Inhibitory control and children's mathematical ability.

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CONTENTS

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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:

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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 that 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 & Dungelhoff, 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 that 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. Interference = Incongruent RT – 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. Facilitation = Baseline RT – 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*