirement in these earlier studies was the inhibition of the irrelevant dimension, there was no significant impact of ability level. However, it could not be determined from these studies whether the increased interference experienced by the low-ability mathematicians was due to the introduction of the switching demands alone or due to the combined switching and inhibition demands. Thus, was the increased interference due the *type* or *amount* of inhibition required?

The following study aimed to determine the locus of this increased interference and subsequently provide more valid conclusions and proposals for educationists regarding the presentation of teaching materials and the assessment/consideration of the inhibition requirements of mathematical tasks.

INTRODUCTION

Executive tasks often require participants to maintain rules in working memory whilst inhibiting any inappropriate responses (Cohen & Servan-Schreiber, 1992; Diamond, 1990; Roberts, Hager, & Heron, 1994; Roberts and Pennington, 1996). Following on from these observations, Beveridge, Jarrold and Pettit (2002) aimed to explore the interrelationship between working memory and inhibition and, based on the belief that there is a limit to executive control, they examined whether working memory and inhibition placed independent or interactive demands on the executive system.

Evidence from a number of empirical studies support this theory that executive control is not unlimited, whether from research examining typical development (e.g. Case, 1995; Welsh, Pennington & Grossier, 1991; Zelazo, Freye, & Rapus, 1996), atypical development (e.g. Barkley *et al.*, 1992; Pennington & Ozonoff, 1996; Swanson, 1993), or neuropsychological functioning (e.g. Baddeley *et al.*, 1996; Shallice & Burgess, 1991; Van der Linden *et al.*, 1992). A number of theoretical explanations also argue that executive control does not possess unlimited resources (e.g. Baddeley, 1986; Duncan, 1986; Engle, Kane, & Tuholski, 1999; Norman & Shallice, 1986; Pennington, 1994).

Considering this, it is probable that where two or more cognitive processes place enough strain on the executive then the effect of these processes will interact. If the strain is not sufficient then it is likely that the effects will simply be additive. This premise is grounded on the assumption that, up until the point is reached where the

resources of the executive system are expended, the operating characteristics of the executive system are basically linear and that it does not start to function more efficiently with increased demands. This hypothesis is actually implicit within current models of executive control and at present there is no contradictory evidence to question this proposal (see Duff and Logie, 2001, for a full discussion). In support of these proposals, Roberts and Pennington (1996) advocate an 'interactionist framework' model of executive function. For example, they proposed that working memory and inhibition both draw on the same set of resources. Consequently, it is expected that enhanced demands will be placed on the executive when the inhibition demands are raised under high as opposed to low working memory demands. Likewise, it is anticipated that increasing memory demands will have a more marked impact on the executive when inhibition demands are high rather than low.

Beveridge *et al.* (2002) further examined this proposal that the effects of working memory and inhibition are interactive. They adopted a within-task manipulation of these cognitive dimensions, which stems from Pennington's (1994) proposal that this methodology may enhance our understanding of the relationship between both tasks and disorders. For example, executive tasks typically place demands on working memory whilst simultaneously requiring the inhibition of an inappropriate response, hence this methodology should enable us to determine whether these are independently functioning components of EF. Indeed Beveridge *et al.* (2002) state:

"In order to demonstrate experimentally that EF tasks have dissociable sub-components it is not sufficient to show that varying a possible component, e.g. memory load, within a task, affects performance. It is

further necessary to demonstrate that within the same task two or more sub-components can be varied so as to produce performance effects that show independence of each other.”(p.109)

A number of other studies have also examined the impact of a working memory load on inhibitory performance (e.g. Conway, Tuholski, Shishler, & Engle, 1999; Roberts *et al.*, 1994) but these have provided mixed evidence for the interactive model. The methodology employed by Beveridge *et al.* (2002) however has an advantage over these earlier studies as it enables us to examine the impact of combining these variables on a common dependent measure of performance.

Beveridge *et al.* (2002) employed a few novel versions of popular executive functioning (EF) tasks (i.e. a Stroop-like task, a continuous performance task and a start/stop task). The working memory and inhibitory demands of these tasks were orthogonally varied¹. The results indicated that both the working memory and inhibition manipulations exerted independent effects on performance (i.e. performance was negatively affected when the working memory or the inhibitory requirements were increased). However, the results offered little support to Roberts & Pennington’s (1996) model as no interaction between the working memory and inhibition manipulations was found suggesting that memory and inhibition are separable components of EF. But, despite these results, Beveridge *et al.* highlighted that it remained possible that memory and inhibition are interactive as it remains possible that the EF tasks employed failed to place sufficient demands on the executive system.

¹ Low and high inhibitory requirements were crossed with low and high memory requirements, resulting in four conditions.

Jarrold, Beveridge, & Pettit (2003)² employed a similar methodology to Beveridge *et al.* (2002) to further explore whether executive functions can interact with one another. The Stroop-like task and continuous performance tasks employed by Beveridge *et al.* (2002) were modified to ensure they were more appropriate and demanding, following the proposal that an interaction between EFs will only occur if a general pool of executive resources is sufficiently stretched. The results again indicated that the working memory and inhibition demands have distinguishable effects on performance. However, a significant interaction between the working memory and inhibition manipulations was also found³. Thus, providing support for Roberts & Pennington's (1996) interactive framework suggesting that the two manipulations are tapping the same underlying processes and consequently place competing demands on a unitary, limited-capacity system. Others argue against this concept of a unitary system of executive function. For example, Stuss & Alexander (2000) propose that specific executive processes are related to different areas of the brain within the frontal lobes and that these processes may be under the control of a 'supervisory system': "... *There is no frontal homunculus, no unitary executive function. Rather, there are distinct processes that do converge in a general concept of control functions. The idea of a supervisory system is very applicable, if the emphasis is on a system constructed of multiple parts.*" (Stuss & Alexander, 2000, p. 291). In addition, Miyake *et al.* (2000) reported convincing evidence to suggest that executive functions are distinguishable but related by '*some underlying commonality*' (Miyake *et al.*, 2000, p. 88). They proposed that inhibition may be the unifying factor, as executive functions typically require some form of inhibitory processes in order to function effectively. Bull & Scerif's (2001) results also

² paper presented at the SRCD Biennial Conference

³ Inhibitory effects increased with memory load and memory effects increased with inhibitory load.

supported Miyake et al.'s (2000) assertions indicating that their model may also be applied to children. For instance, the results of their regression analyses revealed that inhibition efficiency, working memory span and perseveration contributed independently to predicting mathematical performance. However, significant correlations between the different EF measures suggest a degree of unity, which again was attributed to inhibition as all EFs require a degree of inhibition in order to function effectively.

Following Jarrold *et al.*'s (2003) results, it is possible that the increased interference scores of the low-ability mathematicians in Studies 1 – 5 may be attributed to an interaction between the demands of inhibition and switching. Consequently, this hypothesised interaction places competing demands on the executive system. However, this suggestion does not necessarily imply that the executive consists of a single limited-capacity system. It is equally possible that the source of this interaction stems from the shared inhibition requirement of the inhibitory and switching manipulations (Miyake *et al.*, 2000). Similarly, it is possible that the interaction revealed in Jarrold *et al.*'s (2003) study may be due to the common inhibitory requirement of the executive functions explored. For example, as with all Stroop-like tasks, the participants in Jarrold *et al.*'s study were required to inhibit the irrelevant and/or conflicting dimension. In addition, and perhaps less obviously, the working memory manipulations also resulted in participants having to inhibit one potential response in favour of another⁴.

⁴ For example, in Jarrold *et al.*'s (2003) study the children were required to remember two (low working memory) or three (high working memory) dog names, thus for each stimulus presentation, they had to inhibit the irrelevant dog name in favour of the relevant dog name.

It is beyond the scope of this thesis to ascertain whether executive functions are a unitary or diverse cognitive process or construct, and indeed attempts were not made to do so. There is considerable evidence supporting the view that our capacity for executive control is not unlimited. Nevertheless, based on the research available the position adopted here is generally supportive of Miyake *et al.*'s (2000) research that EFs are separable, but that they do contain a degree of unity. This position is adopted here as the two EFs explored clearly require inhibitory control and it is plausible that any interaction revealed will be a direct result of this. For example, even if EFs are diverse cognitive processes, any tasks involving similar demands may interact and place competing demands on one or more components.

Study 6

The main aims of the present study are to determine whether the EFs switching and inhibition place independent or interactive demands on the executive system. In addition, the relationship between these EFs, the experimental manipulations and mathematical ability will be explored. It is intended that this study will enhance our understanding of the relationship between these cognitive processes and mathematical ability.

Following the methodology employed by Beveridge *et al.* (2002), the present study independently and systematically varies the inhibition and the switching demands in order to determine whether these demands are additive and independent or whether they interact with one another. The children are once again required to provide the answer to a series of arithmetical equations. These equations are presented in colour and these colours determine which arithmetic operation the children should

employ (e.g. if the equation is green the children should employ addition). In the low inhibition (i.e. congruent) condition the colour of the equation and the operator symbol match, whereas in the high inhibition (i.e. incongruent condition) the colour of the equation and operator symbol conflict. The switching demands are varied by manipulating the order of presentation of the 'required' arithmetic operations. Low switching demands require participants to switch between blocks of addition and subtraction, while high switching demands require frequent and randomised switching between addition and subtraction⁵. Study 4 revealed that frequent switching (i.e. random presentation format) between addition and subtraction resulted in greater interference from the irrelevant dimension, for the low-ability children, compared with when only infrequent switching between these operations was required (i.e. blocked presentation format). Study 5 also provided some support for this finding although the effect was reduced.

In Studies 4 and 5, the equations were presented within a shape. As the majority of the children in the present study had participated in either Study 4 or 5 a change in stimulus materials was introduced in order to reduce any practice effects. In addition, previous research revealed that the processing of global features overrides that of local features (Navon, 1977; Stirling & Coltheart, 1977). This suggests that in Studies 4 and 5 the shape (global feature) would have been processed prior to the operator symbol, and thus potentially reduced any interference effects. The present

⁵ Study 4 revealed that frequent switching between addition and subtraction placed greater demands on the executive system compared with the infrequent switching required under blocked presentation format.

study aimed to reduce the potential conflict between the global and local features of the stimulus by simply presenting the equation in coloured ink.

Hypotheses

Following Jarrold *et al.*'s (2003) study it is predicted that the inhibition and switching demands will interact with one another particularly considering Miyake *et al.*'s proposal that inhibition may be a unifying factor of executive function. In addition, following the results of Studies 1 – 5 it is anticipated that this interaction effect will be particularly evident in the response time scores of the low-ability mathematicians. These earlier studies indicated that low-ability mathematicians have reduced executive resources, hence it is expected that there will be stronger evidence of an interaction between inhibition and switching among these children.

METHOD

Participants

78 children participated in this study, but 8 were removed due to poor performance levels leaving a final sample of 70 children. Based on the results from the mathematics screening test (i.e. WOND), 24 of these children were classified as low-ability mathematicians, 24 average-ability and 22 high-ability. The sample consisted of 34 boys and 36 girls with a mean age of 9;11 (sd = 6.76 months, range 8:11 – 11;11).

The performance characteristics on each of the screening measures for the three ability levels are displayed in Table 9.1 below:

Table 9.1 . Mean mathematics, IQ and reading standardised scores (& standard deviations) for low, average and high ability mathematicians

Ability	Screening measure		
	Mathematical ability	IQ	Reading ability
Low (N=24)	86.44 (6.36)	88.28 (10.31)	87.6 (10.69)
Average (N=24)	100.58 (3.06)	96.54 (8.71)	99.17 (10.15)
High (N=22)	112.57 (6.04)	102.83 (10.37)	104.13 (12.33)

Materials & Procedure

On any trial participants saw a coloured equation of the form $a*b = ?$ where a and b are single digits ranging from 1 to 8 and $*$ is either $+$ or $-$. All possible pairs of digits from 1 through 8 were used, however, only those equations containing a smaller addend or subtrahend were used (e.g. $4 * 3$ was employed, but $3*4$ was not, so as to avoid negative numbers for subtraction problems). This resulted in a total of 28 equations. The children were instructed to solve the equation by using the arithmetical operation defined by the colour of the equation, irrespective of the actual operation presented. The two rules employed were as follows:

- 1) *If the sum is coloured green you must use addition.*
- 2) *If the sum is coloured red you must use subtraction.*

The stimuli were presented in Times New Roman font, point size 48 on a white background.

Four conditions were formed by crossing low and high switching requirements with low and high inhibition requirements. In the low switching conditions arithmetical operations were presented in blocks (i.e. 7 addition (i.e. green), 7 subtraction (i.e. red), 7 addition, 7 subtraction), whereas in the high switching conditions the arithmetical operations are randomly presented. Low inhibition consisted of stimuli where the two dimensions matched (e.g. $4 + 3 = ?$) whereas high inhibition consisted of conflicting dimensions (e.g. $4 + 3 = ?$). So, the four conditions consisted of the following:

- 1) Low inhibition & low switching
- 2) Low inhibition & high switching
- 3) High inhibition & low switching
- 4) High inhibition & high switching

The testing session consisted of a practice block containing 12 trials and the four conditions described above each consisting of 28 trials. The 4 conditions were randomly presented across participants and the presentation order of the stimuli within each condition was randomised. Every condition contained the exact same set of equations⁶ hence calculation requirements were constant across the four

⁶ of course these equations were presented in a matching ink colour in the low inhibition conditions and a conflicting colour in the high inhibition conditions.

conditions. The children responded by pressing the appropriate number on the computer keyboard (stickers ranging from 1 -20 were placed over the keys). The testing was completed within one session lasting approximately 15 minutes. The children were invited to take a break in between each condition and they resumed testing when they felt ready to do so. The instructions were read out to them by the experimenter and they were reminded of the rules at the start of each new condition. They were asked to respond as quickly as possible but not to sacrifice accuracy for speed.

Analysis

Interference from the inhibitory manipulations was calculated for both the low and high switching conditions using the following equation:

Low switching interference = high inhibition – low inhibition

High switching interference = high inhibition – low inhibition

RESULTS

RT scores

Mean RT scores (and standard deviations) of each ability level for each of the four conditions are shown in Table 9.2 below.

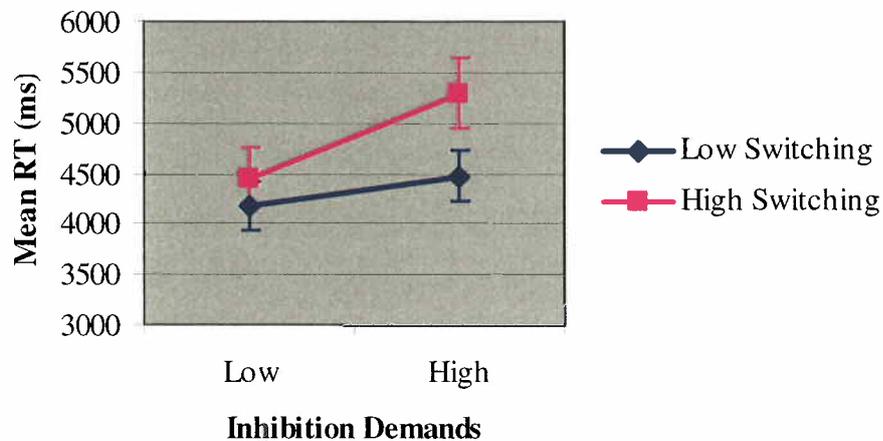
Table 9.2. Mean RT scores (& standard deviations) under high & low inhibition and switching manipulations

Ability Level	Measure	High Switching (Random)		Low Switching (Blocked)	
		Low inhibition	High inhibition	Low inhibition	High inhibition
Low	RT	4447.94	5287.62	4172.37	4469.22
	SD	1460.43	1714.93	1161.32	1229.98
Average	RT	3980.06	4333.97	3556.08	3913.24
	SD	1162.93	1436.09	1215.24	1050.39
High	RT	3476.34	3810.59	3399.07	3647.99
	SD	1378.09	1045.78	1031.47	902.8

As anticipated, RT scores decreased with increasing mathematical proficiency. In addition, every ability level displayed an increase in RT scores when inhibition and requirements were high compared to when they were low under high and low switching demands. Similarly, RT scores were also higher when switching requirements were high in comparison to when they were low under both low and high inhibition requirements. A 2 (switching) x 2 (inhibition) x 3 (ability) mixed design ANOVA confirmed these significant main effects of inhibition ($F(1,67) = 45.45, p < 0.01$), switching ($F(1,67) = 21.01, p < 0.01$) and ability level, $F(2,67) = 4.51, p < 0.05$. The interaction between switching and inhibition approached significance, $F(1,67) = 3.31, p = 0.074$, reflecting a tendency for RT scores to be higher when both switching and inhibition demands were high. Inspection of the data suggests a potential significant interaction effect for the low-ability children – response time scores were substantially higher under high inhibition and high switching demands than the remaining three conditions (see Table 9.2.).

The interaction between the inhibition and switching demands demonstrated in the RT scores of the low-ability mathematicians are displayed in Figure 9.1. below:

Fig. 9.1. Low-ability: Mean RT scores in relation to inhibition and switching demands



A 2(switching) x 2(inhibition) repeated measures ANOVA was conducted on the data of the low-ability children only and confirmed this significant interaction between inhibition and switching demands, $F(1,23) = 8.35$, $p < 0.01$. Also, once again significant main effects of inhibition, $F(1,23) = 31.39$, $p < 0.01$ and switching $F(1,23) = 10.84$, $p < 0.01$ were revealed. So, inhibitory effects increase with switching effects and vice versa.

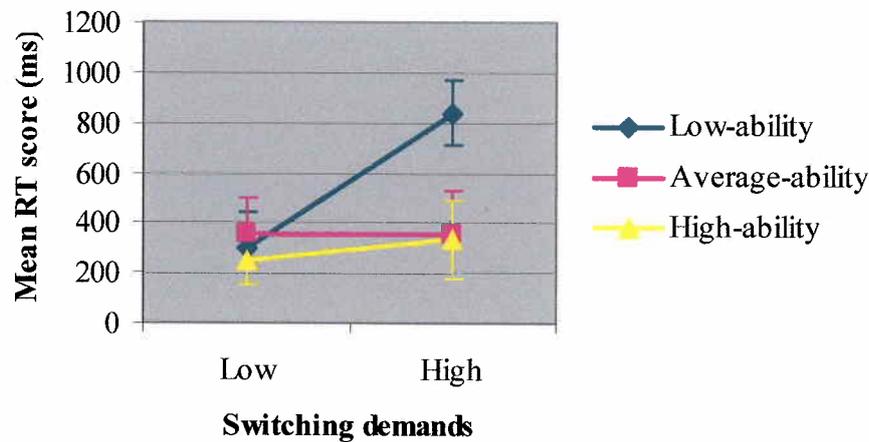
Interference Scores

In order to make a fair and valid comparison between ability levels, within-participant interference scores⁷ were calculated in order to directly compare interference scores across ability levels in relation to the switching manipulations.

These inhibition interference scores are displayed in Figure 9.2. below:

⁷ Interference = high inhibition – low inhibition

Fig. 9.2. Mean interference RT scores under low & high switching demands



When the switching demands were low, the interference scores across the three ability levels were highly comparable. However, when they were high, the low-ability children experienced greater interference than both average- and high-ability children. A 2(switching) x 3(ability) mixed design ANOVA on the interference scores revealed no significant main effects⁸ or interaction effects. However, from Fig. 9.2. it is clear that there exists a simple effect of ability level when switching demands are high. Indeed, independent t-tests revealed that when the switching demands were high, the low-ability children experienced significantly more interference than both the average- ($t = 2.24$, $df = 46$, $p < 0.05$) and high-ability children ($t = 2.48$, $df = 44$, $p < 0.05$). In addition, the interference scores of the low-ability children significantly increased under high switching compared with low switching demands ($t = 2.89$, $df = 23$, $p < 0.01$). The interference scores of the average- and high-ability children, however, indicate that the switching manipulation had little impact on performance.

⁸ Switching effect approached significance, $F(1,67) = 3.31$, $p = 0.074$

The interference scores clearly indicate that the low-ability children possess fewer executive resources to cope with the increased demands placed on the executive when both inhibition and switching demands are high. The average- and high-ability also experienced interference from the inhibitory manipulations. However, the switching manipulation did not alter this level of interference suggesting that they have sufficient resources available to cope with the increased demands when both inhibition and switching demands are high.

Correlational analyses

Correlation coefficients were calculated in order to determine whether any of the screening measures were significantly correlated with each of the four conditions and interference scores. Partial correlation coefficients were also calculated controlling for reading ability and IQ (see Table 9.3.)

Table 9.3. Correlation coefficients between screening measures and interference scores (above principal diagonal) and partial coefficients controlling for IQ and reading ability (below principal diagonal)

	2.	3.	4.	5.	6.	7.	8.	9.
1. IQ	.67**	.64**	-.22	-.24*	-.18	-.16	.06	-.09
2. Reading ability		.6**	-.33**	-.38**	-.31*	-.32**	.01	-.18
3. Math. ability	--		-.35**	-.45**	-.33**	-.34**	.02	-.28*
4. Low inhib – high switch	--	-.21		.87**	.81**	.78**	-.14	-.05
5. High inhib – high switch	--	-.33**	.85**		.85**	.84**	-.1	.45**
6. Low inhib – low switch	--	-.23	.79**	.83**		.85**	-.36**	.25*
7. High inhib – low switch	--	-.25*	.75**	.82**	.83**		.18	.29*
8. Low switching interf.	--	-.01	-.14	-.11	-.38**			.05
9. High switching interf.	--	-.26*	-.12	.42**	.21	.25*	.04	

Note: for the correlation coefficients, $df = 70$. For the partial correlations, $df = 67$.

* $p < 0.05$

** $p < 0.01$

The correlational analyses reveal that, as anticipated, all of the screening measures correlated significantly with one another. Also, each of the four conditions correlated significantly with one another indicating that a higher RT score in one condition was associated with a higher score in another. Mathematical ability was negatively related to RT in each condition indicating that a higher RT score was associated with a lower mathematical ability. After controlling for IQ and reading ability however, the relationship between mathematical ability and RT scores in the ‘low inhibition – low switching’ and ‘low inhibition – high switching’ conditions was no longer significant ($p = 0.064$ and $p = 0.08$ respectively). However, the

significant relationship between mathematical ability and the other two conditions remained. These two conditions both had high inhibition demands suggesting that mathematical ability may be more closely related to the ability to inhibit irrelevant information than the ability to switch frequently between strategies. In addition mathematical ability correlated significantly with random interference ($r = -.28, p < 0.05$), indicating that lower mathematical ability is associated with a higher amount of interference under random presentation format. This relationship remained significant after controlling for IQ and reading ability ($r = -.26, p < 0.05$).

Errors

Error scores were low, nevertheless as anticipated, the low-ability children generally made more errors across conditions than the average- and high-ability children.

Mean error scores under high and low switching and inhibition manipulations are presented in Table 9.4. below:

Table 9.4. Mean error scores (& standard deviations) under low & high switching and inhibition manipulations

Ability	Measure	Condition			
		Low switching		High switching	
		Low inhibition	High inhibition	Low inhibition	High inhibition
Low	Mean	0.75	1	1.17	1.71
	SD	0.99	1.41	1.34	1.97
Average	Mean	0.29	1.04	0.88	1.04
	SD	0.55	1.4	1.03	1.04
High	Mean	0.45	0.68	0.68	0.91
	SD	0.67	0.89	0.78	0.87

As expected, error scores were higher when switching demands were high compared to low and similarly when inhibition demands were high compared with low inhibition demands. Also, error scores were highest when both inhibition and switching demands were high. A 2 (presentation) x 2 (switching) x 3 (ability) mixed design ANOVA confirmed these significant main effects of switching $F(1,67) = 8.34, p < 0.01$, and inhibition, $F(1,67) = 9.39, p < 0.01$. However, there was no significant interaction between inhibition and switching demands.

Interference error scores were also calculated, however statistical analyses revealed no significant main effects or interaction effects.

DISCUSSION

The aim of this study was to determine whether inhibition and switching requirements place competing demands on executive resources and in doing so to determine whether it is the type of inhibition, or the amount of inhibition which causes interference. In particular, the main aim was to determine whether increasing the demands placed on the executive system whilst performing mental arithmetic has a significant detrimental impact on performance. In addition, the relationship between mathematical ability and the inhibition and switching manipulations was examined. It was predicted, following the earlier results, that the low-ability mathematicians would experience the greatest difficulty in responding to the stimuli under high switching and inhibition demands. The earlier studies in this thesis typically revealed that low-ability mathematicians experienced increased

interference when sufficient switching demands were also present. However, it was impossible to determine whether this difficulty resulted from the type of inhibition or the amount of inhibition. The methodology employed in this study overcame this difficulty as the crossing of the inhibition and switching demands enabled us to determine whether these factors placed additive or interactive demands on the executive system.

On the whole, the results indicate that the manipulations employed to vary the inhibition and switching demands were successful. However, there was no overall significant interaction between the inhibition and switching demands. So, at first glance it appears that our data fails to support Roberts and Pennington's (1996) proposals that executive functions may place competing demands on a single limited capacity executive system. In addition, since both 'types' of inhibitory manipulations (i.e. inhibition and switching) had a significant impact on response time scores, the lack of interaction between these two manipulations offers little support for the proposal that increasing the *amount* of inhibition required has a disturbing impact on performance. However, an interaction between the inhibition and switching demands should only occur if these demands placed sufficient demands on the executive system. Thus, it is possible that the absence of any interaction is because the demands placed fail to sufficiently stretch the children's executive resources.

The data from the low-ability children, however, did reveal a significant interaction between inhibition and switching, indicating that increasing the *amount* of inhibition required has a particularly disturbing impact on performance. Both the

inhibition and switching manipulations placed significant independent effects on performance signifying that *both* types of inhibition (i.e. inhibiting irrelevant information and inhibiting strategies) can exert a significant impact on performance. However, it appears that they also place competing demands on the executive system. This interaction effect only occurred for the low-ability participants, supporting the proposal that they possess fewer resources available to cope with increased executive demands. Hence, these data support Roberts and Pennington's (1996) interactive framework suggesting that the combined demands of switching and inhibition sufficiently exceed the capacity of a single limited-capacity system. However, it is equally plausible that executive functions are separable and that the present interaction between switching and inhibition arises due to the fact that both of these functions require some form of inhibitory control. Inhibition has been identified as the unifying factor between executive functions (Miyake *et al.*, 2000). Thus, when the inhibition and switching demands were both high, the inhibitory requirements of the task were increased and for low-ability children these combined demands placed a particular strain on the capacity of the executive system.

Interference scores

The interference RT scores were calculated in order to enable valid comparisons between the three ability levels. These scores revealed that when the switching demands were high the low-ability participants experienced significantly more interference than both the average- and high-ability participants. This result mirrors those of the earlier studies in this thesis which also found that low-ability participants experienced greater difficulty inhibiting the irrelevant dimension when switching requirements were introduced or increased. However, in these earlier

studies, it was impossible to determine whether the increased interference scores were due to the type of interference (i.e. switching between schemas) or the amount of interference (i.e. inhibiting a prepotent response and inhibiting an established strategy). Hence, it was impossible to determine whether the increased interference was a consequence of the switching requirement itself or a product of the *combined* switching and inhibition demands. The within-task methodology employed in the present study, however, enabled us to determine whether executive functions are to some extent, independent of one another or whether they are interactive. The response time data indicates that the difficulty experienced by low-ability participants stems from the interactive nature of these executive functioning components. An interaction was only evident in the data of the low-ability mathematicians, so this supports earlier proposals that low-ability mathematicians possess fewer executive resources and thus possess less efficient inhibition mechanisms. In addition, the data supports the proposal that “...*two processes that tap the same pool of executive resources will interact with one another once sufficient demands are placed on the executive system.*” (Beveridge *et al.*, 2002, p. 110). Thus, clearly the executive system of the low-ability mathematicians, in comparison to the average- and high-ability children, appears to possess a reduced threshold.

As anticipated, mathematical ability correlated significantly with interference levels when switching demands were high. It is proposed that children of lower mathematical ability experience greater difficulty inhibiting prepotent responses and as a result irrelevant information gains greater access to working memory. This fits with Hasher and Zack’s (1988) inhibition theory which asserts that a breakdown of

inhibitory mechanisms not only enables irrelevant information to enter working memory, but it also allows this information to remain active for a longer period of time and hence interfere more with the processing of the relevant information. An alternative explanation could be that children who experience greater interference do so because of greater automatic activation of those counting strategies specific to the irrelevant operation. Performance in the low inhibition conditions should reveal any benefits of this automatic activation. Thus, if the low-ability children experienced greater interference as a result of more automatic activation of the counting strategies one would expect their performance to be improved in the low inhibition conditions. Correlational analyses revealed a negative relationship between mathematical ability and RT scores in the low inhibition conditions, hence providing evidence against this increased automatic activation proposal. Thus, at present the most viable explanation is that low-ability mathematicians possess less efficient inhibition mechanisms.

Error data

The error scores supported the RT data, which revealed that the manipulations designed to increase the switching and inhibition demands were generally successful. They failed to support the predicted interaction between inhibition and switching demands. In addition, examination of the error scores of the low-ability children also failed to support the interaction effect found in the RT scores. Nevertheless, the pattern of the error scores followed those of the RT scores and it is possible that the lack of any significant interaction may be due to the fact that the error scores were low and that participants had to achieve a high level of accuracy in order to be included in the analysis.

Conclusion

The results support the hypothesis that low-ability mathematicians possess less efficient inhibition mechanisms and that their performance is more likely to experience adverse effects if the executive demands are increased. The data also indicate that the increased interference experienced by the low-ability mathematicians in these studies and earlier research (e.g. Bull & Scerif, 2001; Bull *et al.*, 2000) stems from the *amount* of inhibitory demands placed on the executive rather than the *type* of inhibitory demands explored.

The interaction found between the two component processes can be taken as offering some support to Roberts and Pennington's (1996) model suggesting that these two processes place demands on a unitary capacity-limited executive system. Alternatively, and equally plausible, the results offer some support to the proposal that executive functions are multiple processing modules and any interactions revealed may stem from any common requirements shared by these processes (i.e. inhibition). Obviously, further research is required before we can fully appreciate the nature of the executive system (see e.g. Miyake *et al.*, 2000).

Finally, on a more practical level the present results indicate that children experiencing difficulties in mathematics possess fewer executive resources to cope with increased demands placed upon the executive system. Hence educationists must take this into account when designing teaching materials, for example, by reducing the amount of irrelevant information presented and/or reducing the amount of task switching required. Children's poor performance in mathematics may be

related to the level of demands place upon the executive system rather than a poor ability in the task per se. So, if we can reduce the demands placed on the executive or devise strategies to help the children cope with these demands, then performance may improve.

The following study further explores the impact of irrelevant information in an area of mathematics where the ability to select the relevant information and inhibit any irrelevant dimensions is crucial for success.

Chapter 10

Study 7: The impact of irrelevant information on arithmetic word problem solving ability.

INTRODUCTION

What is involved in math word problem solving?

Mathematical word problem solving has been identified as an area of the school curriculum where a substantial amount of children experience difficulties. For example, the National Council of Teachers of Mathematics (2000) identified that word problem solving skills were relatively poor and proposed that the curriculum should focus on problem-solving across all grade levels. Nevertheless, the majority of research in the field of mathematics education has tended to focus on the computational skills of poor mathematicians (Cawley, Miller, School, 1987) with comparatively little research focusing on arithmetical word problem solving ability. This is surprising considering:

“...word problems (good examples of cognitive, linguistic and perceptual integration) are usually the least popular aspects of mathematics education programs. Even many people who solve real word problems regularly and in logical organised ways think they are unable to solve mathematical word problems.” (Sharma, 1981, p.61, cited in Leon, 1994).

Problem solving ability is an essential skill and something most people employ on a daily basis. Nevertheless, the ability to transfer these skills to a mathematical situation poses difficulties for a high proportion of children and adults. In order to successfully solve mathematical word problems the problem ‘text’ has to be translated into an arithmetical equation. Polya (1957) identified 4 steps that are required in order to successfully solve a mathematical word problem (see also Goodstein, 1981; Shaw, 1981):

1. Understanding the problem
2. Planning the solution
3. Solving the problem; and
4. Reviewing the solution within the context of the problem

(Polya, 1957, pp. 5-6)

Children who are learning disabled are believed to experience problems reaching the first step when solving word problems, as they experience difficulty appreciating exactly what is required (Cawley & Miller, 1986). Potentially, a number of factors may contribute to this difficulty, as word problem solving requires a number of skills in addition to understanding the symbolic and technical language used in mathematics. For example, children must possess proficient general reading and comprehension skills and sufficient WM resources. They must also understand the problem typology, competently identify and integrate the critical information, plan a solution, run procedures and calculations, and finally, they must also successfully cope with any extraneous information presented (Cawley, 1985; Englert, Culatta & Horn, 1987; Goodstein, 1974; Mayer, 1992). This study explores this latter requirement and examines whether low-ability mathematicians experience difficulty identifying the necessary information in arithmetical word problems, particularly in the presence of irrelevant information.

Cognitive processes involved in AWPS

Over recent years a number of theoretical frameworks have striven to describe those cognitive processes which are required for solving word problems (e.g. Nathan,

Kintsch & Young, 1992). When solving arithmetical word problems the written text is typically available throughout the solution process. Nevertheless, the controlled components of WM are still involved since understanding the text requires that any new information is integrated with any information being maintained in the WM system (Baddeley, 1990; Cornoldi, De Beni, & Pazzaglia, 1996). In addition, in order to fully understand a problem, solvers have to construct a mental representation and this requires the capacity of the WM system. In terms of Baddeley's 3-component model (see pages 19-20 for a review or Baddeley, 1986 for a full description of the model) it seems that the central executive would be more involved in word problem solving than the phonological loop, as problem solving does not simply involve the maintenance of information in WM, but requires that this information is controlled. Indeed, Swanson & Sachse-Lee (2001) proposed that *'one of the core problems children with LD [learning difficulties] face in solving mathematical word problems, beside the inefficient use of phonological processes, relates to some operations ascribed to a central executive.'* (Swanson & Sachse-Lee, 2001, p. 319). For instance, the relevance of the information has to be determined and, according to its relevance, selected or inhibited, integrated with previous information, used and so on (see also Turner & Engle, 1989). Finally, planning processes are also necessary in arithmetic word problem solving in order to maintain the essential information and organise the necessary steps in order to put in place the appropriate calculation procedures and reach a solution (Mayer, 1992).

WM appears to play a significant role in children's solution of arithmetical word problems (Anderson, Reder, & Lebiere, 1996; Hitch & McAuley, 1991; LeBlanc &

Weber-Russell, 1996; Logie, Gilhooly, & Wynn, 1994; Siegel & Linder, 1984; Siegel & Ryan, 1989; Swanson, 1993a). Cooney & Swanson (1990) found a positive correlation between the ability to successfully represent a problem schemata and WM. Moreover, learning disabled children have been found to display impaired performance on WM measures (Swanson, Cochran & Ewers, 1990; Swanson, 1994). Nonetheless, the relationship between WM and arithmetic word problem solving ability is unclear, as some researchers have failed to reveal a significant relationship. For example, Swanson, Cooney & Brock (1993) found a significant relationship between problem solving ability and WM. However, this relationship was significantly weakened once other factors (i.e. reading ability) had been controlled for. In addition, Kail and Hall (1999) found that performance on WM measures and short-term memory tasks was not reliably related to word problem solving ability.

In an attempt to overcome some of these inconsistencies, Passolunghi and Siegel (2001) aimed to further explore the relationship between WM and word problem solving using a range of tasks designed to measure WM. Siegel and Ryan (1989) found that low-ability mathematicians experienced difficulty on tasks involving numerical information, but not on tasks containing verbal information. Following this, they proposed that mathematical disability may be related to a specific difficulty in remembering arithmetical information rather than a more generalised WM deficit. Passolunghi and Siegel (2001) examined this by comparing the performance of good and poor problem solvers on a range of WM tasks. Their results did not support those of Siegel and Ryan (1989), as they suggested that low-ability mathematicians had a generalised as opposed to a specific WM deficit (i.e.

their performance was impaired on measures of WM involving both verbal and numerical information).

The causal factors of this impaired WM performance were also examined in Passolunghi & Siegel's (2001) study. In the WM tasks employed, the poor problem solvers made a high number of intrusion errors (i.e. they recalled the irrelevant information) suggesting that they experienced difficulty reducing the accessibility of the irrelevant information in WM. This result supports the literature which has postulated a relationship between WM capacity and inhibition efficiency (Bjorklund & Harnishfeger, 1990; Chiappe, Hasher, & Siegel, 2000; De Beni *et al.*, 1998; Gernsbacher, 1993; Passolunghi & Cornoldi, 2000; Passolunghi *et al.*, 1999).

Consequently, Passolunghi & Siegel (2001) proposed that the apparent WM deficit of poor problem solvers signalled problems in the central executive component of Baddeley's model (Baddeley, 1986, 1996; Baddeley & Hitch, 1974). In particular, they concluded that the reduced WM capacity of the poor problem solvers is the result of a less efficient inhibition mechanism. As a result, the poor problem solvers experience difficulty inhibiting information that was initially necessary to process, but which is no longer relevant to intentions (Passolunghi & Siegel, 2001).

Inhibitory control & arithmetical word problem solving

A number of recent studies have revealed that individual differences in WM span may be related more closely to the efficiency of an inhibition mechanism rather than to the quantity of the information presented. For example, the presence of extraneous information in mathematical word problem solving has been found to

have a detrimental effect on performance. Moreover, research has suggested that the difficulties experienced by learning disabled children are due to problems in separating the relevant from the non-relevant information (Cawley, 1985; Englert, Culatta & Horn, 1987; Blankenship & Lovitt, 1976). Leon (1994) examined children's (9-14 years) performance on problems containing extraneous and non-extraneous information and the results revealed that the presence of extraneous information was detrimental to performance. In addition, the solution strategies of the students suggested that the majority of the children were competent at arithmetical computation, but that they experienced difficulties when required to apply these skills to mathematical word problem solving solutions.

A longitudinal study by Passolunghi, Cornoldi & DiLiberto (1999) aimed to extend this research investigating the relationship between WM and problem solving ability. Also, following the results of earlier research, they aimed to examine the role of control processes (e.g. Montague, 1992; Pressley, 1990) and children's ability to select the relevant information when solving problems. They compared the performance of good problem solvers with that of poor problem solvers across a number of tasks and the results revealed that poor problem solvers exhibited poorer performance in WM tasks. In addition, the difficulties faced by the poor problem solvers on the WM tasks stemmed from difficulties in inhibiting the task irrelevant information and this interfered with their ability to recall the relevant information¹. They hypothesised that the difficulties in selecting and processing relevant information stems from an inability to inhibit irrelevant information and that this

¹ The WM task consisted of a variation of Daneman & Carpenter's (1980) listening span task which requires participants to recall specific information whilst ignoring non-specific information.

subsequently overloads WM and interferes with the processing of the relevant information (Passolunghi *et al.*, 1999).

Passolunghi *et al.* (1999) also examined inhibitory control in relation to arithmetic word problem solving ability in a more direct manner by assessing children's memory for orally presented arithmetic word problems. These problems were presented only once and, as they were too long to remember completely, the children had to focus on the more relevant elements and inhibit the less relevant elements. The results showed that poor problem solvers tended to recall less relevant information and more irrelevant information than the good problem solvers indicating that successful problem solvers are more efficient and selective in problem recall.

However, Passolunghi *et al.* (1999) suggested that these results may have stemmed from difficulties experienced in identifying which information was irrelevant rather than being unable to reduce its accessibility. Consequently, a further study examined children's ability to select the relevant information in written word problems by asking the children to underline the relevant information. This check revealed that poor problem solvers did not experience difficulty selecting the relevant information. Thus, it seems that the poor problem solvers are less able to inhibit the irrelevant information and this subsequently interferes with their ability to recall only the relevant information. This finding must be treated with caution however as both poor and good problem solvers were extremely successful at selecting the relevant information (performance was close to ceiling level). Hence, it is possible that this test failed to sufficiently discriminate between the two ability

levels. In addition, it is plausible that the written presentation of these word problems made the identification of the relevant elements easy, since the relevant information was highly salient. For example, the relevant elements typically consisted of numerical data and key terms which are common in word problems (e.g. more, less, how many?). A more appropriate test of children's ability to distinguish between the relevant and irrelevant information in arithmetical word problems would include both relevant and irrelevant numerical information.

Influence of irrelevant information

Marzocchi, Lucangeli, De Meo, Fini, & Cornoldi (2002) examined the impact of both irrelevant numerical and irrelevant verbal information on the problem solving ability of inattentive children. The irrelevant numerical (IN) information contained data which could potentially be incorporated into the problem solution, whereas the irrelevant verbal (IV) information consisted of detailed semantic elements believed to greatly enhance the surface representation of the problem. It was proposed that the IV problems would produce a more memorable trace associated with the richer semantic information (Marzocchi *et al.*, 2002).

Performance was also examined on problems containing only essential information and the inattentive children achieved a similar level of performance to the control children. This suggests that the two groups were not dissimilar in their normal problem solving ability. However, when the word problems contain irrelevant information (numerical or verbal), the performance of the inattentive children was more greatly disturbed than that of the control children. In addition, the results showed that irrelevant verbal information had a particularly disturbing impact on

performance. Marzocchi *et al.* (2002) proposed that the IV problems accessed WM with a higher level of activation due to their semantic richness.

So, the presence of both the IV and IN information impaired the ability of the inattentive children to select appropriate procedures. Procedural accuracy was also more severely impaired than calculation accuracy. This finding is consistent with the hypothesis that selecting procedures relies more on WM resources than specific numerical fact retrieval. Thus, assuming that the irrelevant information places a significant strain on WM, those processes which require greater WM resources will suffer most (i.e. procedure selection). The greater the strain placed on WM by the irrelevant information, the fewer the resources available to select the appropriate procedure (Marzocchi *et al.*, 2002).

Aims of study

The present study employs a similar methodology to Marzocchi *et al.* (2002) to examine the impact of both verbal and numerical irrelevant information on the arithmetical word problem solving ability of low-ability mathematicians. The main goal is to determine what kind of irrelevant information causes these low-ability children the greatest difficulty.

A central assumption of this study is that during problem solving, children process all of the information prior to evaluating what details are critical for the problem solution. Furthermore, in order to avoid overloading WM they must focus on the relevant information and inhibit the non-essential information.

From Marzocchi *et al.*'s (2002) study, both the IN and IV information had a detrimental impact on performance. However, the IV information had the greatest impact. But, as the IV problems were substantially longer, it is impossible to determine whether the inattentive children experienced a particular difficulty with the *type* (i.e. verbal) of irrelevant information or the *amount* of irrelevant information present. As the children were classed as inattentive, it seems probable that, due to the nature of their deficit, the difficulty experienced stemmed from the amount of irrelevant information rather than due to the 'semantic richness' of these problems as proposed by Marzocchi *et al.*, 2002. The present study aims to control for this variable by controlling for problem length in order to provide a more direct comparison between different types of irrelevant information. In addition, as no measure of attention span is taken, it was important to ensure that each condition possessed similar attention requirements.

Three conditions are employed in the present study:

- 1) Relevant Only (RO): these problems contain only the essential information necessary to solve the problem. These problems give an indication of the children's normal problem solving ability.
- 2) Irrelevant numerical (IN): these problems contain irrelevant numerical data which may appear necessary for problem solution.
- 3) Irrelevant verbal (IV): these problems contain irrelevant verbal-semantic information that is intended to enrich the surface representation of the problem. The irrelevant verbal elements consist of visually evocative words

and places and people who are familiar to the children. These were intended to produce a more memorable trace associated with their richer semantic meaning.

So, the IV problems contain interesting and ‘semantically rich’ elements.

Following Marzocchi *et al.*, (2002) it is predicted that these attributes will encourage further processing and thus they will be more difficult to inhibit.

Cornoldi, Braga, Marzocchi, Belotto, Cardi, & De Meo (2002) proposed that even when it is clear that information is irrelevant, it may still have a disturbing impact on the processing of the relevant dimensions as the deeply processed irrelevant information will consume executive resources (cited in Marzocchi *et al.*, 2002).

Thus, it is anticipated that the performance will be more disturbed in the IV condition than in the RO condition.

The IN condition presents the children with irrelevant numerical data, thus it is proposed that the children may be inclined to incorporate this data into their problem solution. This is particularly likely, as a major difficulty experienced by some children when dealing with mathematics concerns their ability to appreciate exactly what is required when they are posed a problem. Teachers have reported that “...students are nearly always searching for the steps to take in solving the problem – “how to plug in the numbers” into the equation, how to follow the algorithm. The more closely the ordering of words in a problem parallels the order of symbols in the equation, the easier the problem is to solve and the more students will like it.” (Gardner, 1991, p. 165). If the children rely on this key word strategy, it is highly likely that the irrelevant numerical information will interfere with

processing, and that these irrelevant elements may be included in the solution. In addition, in the IN condition, the irrelevant data appears potentially relevant. So, it is likely that these irrelevant numerical elements will gain greater access to WM, resulting in difficulty in inhibiting these elements upon realising their irrelevancy. Consequently, contrary to Marzocchi *et al.*'s (2002) findings, it is hypothesised that the children will experience greatest disturbance in this condition since it is less clear which information is relevant to intentions than in the IV and RO conditions.

Blankenship & Lovitt (1976) provided evidence to support the existence of this key-word strategy. They measured children's normal reading rates and found that when calculating AWPS containing extraneous information, reading rates were approximately three times faster than normal and even faster than this when solving AWPS containing only essential information. Blankenship & Lovitt (1976) also found that encouraging the children to read the problems carefully improved their performance on problems containing extraneous information. In the present study attempts were made to reduce this reliance on a key-word strategy by orally presenting the problems to the children². The children were asked to listen carefully while a problem was read out to them and only after the experimenter had finished reading the problem could they begin working out their solution.

Furthermore, it is hypothesised that the irrelevant elements will be more critical in producing procedural rather than calculation errors. The choice of appropriate procedures requires that all pieces of relevant information are processed together and appropriately integrated. Hence, this process necessarily relies more on central

² This was also required to as some of the children were also poor readers.

resources of WM (Baddeley, 1986; Douglas, 1999) than calculation processes, which may occur independently without consideration of all of the problem elements. As a result, if the irrelevant elements place sufficient demands on the executive, then these will draw upon the resources necessary for selecting an appropriate procedure.

METHOD

Participants

28 low-ability mathematicians participated in this study. 6 participants were removed due to high error rates leaving a final sample of 22 children (mean age = 10;04, sd = 4.69 months, range 9;07 – 10;10). The children had been classified as low-ability mathematicians according to their performance on a standardised mathematics test (WOND). Measures of IQ (WASI) and reading ability (WORD) were also taken. The performance characteristics of the children across these screening measures are contained in Table 10.1.

Table 10.1. Performance in mathematics, reading and IQ screening tests

Measure	Screening Test		
	Mathematics (WOND)	IQ (WASI)	Reading Ability (WORD)
Mean Score	87.82	91.64	89.91
SD	5.33	10.12	11.96
Range	78-94	75-109	72-111

Materials and procedure

A set of 15 arithmetic word problems was developed. Each problem was presented in three different versions resulting in a total of 45 problems. Descriptions of each condition and an example of each are provided below:

Relevant Only (RO): these problems contained essential information only, for example:

Mark and Alison were decorating their new club hut. They wanted to paint it and they needed 4 cans of paint. The paint cost £13 per can. How much did the paint cost?

Irrelevant Numerical (IN): these problems contained irrelevant numerical information, for example:

*Mark and Alison were decorating their new club hut. They wanted to paint it and they needed 4 cans of paint. The paint cost £13 per can. **They had saved £65 of their pocket money to buy the paint**³. How much did the paint cost?*

Irrelevant verbal-semantic (IV): these problems contained irrelevant verbal-semantic information:

*Mark and Alison were decorating their new club hut. They wanted to paint it and they needed 4 cans of paint. The paint cost £13 per can. **Alison wanted to paint Harry Potter and Ron playing quidditch on the wall.** How much money did the paint cost?*

³ Note: this information was presented in black ink to the children.

Every participant completed all 15 arithmetical word problems, which were split equally among the three conditions (i.e. 5 RO, 5 IN, 5IV). The procedural and calculation requirements were the same across participants, but the condition in which the problem was presented was randomised across participants. Within each condition, every child completed two multiplication problems, one addition problem, one subtraction problem and one two-step addition and subtraction problem. So, every child completed a set of problems which were essentially the same, apart from the type of irrelevant information they contained. The problems were presented in a mixed order which was randomised across participants.

Steps were taken to ensure that the IN and IV problems were similar in terms of word count. The RO problems were one sentence shorter due to the absence of any irrelevant information.

Participant's responses were scored according to their performance in each condition. Each response was scored for correctness. If the response was incorrect, solution strategies were examined in order to determine where the error was made (i.e. procedural or calculation). Responses were classed as procedurally incorrect when a child selected an inappropriate operation, independently of the correctness of the computation and/or the inclusion of the irrelevant numerical information (in the IN condition). Calculation errors included solutions which were procedurally correct, but incorrect in terms of computation. In the irrelevant-numerical condition an additional category was included as it was possible for the solution to be correct in terms of both procedure and calculation, but incorrect due to the substitution of a *relevant* element with an *irrelevant* element.

If they were unable to solve a problem they were told that they could ‘pass’, but that they should try to make some attempt.

Each problem was presented separately on a piece of paper, which was placed in front of the child and remained visible during problem solution. The experimenter read the problem out to the child as the child followed along. Once the problem had been read out, the child was instructed to begin and the stopclock was started. The children were asked to inform the experimenter as soon as they had finished each problem. The experimenter sat to the right of the children with a chair space in between in order to ensure that they did not feel like someone was watching over them. The children were informed that they would be timed and that the reason for this was to explore what kinds of problems took longest to solve. They were told not to worry about the time and to take as much time as they needed, but whilst they were solving a problem to concentrate as much as possible and to avoid getting distracted. The children were reassured that it was not a test and that they were just to try their best. RT scores to ‘pass’ items were removed from analysis. They were asked to write down all of their working as we were not only interested in their ability to compute correctly, but we were also interested in whether they knew which operations to employ.

The children were tested individually in a room away from the classroom and each testing session lasted approximately 15 minutes.

RESULTS

In Table 10.2, the mean number of correct/incorrect solutions and pass rates for each condition are shown.

Table 10.2. *Mean correct, incorrect and pass scores across conditions.*

Condition	Correct	Incorrect	Pass
Irrelevant Numerical (IN)	2.59 (1.1)	2.27 (1.16)	0.14 (0.35)
Irrelevant Verbal (IV)	3.82 (1.1)	1.18 (1.1)	0.05 (0.21)
Relevant Only (RO)	4.05 (0.79)	0.91 (0.75)	0.05 (0.21)

As expected, the children experienced a lower rate of success in the IN condition than in the IV and RO conditions. Paired t-tests on the correct scores confirmed this significantly reduced success in the IN condition than in both the RO ($t = 5.58$, $df = 21$, $p < 0.001$) and the IV ($t = 4.1$, $df = 21$, $p < 0.001$) conditions. The children were slightly more successful in the RO condition than in the IV condition however there was no significant difference between these conditions.

The errors were placed into categories according to the source of the error. If the children employed an inappropriate arithmetical operation, this was classified as a procedural error and if they employed the correct procedure but failed to calculate the sum correctly this was classified as a calculation error. In the IN condition the children may have employed the correct procedure and calculated the sum correctly,

however the achieved answer remained incorrect due to the inclusion of an irrelevant value rather than a relevant value. The error scores for each of these categories under the three conditions are displayed in Table 10.3.

Table 10.3. Mean error scores (& standard deviations) in relation to error categories across conditions

Error category	Condition		
	IN	IV	RO
Procedural	1.5 (1.14)	0.5 (0.86)	0.45 (0.67)
Calculation	0.59 (0.8)	0.68 (1.00)	0.45 (0.6)
Irrelevant included	0.18 (0.4)	n/a	n/a
Total	2.27 (1.16)	1.18 (1.1)	0.91 (0.75)

In total, significantly more errors were made in the IN condition than in both the IV ($t = 3.72$, $df = 21$, $p < 0.01$) and RO ($t = 5.26$, $df = 21$, $p < 0.01$) conditions.

Procedural error scores were highly comparable between the IV and RO conditions indicating that the presence of the irrelevant verbal information failed to have a significant impact on performance. In the IN condition, however, procedural error scores were higher than those in both the IV and RO conditions. Planned comparisons confirmed the predicted significant difference between the IN and both the IV ($t = 3.1$, $df = 21$, $p < 0.01$) and the RO ($t = 4.33$, $df = 21$, $p < 0.01$) conditions. There was no difference in terms of calculation errors across conditions. In addition, a higher proportion of the errors within the IN condition were due to procedural errors than calculation errors ($t = 3.38$, $df = 21$, $p < 0.01$).

Inclusion of Irrelevant Numerical Data

The phenomenon of including the irrelevant numerical information in the problem solution could only occur in the IN condition, hence there was greater scope for making errors in this condition compared with the IV and RO conditions. In Table 10.3., a small proportion of the errors (0.18) on the IN condition were classified as incorrect due to the inclusion of the irrelevant numerical data in the problem solution. This category included only those problem solutions which were otherwise procedurally and computationally correct. Thus, these errors simply consisted of those occasions where a child had substituted the relevant numerical data for the irrelevant numerical data. Consequently, this value failed to account for those errors which included the irrelevant data and were also procedurally or computationally incorrect. In order to overcome this problem, the error scores of the IN condition were re-categorised in order to account for the wider range of potential errors. Once again the categories, ‘procedural error’, ‘calculation error’ and the ‘irrelevant included’ were employed. However, in addition to this, the categories ‘procedural & irrelevant’ and ‘calculation & irrelevant’ were included to cover those response solutions which incorporated the irrelevant data in addition to being procedurally or computationally incorrect. These ‘revised’ error scores are contained in Table 10.4.

Table 10.4. Mean error scores (& standard deviations) in relation to the error categories of the IN condition

Procedural	Calculation	Procedural & irrelevant	Calculation & irrelevant	Inclusion of irrelevant
0.91 (0.8)	0.5 (0.7)	0.59 (0.7)	0.09 (0.3)	0.18 (0.4)

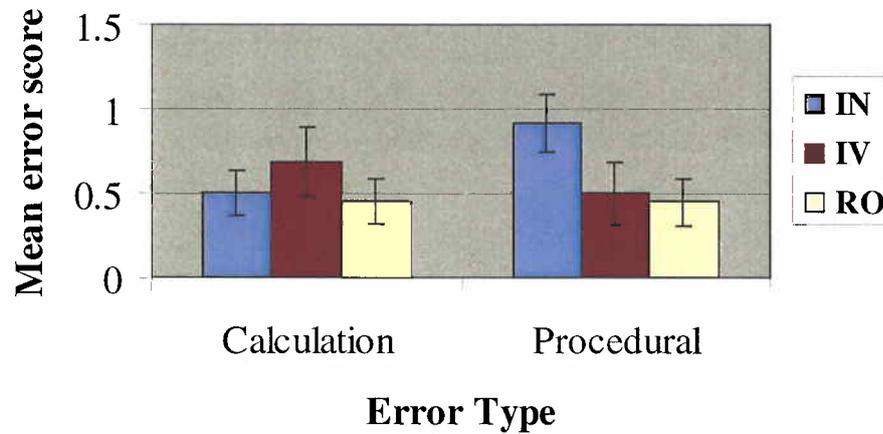
This re-categorisation resulted in a significant reduction in the number of ‘procedural’ errors ($t = 4.16$, $df = 21$, $p < 0.01$) indicating that a high proportion of the procedural errors also contained the irrelevant numerical data. There was no such significant reduction in the calculation error scores. The significant difference between the ‘procedural’ and ‘calculation’ error categories was removed, however, there were significantly fewer calculation errors containing the irrelevant data than the number of procedural errors containing the irrelevant data ($t = 2.93$, $df = 21$, $p < 0.01$). Thus, support is provided for the hypothesis that the inclusion of the irrelevant information would be more critical in producing procedural errors rather than calculation errors.

Overall, a mean of 0.86 ($sd = 0.64$) problem solutions in the IN condition contained the irrelevant information. Nevertheless, this accounted for a relatively small proportion of problem solutions (17.2%). Thus, the children were generally successful at selecting the relevant information (82.8%).

As there was more scope for making errors in the IN condition⁴, it was deemed appropriate to explore the impact of condition (i.e. IN, IV and RO) on children’s ability to adopt the appropriate procedure after managing to successfully identify the relevant elements. So, only those incorrect solutions containing the relevant elements were included in the following analysis. Fig. 10.1. below displays these ‘revised’ IN procedural and calculation error scores alongside those of the IV and RO conditions.

⁴ This was the only condition which provided the opportunity to include irrelevant numerical data in the problem solution.

Fig. 10.1. Mean error scores across conditions for those errors containing relevant only information

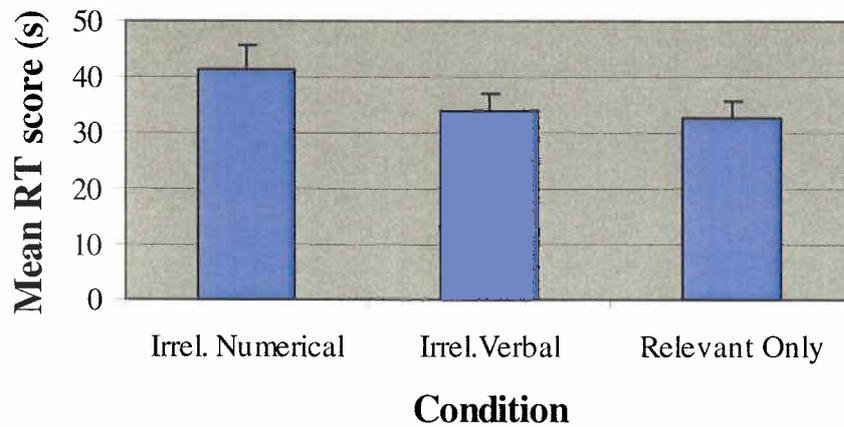


Once again, there was no significant difference in calculation error scores across conditions. However, difficulties selecting the appropriate procedure persisted in the IN condition in comparison to the IV and RO conditions. Paired t-tests revealed that even after successfully identifying the relevant elements, the children continued to experience greater difficulty selecting the appropriate procedure in the IN condition than in the RO condition ($t = 2.34, df = 21, p < 0.05$). They also continued to experience greater difficulty in the IN condition compared with the IV condition however this no longer achieved significance. These results indicate that even after successfully identifying the irrelevant numerical elements and excluding them from the solution process, they continued to interfere with processing.

Response Time

The mean response times for problem solution across conditions were calculated and are displayed in Fig. 10.2.

Fig. 10.2. Response time scores across conditions



Participants took longer to respond in the IN condition than in both the IV ($t = 2.714$, $df = 21$, $p = 0.013$) and the RO conditions ($t = 2.590$, $df = 21$, $p = 0.01$). Thus, supporting the hypothesis that the presence of irrelevant numerical information would interfere more with the children's ability to solve the arithmetical word problems than irrelevant verbal or relevant only information. The RT scores in the IV and RO conditions were highly comparable indicating that the irrelevant verbal information had little impact on processing.

DISCUSSION

Research has identified a number of different cognitive abilities and processes which are involved during problem solving (see Mayer, 1992, for a review). This study focused on the proposal that low-ability mathematicians experience difficulty inhibiting less relevant information during problem solving. In addition, those conditions which may emphasise this difficulty were also examined.

A key assumption of this study was that during problem solving both relevant and irrelevant information is processed prior to any decisions being made about which information is necessary i.e. comprehension of the problem requires that all the sentences are processed (Mayer, Larkin, & Kadane, 1984). Thus, in order to avoid overloading the WM system while successfully performing the correct procedures and calculations, the children have to concentrate on the relevant information and ignore any irrelevant information. However, any processed information unavoidably accesses WM. Nevertheless, it was presumed that irrelevant numerical information would access WM with a higher level of activation than irrelevant verbal information and consequently would interfere more with arithmetical word problem solving.

The results confirmed these expectations as performance was significantly poorer in the IN condition compared with both the IV and RO conditions. The children experienced a similar level of success in the RO and IV conditions; hence the presence of the irrelevant verbal information had little impact on performance. Of course, it was expected that the children would achieve the greatest success with those problems containing only relevant details. However, following Marzocchi *et al.*'s (2002) suggestions, it was anticipated that the irrelevant-verbal information would produce a more memorable trace in WM, as a result of its semantic richness, and that this would also interfere with their performance (Marzocchi *et al.* (2002) found that the IV information had a particularly disturbing impact on performance). However, as noted earlier, the difficulties experienced by the inattentive children with the irrelevant verbal problems may have been due to the *amount* of irrelevant

information rather than the *type* of irrelevant information. The irrelevant-verbal problems required more prolonged elaboration of the text, which increased the demands on WM and, of course, stretched the executive resources of these inattentive children. In the present study, the irrelevant-verbal problems were similar in length to the irrelevant-numerical problems, which removed this variable of problem length. The aim here was to determine whether irrelevant numerical and verbal information had a differential impact on problem solving ability and if so to determine which kind of irrelevant information enhanced these difficulties whilst controlling for any confounding variable such as problem length. In comparison with the RO problems, the IV problems contained more semantic details and they required slightly more prolonged processing (they were one sentence longer). The results revealed no difference in the accuracy or response time scores between these two conditions, suggesting that low-ability mathematicians can successfully inhibit irrelevant verbal-semantic information. However, it remains possible that if the amount of irrelevant verbal-semantic is increased to a sufficient level, excessive demands may be placed on WM and performance levels may decline. Further research is necessary to examine the impact of increasing the amount of irrelevant verbal information on performance.

The response time scores mirrored the error data; the children took longer to respond to the problems in the IN condition than both the IV and RO conditions, and the RT scores were very similar in the IV and RO conditions. This provides further support to the proposal that the irrelevant numerical information achieves a higher level of activation in WM and consequently interferes more with the solution of the arithmetical word problems.

In the IN condition, the solution processes revealed that the children successfully distinguished between the relevant and irrelevant data more than 80% of the time. Thus, even in the presence of the irrelevant numerical data, these low-ability children were generally successful at identifying the relevant data. Nevertheless, even after successfully selecting the relevant numerical information, the children continued to make significantly more procedural errors in the IN condition compared with the RO condition. Hence, even after identifying the relevant information, the irrelevant information continued to significantly disturb performance. This finding supports those of Passolunghi *et al.* (1999) where despite being able to identify the relevant elements, poor problem solvers experienced difficulty recalling only these relevant elements (i.e. they recalled irrelevant information also). In addition, these results suggest that the children were not simply adopting a key word strategy (Gardner, 1991). For instance, the irrelevant numerical data were included in the problem solutions less than 20% of the time revealing that the children were generally successful at comprehending what information was crucial. Their ability to do this may be linked to the aural presentation of these problems. This presentation format may have encouraged the children to process all of the information, prior to attempting solution, rather than using a key word strategy. Consequently, this may improve their problem comprehension enabling them to identify the relevant elements more readily. Future studies may like to examine various methods of presentation.

Overall, the results suggest that these low-ability children have little difficulty activating the relevant information, but that they do experience difficulty

suppressing the activation of any irrelevant information, particularly when this irrelevant information is in a numerical format. These results also support research examining children's reading and learning difficulties which has revealed that less-skilled readers are capable at activating the relevant information, yet they experience difficulty suppressing the activation of irrelevant information (Gernsbacher, 1993; DeBeni, Palladino, Pazzaglia, & Cornoldi, 1998). In addition, the proposals also correspond with Hasher & Zack's (1988) inhibition theory which asserts that a breakdown of inhibition mechanisms allows irrelevant information to enter WM and maintain its presence there for longer, thus allowing it to have a more damaging impact on performance.

The results also revealed that the introduction of the irrelevant numerical information impairs the children's ability to select the appropriate procedure more severely than their calculation ability. This is consistent with the hypothesis that the selection of procedures places greater demands on WM, than specific numerical fact retrieval. Thus it is likely that when any additional demands are placed (i.e. irrelevant information), procedural errors are increasingly likely to occur (see Passolunghi *et al.*, 1999). This was also supported by Marzocchi *et al.* (2002) as they found that inattentive children's ability to select the appropriate procedure was more impaired than their calculation ability by the presence of irrelevant information. In the present study, procedural accuracy was significantly more disturbed in the IN condition than in both the IV and RO conditions. This supports the proposal that the IN information placed increased demands on WM, and that this had a detrimental impact on the children's ability to make appropriate decisions concerning which arithmetical procedure to employ. The procedural requirements

were the same across conditions, thus the difficulty in the IN condition can only be attributed to the presence of the irrelevant numerical information and the enhanced demands this information places on the executive. The following quote from Marzocchi *et al.* (2002) summarises these ideas:

*“Having a larger WM space occupied by irrelevant information...children would not have sufficient space for making appropriate decisions concerning the procedures and should have a greater problem of using the irrelevant information still highly activated in WM.” (Marzocchi *et al.*, 2002, p.88).*

The present results support this proposal that the irrelevant numerical information is highly activated in WM⁵ and as consequence, increased demands are placed on WM, leaving fewer resources to cope with the demands of the word problems. This also supports Craik and Tulving's (1975) proposal that it is more difficult to inhibit those items which are subjected to more extended encoding.

Concluding points

In conclusion, from an educational point of view, these results reveal that some of the difficulties experienced by low-ability mathematicians may be due to a reduced ability to control irrelevant information, particularly when this irrelevant information appears highly relevant to intentions (i.e. the numerical data). The children achieved a high level of success in the IV and RO conditions indicating that their conceptual and procedural knowledge was sufficient. They were also

⁵ The irrelevant numerical information receives a high level of activation as it may initially appear critical to problem solution.

generally successful in the IN condition at selecting the relevant information, however, the presence of the irrelevant information appeared to continue to disturb their performance. This result strengthens the proposal that the difficulties experienced by these low-ability mathematicians may be more closely related to an inability to control the influence of irrelevant information, rather than simply being due to poor mathematical ability. Moreover, although the difficulty with inhibiting irrelevant information is presumably associated with some basic deficit, intervention strategies designed to enhance the ability to inhibit irrelevant information could be successfully implemented. For example, in terms of mathematical word problem solving, the children could be made aware of the types of irrelevant information that mainly interfere with their solution process. Furthermore, they could be trained to underline the relevant information which could serve as a memory aid, helping them to identify and retrieve the essential elements of the problem (see Jittendra, DiPipi, & Perron-Jones, 2002).

Chapter 11

General Discussion

GENERAL DISCUSSION

The role of inhibition efficiency in relation to children's arithmetical ability has been explored throughout this thesis. The overall aim of this research was to determine whether inhibition efficiency plays a specific role in the development of mathematical skills. In particular, the aim was to establish whether low-ability mathematicians possess less efficient inhibition mechanisms than average- and high-ability mathematicians. Recent research proposed that low-ability mathematicians possess less efficient inhibition mechanisms when dealing with numerical stimuli. The present research further explored this and examined whether low-ability mathematicians also experience difficulties inhibiting irrelevant information whilst performing mental arithmetic. The aim was to devise a task which would provide an accurate and natural simulation of the cognitive processes required for successful arithmetical performance and examine the impact of increased inhibitory demands on performance. A summary of the main experimental findings will be provided.

Summary of findings

Studies 1 & 2

Earlier research revealed that low-ability mathematicians demonstrated difficulties inhibiting strategies for dealing with a task. For example, Bull and Scerif (2001) employed the traditional colour-word Stroop task and a numerical Stroop variant. The results suggested that low-ability mathematicians may have a domain-specific problem with the inhibition of numerical information. Studies 1 and 2 explored this proposal

further by examining children's performance across a wider range of Stroop tasks containing verbal, numerical and pictorial stimuli.

In Studies 1 and 2, each of the six Stroop variants employed successfully produced Stroop-like interference indicating that they are all valid measures of interference. Significant presentation effects were revealed in the verbal and numerical variants, where greater interference was experienced under blocked compared with random presentation format. This supports the results of Bull *et al.*'s (2000) preliminary study. They proposed that this presentation effect stemmed from the opportunity to develop an alternative temporary strategy during the recurrent presentation of the congruent stimuli. Consequently, in addition to the inhibition requirement of the incongruent stimuli, a switching requirement is also introduced as any alternative strategy must be inhibited when it is no longer viable. The results of both the verbal and numerical variants support the proposal that blocked presentation introduces additional switching demands. However, it was proposed that a more plausible switching demand consists of switching between strategies requiring no inhibition and those which do require inhibition. This seemed more plausible as the children displayed difficulties switching from the baseline (which offered no alternative strategy) to the incongruent condition as well as when switching from the congruent to the incongruent condition.

In addition, in the numerical variants, children of lower mathematical ability showed reduced inhibition efficiency compared to high ability children in the blocked presentation format. However, under random presentation format, where there was no

necessity to inhibit temporary strategies, there were no differences between ability levels. In the 'Highest Number' variant the significant relationship between mathematical ability and inhibition efficiency held even after controlling for reading ability and IQ, indicating that inhibition efficiency may be a specific element of mathematical ability, rather than simply being an element of general intelligence.

Finally, support is also provided for the domain-specificity hypothesis as a significant relationship between mathematical ability and Stroop interference was only revealed in the numerical Stroop variants. Thus, it seems that low-ability mathematicians may have a domain-specific problem inhibiting numerical information (see Swanson, 1993) or a reduced domain-specific working memory capacity (Dark & Benbow, 1994).

Following the success of the numerical Stroop variants in supporting earlier research proposals that low-ability mathematicians possess less efficient inhibition mechanisms, the remaining experiments aimed to examine inhibition efficiency in a more naturalistic setting. It was argued that using arithmetic stimuli to examine the relationship between inhibition efficiency and mathematical ability would produce a more valid and accurate assessment of the relationship between inhibition efficiency and arithmetical ability.

Study 3

The initial attempt to construct an arithmetical Stroop variant (Study 3) was unsuccessful, as the children did not display any interference effects. In this study, the children were required to verify simple arithmetical equations. The 'incongruent' (i.e.

false-confusing) condition consisted of equations where the answer provided would have been correct, if an operation other than the one presented was employed. For example, for the equation $4 + 3 = 1$, the equation would have been true if the subtraction operator symbol had been displayed. The failure of this variant to produce Stroop-like interference was attributed to the fact that interference was reliant upon a high level of automatisisation of basic arithmetical facts.

Nevertheless, this study revealed that the children experienced greater difficulty (i.e. increased RT) under the mixed presentation formats, which required switching between two arithmetical operations, in comparison to the unmixed presentation format, where only one operation was required throughout. The switching demands of mixed presentation format also had a greater detrimental impact on the performance of the low-ability mathematicians than on the performance of children of higher mathematical ability. These results support the findings of Studies 1 and 2, suggesting that the presence of switching demands places enhanced demands on the executive system and that low-ability mathematicians have fewer resources available to cope with these increased demands. In addition, these results also suggest that the maintenance of two schemas (i.e. two counting strategies) in working memory places greater strain on the executive system and consequently reduces inhibition efficiency.

Study 4

In this study, Stroop-like interference was successfully replicated in an arithmetic Stroop variant. Following Study 3, steps were taken to ensure that conflict would be

experienced between the relevant and irrelevant stimulus dimensions in the incongruent condition. The children were presented with a simple arithmetical equation contained within a shape and instructed to employ the arithmetical equation, as defined by the shape (e.g. circle = addition, square = subtraction). In the congruent conditions, the shape and presented arithmetic operator symbol matched (i.e. circle and +), and in the incongruent condition the shape and operator symbol conflicted (i.e. square and +).

This study also presented the stimuli in blocked and random presentation formats. However, unlike Studies 1 and 2, both blocked and random presentation formats consisted of a randomised mix of congruent and incongruent stimuli. 'Blocked' and 'random' presentation therefore, referred to the presentation format of the arithmetical equations. For instance, random presentation format required frequent switching between arithmetical operations, whereas blocked presentation required switching, less frequently, between *blocks* of addition and subtraction. These switching demands were explored as they were deemed more representative of the actual switching demands present within a mathematics lesson.

The results revealed that low-ability mathematicians showed greater difficulty inhibiting a prepotent response in the random presentation format, than children of higher mathematical ability did. Thus, it seems that the high switching between arithmetical operations required under random presentation format, places additional demands on the executive system and that the low-ability children have fewer available resources. This significant impact of ability level under random presentation format

held even after controlling for reading ability and IQ, indicating that mathematical ability is specifically related to inhibition efficiency.

Study 5

Study 5 also explored Stroop-like interference using a similar arithmetical variant of the Stroop task. The stimuli included in the task were essentially the same as those in Study 4, however, an additional shape and, hence, 'rule' was included. It was anticipated that this additional rule would increase the demands placed on the executive due to the enhanced working memory requirements. Moreover, the presentation format employed was more comparable to that of Studies 1 and 2. So, blocked presentation format consisted of blocks of congruent and incongruent whereas random presentation format consisted of a randomised mix of congruent and incongruent stimuli. The presentation of equations requiring addition, subtraction or multiplication was completely randomised across both of these presentation formats.

Thus, under random presentation format the children were frequently switching between both arithmetical operations and the congruent and incongruent conditions. Consequently, under random presentation format the switching and inhibition demands were similar to those in Study 4. However, blocked presentation in Study 5 consisted of blocks of congruent and incongruent stimuli and a randomised presentation of arithmetical operations, whereas the converse was true in Study 4.

Following the results of Study 4, it was anticipated that low-ability mathematicians would experience greater difficulty inhibiting prepotent information when required to switch frequently between arithmetic operations. The pattern of results did follow this predicted trend, however, they failed to achieve significance. Thus, the presence of an additional 'rule' does not appear to significantly increase the level of strain placed on the executive system. This was contrary to expectations and contradicts the proposals of Roberts and Pennington (1996)¹. However, this lack of support may be attributed to the fact that these children possess less well-established strategies for multiplication than addition and subtraction. Hence, any unintentional activation that is related to this operator symbol is reduced, making it easier to inhibit. Furthermore, these results suggest that interference is more dependent upon the level of conflict between dimensions rather than simply on the amount of information to be remembered².

Nevertheless, as anticipated, greater interference was experienced by children of lower mathematical ability than those of higher mathematical ability under blocked presentation format. This presentation format afforded the opportunity to establish a temporary schema hence, introducing a requirement to switch between schemas in addition to the frequent switching between arithmetical operations. The results indicate that this presentation format places increased demands on the executive system and that, once again, the low-ability mathematicians demonstrate a reduced ability to cope with these demands.

¹ They proposed an 'interactive framework' model of executive functions where working memory and inhibitory task demands place a common load on a limited set of resources.

² It was proposed that there was greater conflict between addition and subtraction as they are both well-established strategies and the children may employ similar strategies to solve these problems.

Therefore, in both Studies 4 and 5, the low-ability children experienced greater difficulty inhibiting the prepotent response when required to switch between temporary schemas (i.e. blocked presentation in Study 5) and/or switching frequently between arithmetical operations (i.e. random presentation in Study 4). However, it was impossible to determine whether the increased interference experienced derived directly from the introduction of and/or increase in switching demands or whether they were the result of the combined switching and inhibition demands.

Study 6

Studies 1, 2, 4 and 5 all support the hypothesis that low-ability mathematicians possess less efficient inhibition mechanisms when dealing with numerical and arithmetical stimuli. However, as noted above, it was impossible to determine whether the increased interference scores stemmed from the additive or interactive effects of the component processes inhibition and switching. Study 6 aimed to explore this by independently and systematically varying the inhibition and switching demands of an arithmetic Stroop task.

The children were asked to provide the answer to simple arithmetic equations and to employ the operation defined by the ink colour of the equation (e.g. red = addition). These equations were placed into four conditions formed by crossing low and high inhibition requirements with low and high switching requirements. The results revealed an interaction effect between these two component processes for the low-ability children only. This indicates that the combined demands of these processes

placed sufficient demands on the executive system of these children, suggesting that they have fewer resources available to cope with the increased demands.

Thus, the results support Roberts and Pennington (1996) proposals that two component processes of executive functions will compete with one another for resources when sufficient demands are placed on a single-limited capacity system. However, the present results also offer support to Miyake *et al.*'s (2000) convincing evidence that "...executive functions may be characterised as separable but related functions that share some underlying commonality." (p.88). The source of this underlying commonality was attributed to inhibition. Consequently, the interaction found between the component processes inhibition and switching may stem from the fact that both processes placed 'inhibitory' demands on the executive system. It was beyond the scope of this thesis to determine whether executive functions possess a unitary or nonunitary nature and all that can be said at present is that there is evidence supporting the proposal that switching and inhibition demands interact for the low-ability mathematicians and that these children appear to possess fewer executive resources to cope with increased executive demands. However, further research is necessary to determine whether executive functions place separable or interactive demands on the executive system.

For present purposes, however, the findings of Study 6 suggest that increasing the *amount* of executive demands has a detrimental impact on the performance of low-ability mathematicians. Thus, suggesting the increased interference scores of the low-

ability mathematicians, under particular presentation formats, in the earlier studies stemmed from the *amount* of executive demands. However, it must be noted that any increased demands have to be sufficiently taxing on the executive system.

Study 7

Study 7 explored the hypothesis that success on arithmetical word problems (AWPs) may also be related to functions ascribed to the central executive. For example, the relevance of information has to be determined, and according to its relevance, it has to be selected, inhibited or integrated with previous information.

The performance of a group of low-ability mathematicians on AWPs containing Relevant Only (RO), Irrelevant Verbal (IV) or Irrelevant Numerical (IN) information was examined. As anticipated, the results revealed that these children experienced greater difficulty inhibiting the IN information. It was proposed that during AWPs, in order to avoid overloading the working memory system, the children have to concentrate on the relevant information and inhibit any irrelevant information. However, any information processed unavoidably accesses working memory. It is argued that the IN information interferes more with processing, as it initially appears more relevant to intentions than the IV information and hence, it enters working memory with a higher level of activation. Consequently, this information is more difficult to inhibit enabling it to stay active in working memory for a longer period of time and interfere more with processing.

As anticipated, procedural errors were higher than calculation errors. This was consistent with the hypothesis that the selection of appropriate procedures places greater demands on working memory than specific numerical fact retrieval. Procedural errors were also significantly higher in those problems containing IN information than those containing IV and RO information. This was apparent even on those occasions where the children successfully identified the relevant data. Consequently, this indicates that the children were generally successful at identifying the relevant information, but that they experience difficulty suppressing the activation of any irrelevant information.

The role of intentions

Throughout this thesis suggestions have been made indicating that the children's intentions during the tasks may have had an impact on the degree of interference experienced. Indeed, it is argued that intentionality plays a more significant role in executive functioning performance than previous theories of executive functioning have allowed: *"To date, theories of executive function have focused almost exclusively on the processing of information defined objectively from a third person perspective. Eventually, however, if we are to take seriously the suggestion that executive functioning corresponds to consciously controlled behaviour, we must attempt to reconcile our third person descriptions of cognition and behaviour with first person intentional characterisations of meaningful thought. Although this objective has largely been lost since the days of Baldwin (1897) and Piaget (1963), it is increasingly being rediscovered, both in developmental psychology (e.g. Barresi & Moore, 1996;*

Bloom & Tinker, 2001; Deák, 2000; Overton, 2003) and in other areas of psychology (e.g. Thompson & Varela, 2001; Varela, 1996)." (Zelazo *et al.*, 2003, p. 110)

A summary of the potential role of intentions in relation to the present results is now appropriate. For instance, when switching between blocks of congruent and incongruent stimuli (i.e. Studies 1, 2 and 5) there is an opportunity to establish a temporary strategy with no inhibitory component during the recurrent presentation of the congruent stimuli³. As a result, the intention to inhibit any irrelevant prepotent dimension (e.g. the operator symbol) and attempts to focus purely on the relevant dimension (e.g. the shape) diminishes. Consequently, when a switch in strategy is required, the children must inhibit this temporary strategy in favour of the more appropriate strategy. This requires the inhibition of the prepotent irrelevant dimension, which has become more relevant to intentions. This switching requirement increases the demands placed on the executive system and results in increased interference scores for those children with fewer resources available. On the other hand, when required to switch between blocks of addition and subtraction (Studies 4 & 6), the intention to perform say subtraction decreases during an addition block, whilst the intention to perform addition increases. As a result, during an addition block, for example, it is easier to inhibit the irrelevant subtraction symbol due to its reduced saliency to intentions.

³ Also during the recurrent presentation of the baseline stimuli in Studies 1 and 2.

Intentions also have a role to play under random presentation format. For example, when switching frequently between the congruent and incongruent conditions⁴, the only viable strategy is to maintain a strategy where the intention to inhibit an irrelevant dimension is high. Thus, the irrelevant dimension has less opportunity to interfere with processing, as 'inhibitory defences' are high. However, when random presentation format also consisted of frequent switching between arithmetical operations (Studies, 4, 5 and 6) the intention to perform each arithmetical operation is also high throughout. The children possess well-established addition and subtraction strategies, hence conflict is experienced between the experimenter's instructions (i.e. to use the operation defined by the rule) and the unintentional activation of strategies associated with the irrelevant operator symbol. Thus, when both operations were equally relevant to intentions and, hence, equally activated in working memory, the irrelevant operation (i.e. operator symbol) gained greater access to working memory and was able to remain activated for a longer period of time providing greater opportunity to interfere with processing.

As stated above, it appears that certain switching requirements enhance the saliency of the irrelevant dimension, making it more relevant to intentions and consequently more difficult to inhibit. Goschke (2000) supports this proposal that switch costs are influenced by intentions: *"intentions modulate or 'configure' automatic processes for voluntary action, whereas the selection of responses, though dependent on prior intentions, is influenced by various forms of involuntary processing"* (p.350). So, in the present context, children's ability to inhibit the irrelevant operator symbol in

⁴ Random presentation format of Studies 1 to 5 consisted of randomised switching between the congruent and incongruent conditions.

Studies, 4, 5 and 6 is somewhat dependent on how relevant to intentions that operator symbol is.

These proposals indicate that intentions and/or expectations may exert a significant impact on inhibition efficiency. Hence, future studies should consider their potential influence on executive functioning performance.

Implications for schools & proposals for future research

From an educational point of view, the data offer important information on low-ability mathematicians. Many difficulties met by low-ability mathematicians in learning and problem-solving may be due to an inability to control irrelevant information, rather than a poor ability in the task as such. Furthermore, although the ability to inhibit irrelevant information appears to be due to a basic inhibition deficit (at least with numerical data), this does not imply that we cannot help the children to improve this ability. It may be possible to devise strategies to improve inhibition efficiency. For example, the children could be made aware that problems may contain irrelevant information and that this may interfere with their ability to solve the problem. In addition, they could be provided with strategies to help them identify and inhibit any irrelevant information. For instance, Jitendra, DiPipi, & Perron-Jones (2002) proposed that underlining the relevant elements serves as a memory aid, which helps children to identify and retrieve the essential problem elements

The data also clearly revealed that switching between tasks and/or arithmetical strategies placed greater strain on the executive resources of the low-ability mathematicians. This should be taken into consideration when designing teaching materials and attempts could be made to minimise the number of task switches required. The children could also be made aware of the impact of task switching and they could be provided with strategies to assist their strategy switching ability. For example, in relation to switching between arithmetical operations, the children could be encouraged to note down which operation is relevant prior to solving any equation⁵.

Increasing the switching requirements failed to have a significant impact on the performance of the average- and high-ability mathematicians. This may be due to their higher level of skill, as it may be that the role of executive functions diminishes as a skill becomes more automatic. For instance, when the children are able to directly retrieve arithmetic facts and strategies from long-term memory, executive functions may play a less crucial role (Bull & Scerif, 2001). Thus, in terms of the arithmetic Stroop variants employed in the present research, the lower interference scores of the average- and high-ability children may stem from the reduced opportunity of the irrelevant information to interfere with processing. This reduced opportunity derives from their superior ability to retrieve arithmetic facts directly from LTM and to switch quickly, and with little effort, between arithmetical operations. With this in mind, it

⁵ The benefit of highlighting useful strategies stems from Vygotsky's (1962) proposals and Berk (1992) found that when children are offered strategies whilst they are actively engaged in problem solving they demonstrate improved cognitive control, self-correction and error-detection.

may be particularly important to limit the level of strategy switching and/or degree of irrelevant information present when the children are developing new strategies.

There appears to be a crucial need for longitudinal studies in order to gain a more complete understanding of developmental changes and constancy in strategy use. They would also enable us to determine whether an early delay in executive functioning results in a developmental lag in mathematical skills and whether they can be predictive of later academic performance (see Rourke & Conway, 1997). Longitudinal studies would also enable us to determine whether certain executive functions develop at different critical periods (Espy, 1997).

Finally, research has also indicated that a child's sense of control over their own learning is positively related to scholastic achievement (Dweck, 1986; Skinner, Zimmer-Genbeck, & Connell, 1998). Similarly, several researchers have suggested that the degree to which children can become self-regulators of their own learning plays a significant role in their academic success (e.g., Blair, 2002; Zimmerman & Schunk, 1989). During the primary school years, increases in cognitive control are associated with increasing internalisation of self-speech (Berk, 1992; Vygotsky, 1962). Therefore, it is possible that children experiencing difficulties in mathematics may benefit greatly from efforts to encourage them to be more actively involved in their own learning. In addition, encouraging children to "*...verbally mediate goal-directed problem solving...*" from an early age may enhance self-regulation and consequently executive control (Carlson, 2003). So, if the children feel more in control of their learning and

they appreciate the usefulness of internal speech, their level of cognitive control and consequently inhibition efficiency will increase. Carlson (2003) intimated that “*This line of research promises to show that adults have a hand in teaching children not only how to behave, but also how to think.*”

Concluding comments

Throughout this thesis, mathematical ability correlated highly with reading ability and IQ. Steps were taken to control for this through the use of analysis of covariance and partial correlation coefficients, and in Studies 2⁶, 4, 5, and 6, the results revealed a significant relationship between mathematical ability and the dependent variable after controlling for these confounding variables. Thus, it seems that inhibition efficiency may be a specific element of mathematical ability rather than simply of intellectual ability in general. However, it would be beneficial for example, to examine whether math disabled children with co-morbid reading difficulties perform differently to math disabled children with normal reading ability, across executive functioning measures.

Confusion remains surrounding the precise definition and organisation of executive functions (see, for example, Miyake et al, 2000). It was not a specific aim of this research study to provide any further clarification on these issues. The aim was simply to further explore proposals that low-ability mathematicians possess less efficient inhibition mechanisms than children of higher mathematical ability. A further goal was to determine whether the findings from the relatively artificial Stroop tasks could be

⁶ Highest Number variant only.

extended to the more naturalistic task of mental arithmetic. It was intended that this would simulate the cognitive demands of arithmetic and hence provide a more reliable representation of performance effects when executive demands are increased.

Consequently, it is argued that this research provides a more reliable indicator of the relationship between mathematical ability and inhibition efficiency. Moreover, the adoption of the more naturalistic arithmetic stimuli was intended to simulate the typical cognitive demands and consequences experienced whilst performing arithmetic. This may be extremely important, particularly as recent research has revealed that even in children, a negative relationship between mathematics anxiety and achievement in mathematics exists (Hembree, 1990). Thus, math anxiety may be more common in the low-ability mathematicians and it may contribute to their reduced inhibition efficiency. For example, mathematics anxiety has been found to interfere with conceptual thinking and memory processes (Skemp, 1986). In particular, it was proposed that MA disrupts working memory functioning, as attentional resources are diverted from the solution process by intrusive thoughts and worries (see for example, Eysenck & Calvo, 1992).

Consequently, by employing these more naturalistic stimuli, the cognitive demands placed on the executive ought to be more representative of the demands placed on the system during a typical mathematics lesson. Thus, for those children who do suffer from MA, the arithmetical Stroop variants should be more representative of the cognitive consequences of MA and of the consequent effects of manipulating the inhibition and switching demands than the more traditional Stroop variants.

This thesis has supported the proposal that low-ability mathematicians possess less efficient inhibition mechanisms. In addition, Stroop-like interference effects were successfully replicated in an arithmetic Stroop variant, which further validates the proposal that inhibition efficiency is related to mathematical proficiency. The children's performance in Study 7, the arithmetical word problem task, extended the findings from the Stroop variants employed. The results also further supported proposals that low-ability mathematicians experience difficulty inhibiting irrelevant information, particularly when this irrelevant information is highly salient to intentions.

In the Stroop task variants, significant effects of ability level were only revealed when both inhibition and switching demands were present. Study 6 indicated that inhibition and switching place competing demands on a limited capacity system. These competing demands significantly reduced the performance of the low-ability children, in comparison to that of the average- and high-ability children, suggesting that they have fewer executive resources available.

The arithmetic Stroop task devised in this thesis may also serve as a useful and indeed more reliable indicator of arithmetic performance, or indeed of an inhibitory and/or switching deficit. Hence, subject to satisfactory evidence regarding its reliability, this task may be appealing to educators.

Nonetheless, it must be noted that this research was exploratory in nature and the precise relationship between mathematical ability and executive functioning remains

undefined. Clearly, a considerable amount of research is required to further our understanding of the nature of executive functions and their impact on scholastic achievement. In order to fully understand the nature of executive function, future research must adopt longitudinal and multi-method approaches and also take into account developmental issues, the role of intentions, experiences and emotions.

Finally, this research has revealed that when sufficient demands are placed upon the executive system, low-ability mathematicians demonstrate a lack of inhibition efficiency, resulting in difficulties inhibiting irrelevant information and switching between schemas. Nonetheless, it is clear that further research examining the relationship between executive functioning and mathematical skills is required. It is hoped that future research will result in a clearer understanding and appreciation of the difficulties experienced by low-ability mathematicians. Accordingly, this will enable more tailored intervention strategies, aimed at helping these children to overcome and/or circumvent any problems.

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