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Working Memory and its Role in Children's Scholastic Attainment

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Thesis submitted for the Degree of Doctor of Philosophy

University of Durham, Department of Psychology

2005

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Declaration

None of the data or material contained in this thesis has been submitted for previous or simultaneous consideration for a degree in this or any other university.

Study 1 is reported (under my maiden name) in:

Jarvis, H.L. & Gathercole, S.E. (2003). Verbal and nonverbal working memory and achievements on national curriculum tests at 11 and 14 years of age. *Educational and Child Psychology, 20,* 123-140.

Study 3 is reported in:

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Statement of copyright

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Helen St Clair- Thompson

Working memory and its role in children's scholastic attainment

PhD, 2005

Abstract

Previous research has identified links between working memory and scholastic skills. This thesis reports five studies that investigated both the role of working memory in children's scholastic attainment and the resources that underlie working memory task performance. Study 1 demonstrated that both verbal and nonverbal working memory were important predictors of children's academic achievement at 11 and 14 years of age. Study 2 provided evidence for the utility of working memory as a predictor of later academic achievement. Study 3 demonstrated a distinction between the executive processes of inhibition and updating working memory, both of which were uniquely related to children's scholastic attainment scores. Study 4 revealed that both speeds of processing and working memory span scores predicted unique variance in children's educational attainment. The relationships between speed and span in tasks varying in difficulty were also explored. Speed and span did not always conform to the same linear relationship. Study 5 explored a metric of cognitive cost suggesting that working memory task performance is determined by the difficulty of the retrievals required and the number of these retrievals divided by the time allowed to perform them. The results demonstrated that working memory task performance is constrained by temporal duration and the nature of processing activities. The results were discussed in terms of implications for models of working memory and implications for educational practice.

Chapter 1

General Introduction

The term 'working memory' refers to a limited capacity system responsible for the simultaneous storage and manipulation of information during the performance of cognitive tasks (Baddeley, 1986). It plays an essential role in cognitive tasks such as reading and arithmetic and has thus been linked with scholastic achievement (e.g. Gathercole, Brown, & Pickering, 2003; Gathercole & Pickering, 2000, Gathercole, Pickering, Knight, & Stegmann, 2004). This thesis is concerned with both the measurement and assessment of working memory and the role of working memory in children's educational attainment. As an introduction to the experiments presented in this thesis this chapter will provide a general overview of working memory, the tasks used to assess working memory, and the role of the components of working memory in sub- domains of skill related to education. Section 1.1 will describe models of working memory. Section 1.2 will review the tasks commonly used to assess each of the components of working memory. Section 1.3 will discuss the role of working memory in complex cognitive skills including vocabulary acquisition, language comprehension, reading, spelling and writing, speaking, counting, mental arithmetic, and other mathematical skills. Section 1.4 will draw together this literature in suggesting a role for working memory in educational attainment. Finally, section 1.5 will summarise the main points addressed in the thesis.

1.1: Models of Working Memory

The resources proposed to underlie working memory differ widely across alternative models. According to the most widely accepted model (Baddeley, 2000; Baddeley & Hitch, 1974) working memory consists of four components. At the heart of working memory is the central executive system, a domain general limited capacity system believed to be responsible for the control and regulation of cognitive processes, including controlling the flow of information throughout working memory, the retrieval of long- term knowledge, and the completion of multiple concurrent tasks (e.g. Baddeley, 1986, 1996a; Baddeley, Emslie, Kolodny, & Duncan, 1998; Baddeley & Hitch, 1974). The central executive system is supported by two domain specific storage components: the phonological loop that is responsible for the maintenance of auditory information, and the visuo-spatial sketchpad that is specialised for dealing with visual and spatial information. Baddeley (2000) identified the episodic buffer as a further subcomponent of working memory, responsible for integrating information from the subcomponents of working memory and long- term memory.

Other theorists, however, have conceptualised working memory as a limited capacity system in which processing and storage operations compete for a limited pool of resources (e.g. Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992). The working memory in this theory corresponds approximately to the central executive system within the Baddeley and Hitch (1974) model of working memory (Just & Carpenter, 1992; Richardson, 1996). Another influential theory proposes that working memory consists of long- term memory representations activated by a limited attentional resource (e.g. Barrouillet, Bernadin, & Camos, 2004; Engle, Kane, & Tuholski,

1999). Both of these models are considered in this thesis, particularly in Chapters 4 and 5, but it is the multiple component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000) that forms the basis of the initial studies. The following sections describe, in detail, the components of this model.

1.1.1: The central executive system

The central executive is considered to be important for the processing or manipulation of information during cognitive tasks (Baddeley, 1996a). Early attempts to characterise executive processes (Baddeley, 1986) likened the central executive to the Supervisory Attentional System (SAS) discussed by Norman and Shallice (1980), a limited capacity system responsible for the control of action and attention. Baddeley has subsequently identified further functions of the central executive. These include the capacity for temporary activation of long-term memory (Baddeley, 1998), coordination of multiple tasks (e.g. Baddeley, Della Sala, Papagno, & Spinnler, 1997), shifting between tasks or retrieval strategies (Baddeley, 1996a) and the capacity to attend and inhibit in a selective manner (Baddeley & Emslie et al., 1998). It is unknown whether these functions are performed by separate cognitive systems that can be selectively impaired, or whether they are subsystems of a single executive controller (Baddeley, 1996a).

Some evidence suggests that there is some diversity among functions. It is common that only modest correlations are found between tasks tapping different central executive functions (e.g. Duncan, Johnson, Swales, & Freer, 1997; Lehto, 1996; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). There are also findings of patients with deficits in one function but

preservations in another (e.g. Baddeley et al., 1997). Such findings have prompted individual differences studies into executive functions. In a study of adult participants, Miyake et al. (2000) identified three key functions; updating, inhibition, and shifting. Updating requires monitoring and coding of incoming information and appropriately revising items held in working memory by replacing no longer relevant information with newer more relevant information (e.g. Morris & Jones, 1990). Inhibition refers to the ability to deliberately inhibit automatic or pre- potent responses (e.g. Stroop, 1935). Shifting involves shifting back and forwards between multiple tasks or mental sets (e.g. Monsell, 1996), although it is also necessary to retain trial information in the phonological loop (see Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Liefooghe, Vandierendonck, Muyllaert, Verbruggen, & Vanneste, in press; Saeki & Saito, 2004). Factor analysis indicated that the three executive functions were separable, although moderately correlated. Updating scores were also highly related to performance on operation span, a measure of working memory capacity, suggesting that a common factor underlies updating and working memory (see also: Oberauer, SüB, Wilhelm, & Witmann, 2003). The diversity of executive functions has also been studied in children. For example, Lehto, Juujarvi, Kooistra, and Pulkkinen (2003) distinguished factors for inhibition, shifting, and working memory, in line with the findings of Miyake et al. (2000) with adult participants (see also: van der Sluis, de Jong, & van der Leij, in press).

The central executive will be considered throughout this thesis in terms of its involvement in the processing of information in working memory. However, in addition to this, Chapter 3 of this thesis examines dissociations between shifting, updating, and inhibition, and looks at the relationship between these

processes and working memory. It also investigates the executive processes associated with children's attainment levels in standardised assessments of English, mathematics and science.

1.1.2: The phonological loop

The phonological loop is specialized for the storage of auditory information in working memory. It consists of two sub- components. The first is a temporary phonological store (e.g. Shallice & Warrrington, 1970; Waters, Rochon, & Caplan, 1992). This is supported by findings of phonological similarity effects in immediate serial recall i.e. poorer short- term memory for similar sounding stimuli (Baddeley, 1966; Conrad & Hull, 1964). It is assumed that this occurs because information in the loop is registered in terms of phonological features. Due to decay, items that share a similar phonological structure become more rapidly indiscriminable from one another than items with non- overlapping structures (Baddeley, 1986). Evidence suggests that all speech-based information has obligatory access to the store. For example, Colle and Welsh (1976) demonstrated that irrelevant background German speech reduced English- speaking participant's recall of digits. Spoken digits, and other words containing the same phonemes, interfere equally with digit span (Salamè & Baddeley, 1982), words that are phonologically dissimilar from words to be remembered interfere somewhat less, and pulsed noise has no effect on serial recall (Salamè & Baddeley, 1987).

The second component of the phonological loop is an active articulatory rehearsal mechanism (e.g. Shallice & Warrrington, 1970; Waters et al., 1992). Support for a rehearsal mechanism comes from findings of word length effects

i.e. findings that lists containing words of short spoken duration are better recalled than lists of words of longer spoken duration (Baddeley, Thomson, & Buchanan, 1975). The effect of word length on serial recall has been replicated many times with both children and adults (e.g. Hitch, Halliday, & Littler, 1989; Hulme, Thomson, Muir, & Lawrence, 1984; LaPointe & Engle, 1990). It is attributed to the fact that items in the phonological loop decay at a fixed rate, but can be refreshed by rehearsal. Rehearsal is assumed to be a real- time process resembling covert speech (Landauer, 1962), and therefore recall is superior for short- duration words because more of them can be rehearsed within the decay time of the phonological store. A number of studies have demonstrated linear relationships between serial recall and speech rate (see Schweickert & Boruff, 1986, for a review). Participants speaking in languages in which items are more slowly articulated also show reduced spans (e.g. Chen & Stevenson, 1988; Ellis & Henneley, 1980; Naveh- Benjamin & Ayres, 1986), and suppressing articulation by requiring participants to repeat a syllable or word aloud, impairs short- term memory for phonological material (Murray, 1967).

It is worthy of note, however, that the traditional model of the phonological loop may not be sufficient for explaining a number of phenomena attributed to verbal short- term memory. For example, a phonological similarity effect has been found with both words and nonwords of high associative value, but not with nonwords of low associative value (Lian, Karlsen, & Winsvold, 2001). This suggests that the effect may depend upon the activation of long- term memory mechanisms and occur in a higher phonological space than the phonological loop (Lian et al., 2001).

Research implicating spoken duration in the word length effect has also

been difficult to replicate (e.g. Lovatt, Avons, & Masterson, 2000). Word length

effects have been found with words matched for spoken duration (Caplan,

Rochon, & Waters, 1992), and when rehearsal has been prevented (LaPointe &

Engle, 1990). The assumption that the word length effect arises as a result of

rehearsal also assumes that different output methods should not influence the

word length effect. However, word length effects are smaller with probed recall

than serial recall (Avons, Wright, & Pammer, 1994; Henry, 1991). It has thus

been suggested that word length effects occur during the recall process rather

than during rehearsal prior to recall (Cowan, 1992, Dosher & Ma, 1998), and that

they may be a result of output complexity (Caplan et al., 1992; Service, 1998).

There are now a number of alternative models of serial recall that account for the

word length effect (e.g. Brown & Hulme, 1995; Neath & Nairne, 1995; Page &

Norris, 1998).

Within a traditional model of working memory (Baddeley & Hitch, 1974;

Baddeley, 1986) the phonological loop is also characterised as a 'slave' system

regulated and controlled by the central executive. However, recent evidence from

research into task switching suggests that inner speech can support executive

control processes (e.g. Baddeley et al., 2001; Emerson & Miyake, 2003; Saeki &

Saito, 2004; Liefooghe et al., in press), suggesting that the phonological loop

may have a more mutually reciprocal relationship with the central executive than

previously thought (Emerson & Miyake, 2003).

1.1.3: The visuo- spatial sketchpad

Evidence suggests that visuo- spatial information is stored in a system dissociable from the phonological loop. For example, memory for movements or spatial sequences is impaired by concurrent visuo-spatial tasks (Smyth, Pearson, & Pendleton, 1988; Smyth & Pendleton, 1989) but not concurrent articulation (Smyth et al., 1988). Different brain regions have also been implicated in verbal and visuo-spatial storage using positron emission tomography (PET) (e.g. Smith, Jonides, & Kroeppe, 1996), and dissociations have been found in neuropsychological patients (Baddeley, Della Sala, & Spinnler, 1991; De Renzi & Nichelli, 1975; Hanley, Pearson, & Young, 1990). Visual and spatial information is thus considered to be stored in a visuo-spatial sketchpad.

Both in its original concept (Baddeley & Hitch, 1974) and in more recent discussions (Baddeley, 1986; Logie, 1989; 1991; Morris, 1987) the visuo-spatial sketchpad has been thought of as complementary to the phonological loop. For example, Baddeley (1986) suggested that like the phonological loop, the visuo-spatial sketchpad might consist of a passive store and an active rehearsal mechanism. Evidence for a passive visual store comes from findings of visual similarity effects (e.g. Hitch, Halliday, Schaafstal, & Schraagen, 1988; Hue & Ericcson, 1988; Logie, Della Sala, Wynn, & Baddeley, 2000; Wolford & Hollingsworth, 1974), which are akin to phonological similarity effects in the phonological loop. In addition, the presentation of irrelevant pictures disrupts retention in the sketchpad (e.g. Logie, 1986; Quinn & McConnell, 1999), suggesting that visual information has obligatory access to the store, as verbal information does to the phonological loop.

Regarding the active rehearsal mechanism of the visuo-spatial sketchpad, Baddeley (1986) proposed that it might be based on a response system such as

eye movements. Idzidowski et al. (cited in Baddeley, 1986) found that voluntary eye movements interfered with spatial short- term memory performance. Baddeley also acknowledged, however, that the rehearsal mechanism could be based upon a visual attentional control system rather than eye movements.

An important distinction in the visuo-spatial sketchpad is that between visual and spatial components. A common finding is that one visual and one spatial task can be performed better than two visual tasks or two spatial tasks (Hecker & Mapperson, 1997; Logie & Marchetti, 1991; Tresch, Sinnamon, & Seamon, 1993). Logie and Pearson (1997) also tested children of different ages on a visual and a spatial task and found that performance on the tasks correlated poorly within age groups. Visual span also increased with age more rapidly than spatial span (see also; Coates, Sanderson, Hamilton, & Heffernan, 1999; Pickering, Gathercole, Hall, & Lloyd, 2001). Neuropsychological evidence also supports a fractionation between visual and spatial working memory (Farah, Hammond, Levine, & Calvanio, 1988; Hanley, Young, & Pearson, 1991; Luzzati, Vecchi, Agazi, Lesa- Bianchi, & Vergani, 1998).

Therefore, in a revised version of visuo-spatial working memory (Logie, 1995), the sketchpad consists of two subcomponents; a passive visual storage system (the 'visual cache') and an active spatial rehearsal mechanism (the 'inner scribe'). Information held in the visual cache is subject to decay and interference from new visual input. The inner scribe can refresh the contents of the cache and is also involved in planning and executing movements. Although the cache can represent spatial locations in the form of static visual patterns (Smyth & Pendleton, 1989) the retention of sequential locations or movements requires the operations of the inner scribe.

A further dissociation between visual and spatial immediate memory may lie in the requirement for executive control. Spatial memory appears to be closely related to spatial attention (e.g. Pearson & Sahraie, 2003; Smyth & Scholey, 1992), and disrupting the central executive impairs performance on spatial tasks (Morris, 1987). This link also highlights a difference between the visuo-spatial sketchpad and phonological loop. Researchers have suggested a much stronger tie between the visuo-spatial sketchpad and the central executive than between the phonological loop and central executive (e.g. Baddeley, 1996b; Baddeley, Cocchini, Della Sala, Logie, & Spinnler, 1999; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Quinn, 1998; Quinn & McConnell, 1996). For example, Baddeley et al. (1999) argued in the context of a vigilance study that maintaining a mental representation of even a single visual stimulus can be effortful and place demands upon the central executive. Miyake et al. (2001) also found that visual short- term memory and visual working memory tasks loaded on to the same factor during factor analysis. This issue will be returned to in section 1.2.3.

1.1.4: The episodic buffer

In the original conceptualisation of working memory (Baddeley & Hitch, 1974) it was assumed that the central executive comprised one or more attentional control systems, but did not itself have storage capacity, relying instead on information stored in the phonological loop, visuo-spatial sketchpad, and long- term memory (Baddeley, 1996a; Baddeley & Logie, 1999). However, this assumption created a number of problems for the working memory model. Evidence that visual and phonological factors can simultaneously influence the

recall of verbal information (Logie et al., 2000) suggests that there must be some system capable of integrating information from the subcomponents of working memory. The original model of working memory did not incorporate such a system. Also, the model did not account for the temporary storage of materials in quantities that exceed the capacity of the phonological loop and visuo-spatial sketchpad. For example, 16 or more words can be recalled if they make a meaningful sentence (Baddeley, Vallar, & Wilson, 1987), and when engaging in articulatory suppression, digit span can still be as high as five (Baddeley, Lewis, & Vallar, 1984). Patients with an impaired short- term memory and a span of only one digit can also recall four digits (Baddeley et al., 1987). This suggests that there may be an alternative means of storing verbal information.

Baddeley (2000) attempted to rectify these problems by proposing a further component of working memory, the episodic buffer. This is a limited capacity system that stores information in a multimodal code. It is capable of binding information from the slave systems of working memory and from long-term memory in to a unitary episodic representation.

1.2: The Measurement and Assessment of Working Memory

The experiments presented in this thesis employ two main methodologies: correlational and experimental. The correlational approach involves measuring performance on tasks assumed to require a particular resource such as working memory, and comparing this with another ability of interest such as educational attainment. Statistical techniques can be used to identify the amount of variance shared between the measures. It is also possible

to partial out the variance associated with other variables such as age, or even performance on another ability measure. This allows unique relationships between measures to be identified. This type of methodology is used in the experiments presented in Chapters 2 and 3. Experimental manipulations of working memory involve modifying working memory paradigms e.g. in terms of complexity. This approach is used in Chapters 4 and 5 which examine the effect of cognitive demand on performance on working memory span tasks. The following sections will review the tasks used within both correlational and experimental studies to tap the different components of working memory.

1.2.1: The central executive system

The most widely used measures of the central executive are working memory, or complex span tasks, which require both the processing and storage of information. For example, in the listening span task (Daneman & Carpenter, 1980), participants make judgements about the veracity of sentences while remembering the last word of each, and in counting span (Case et al., 1982), participants count the number of dots in a series of arrays, while remembering the successive tallies of each array. Another popular complex span task is backwards digit recall. Recalling a sequence in reverse order increases task demands, making for a central executive task (Elliot, Smith, & McCulloch, 1997; Gathercole, 1999; Gathercole & Pickering, 2000; Groeger, Field, & Hammond, 1999; Rosen & Engle, 1997). The majority of complex span tasks require verbal processing and storage. However, analogous tasks involving the processing and storage of visuo-spatial information have also been developed. For example,

Shah and Miyake (1996) developed the spatial span task, in which participants have to mentally rotate stimuli while remembering their orientations (see also: Bayliss, Jarrold, Gunn, & Baddeley, 2003; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004).

The major theoretical approaches to working memory differ in terms of the resources proposed to underlie performance on complex span tasks. The tasks were originally assumed to measure a capacity for resource sharing (Case et al., 1982; Daneman & Carpenter, 1980, Just & Carpenter, 1992). According to this view, mentioned in section 1.1, working memory capacity corresponds to the size of a limited capacity system in which resources are employed for processing and storage. For example, in the counting span task, Case et al. (1982) found a linear relationship between memory capacity and processing difficulty, as indicated by counting speed. Case et al. accounted for these results by proposing that individuals with a faster speed of processing require fewer resources for counting, enabling them to allocate more resources to memory operations. Similar resource sharing interpretations have been used to explain performance on other complex span tasks (e.g. Daneman & Carpenter, 1980; Just & Carpenter, 1992; Turner & Engle, 1989).

However, whilst consistent with a resource sharing account of working memory, the data from Case et al. (1982) have an alternative interpretation. Processing difficulty may influence working memory span not because of a trade- off between processing and storage, but because more demanding processing extends the time period over which items may be forgotten (Towse & Hitch, 1995). This account is consistent with the multiple component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000) and assumes that

participants alternate between processing and storage so is sometimes referred to as a task switching explanation. Subsequent research has provided support for this view by demonstrating that working memory span is sensitive to duration but not to difficulty of processing operations (e.g. Towse & Hitch, 1995; Towse, Hitch, & Hutton, 1998; 2000). Bayliss et al. (2003) also took independent measures of processing efficiency and storage capacity, along with administering complex span tasks. Domain- specific storage tasks made substantial contributions to performance on complex span tasks involving the same type of storage, either verbal or visuo- spatial, independently of processing efficiency. Working memory tasks are also distinguishable from tasks that measure short-term memory capacity. Several studies have demonstrated this through factor analysis (e.g. Cantor, Engle, & Hamilton, 1991; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kail & Hall, 2001; Oberauer et al., 2003). These findings present difficulties for resource sharing accounts of complex span performance.

Within the multiple resource model of working memory (Baddeley, 2000; Baddeley & Hitch, 1974), it is not entirely clear which cognitive processes are engaged by all types of complex span tasks but it is thought that the storage component of verbal complex span tasks is mediated by the phonological loop, whereas processing is supported by central executive resources (Baddeley & Logie, 1999; Duff & Logie, 2001; LaPointe & Engle, 1990; Lobley, Gathercole, & Baddeley, 2003). Some authors have linked complex span task performance more specifically with central executive functions, for example with the ability to update the contents of working memory (Engle & Tuholski et al., 1999; Jonides & Smith, 1997; Lehto, 1996; Miyake et al., 2000), the ability to shift between the

processing and storage requirements (e.g. Conway & Engle, 1996; Towse et al., 1998) and also with inhibitory processes and strategy generation (e.g. Cataldo & Cornoldi, 1998). This issue will be returned to in Chapter 3, which aims to explore the specific executive functions tapped by both verbal and visuo-spatial complex span measures.

In addition to resource sharing and resource switching, there is also a third account of the resources involved in complex span task performance. Barrouillet and Camos (2001) argued that when Towse and colleagues (Towse & Hitch, 1995; Towse et al., 1998; 2000) manipulated the duration of counting or operation solving the cognitive cost of activities might also have been altered. This issue is discussed in more detail in Chapter 5. Barrouillet and Camos (2001) suggested comparing performance on tasks in which the processing activity retained the same duration but varied in cognitive cost. Children's performance on a counting span task and an operation span task were compared. In both tasks children were asked to remember letters presented at the end of each array to be counted or operation to be solved, and then subsequently recall these letters. In a further task, children were asked to repeatedly say 'ba-ba' over the same length of time as counting dots or solving operations in the other two tasks. No difference was found between ba-ba spans and counting spans, as predicted by the task switching hypothesis. However, operation span was systematically lower than ba-ba span. From this, Barrouillet and Camos concluded that Towse et al's (1998) task switching model was an oversimplification.

Barouillet and colleagues integrated both time and resource constraints into a time- based resource- sharing model of working memory in which participants switch their attention from processing to storage *during* processing

intervals. The model is based on cognitive cost. For a given period of time the cognitive cost of a task is a function of the time during which it captures attention in such a way that the refreshing of memory traces is prevented. The longer this time, the fewer and shorter the periods of time that can be allocated to retrieving the information to be recalled (Barouillet et al., 2004). In one series of experiments Barouillet et al. demonstrated that adults working memory spans depended on the cognitive cost imposed by a processing activity and not on the total duration of processing. In a second series of experiments they provided evidence that working memory span is a function of both the number of memory retrievals the processing component requires and the time allowed to perform them. Chapter 5 of this thesis will explore this time- based resource- sharing view of complex span task performance.

A second, but related debate surrounding working memory span tasks is whether they reflect a domain free ability (e.g. Engle, Kane, & Tuholski, 1999; Turner & Engle, 1989) or specialised pools of resources (e.g. Daneman & Carpenter, 1980; Daneman & Tardiff, 1987; Just & Carpenter, 1992). The resource sharing approach to working memory originally hypothesised that the trade- off between processing and storage was domain- specific, resulting in dissociations between span tasks involving different domains of information (Daneman & Carpenter, 1980). However, the resource switching approach assumes that tasks involving different types of information are related because they employ domain- general executive resources. There does appear to be close links between verbal and numerical working memory (e.g. Engle, Cantor & Carullo, 1992; Turner & Engle, 1989), both of which correlate highly with general ability (Kyllonen & Christal, 1990) and even with nonverbal tests of

general fluid intelligence (e.g. Conway et al., 2002; Engle & Tuholski et al., 1999). However, there is contrasting evidence surrounding verbal and visuo-spatial complex span tasks.

Kane et al. (2004) suggested that there are four categories of data supporting the generality of working memory resources across verbal and visuo-spatial domains. First, verbal span can sometimes predict spatial ability, and spatial span can sometimes predict verbal ability, with cross- domain correlations as high as those within domains (Bayliss et al., 2003; Salthouse, Babcock, & Shaw, 1991; Salthouse & Mitchell, 1989; Salthouse, Mitchell, Skovronek, & Babcock, 1989; SüB, Oberauer, Wittmann, Wilhelm, & Schulze, 2002; Swanson, 1996; Swanson & Howell, 2001). Second, correlations among working memory span tasks that vary in domain are higher than those of short- term memory tasks, suggesting that short-term memory reflects more domain- specific skills and storage abilities than working memory (Babcock & Salthouse, 1990; Henry, 2001; Park, Lautenschlager, Hedden, Davidson, Smith, & Smith, 2002; Swanson & Howell, 2001). Third, individual differences in domain- specific ability can be reduced by accounting for working memory span in a different domain (Salthouse et al., 1989; Swanson & Sachse- Lee, 2001; Wilson & Swanson, 2001). Fourth, studies using latent- variable approaches find that constructs comprised of multiple verbal and spatial working memory tasks are identical or share at least 65 % of their variance (Ackerman, Beier, & Boyle, 2002; Kyllonen, 1993; Law, Morin, & Pellegrino, 1995; Oberauer, SüB, Schulze, Wilhelm, & Wittmann, 2000; Oberauer et al., 2003; Park et al., 2002; Salthouse, 1995, SüB, et al., 2002; Wilson & Swanson, 2001). Kane et al. (2004) further used a latent

variable study and found that working memory tasks largely reflected a domain-general factor.

However, there is some evidence for dissociations between verbal and visuo-spatial complex span tasks. For example, complex span tasks involving verbal information correlate highly with verbal abilities such as text comprehension, where as those involving spatial information do not (Daneman & Tardiff, 1987; Jurden, 1995; Morell & Park, 1993). Further evidence was provided by Shah and Miyake (1996) who demonstrated that performance on a verbal complex span task correlated with performance on measures of verbal ability, but not measures of spatial ability. Spatial span showed the converse pattern. In a factor analysis the spatial task and spatial ability measures yielded one factor, and verbal span and verbal abilities yielded another. Similar findings have been reported by Friedman and Miyake (2000) and Handley, Capon, Copp, and Harper (2002). The separability of verbal and nonverbal working memory resources is further examined in Chapter 2 of this thesis, which also examines the associations between verbal and nonverbal working memory and children's attainment levels on standardised tests of English, mathematics and science.

1.2.2: The phonological loop

The paradigm that is commonly used to assess phonological loop functioning is the immediate serial recall of verbal information. In such tasks presentation of a sequence of memory items is followed by a cue for the participant to recall the items in their original order (e.g. Conrad & Hull, 1964). Recall is typically either spoken or written, and responses are only scored correct

if an item is recalled in the correct position in the sequence. Examples of such tasks include digit recall and word recall. Digit recall is the most widely used measure of verbal short- term memory and is present as a sub-test in most major standardised ability test batteries such as the Wechsler Intelligence Scale for Children (Wechsler, 1974) and the British Abilities Scale (Elliot, 1983). Tasks such as digit recall, word recall and non- word recall are included in the Working Memory Test Battery for Children (Pickering & Gathercole, 2001) which is a battery of tests designed to tap each of the phonological loop, visuo-spatial sketchpad, and central executive aspects of working memory. A number of tasks from the Working Memory Test Battery for Children are used in the experiments presented throughout this thesis.

Although it is widely believed that serial recall is supported by the phonological loop (e.g. Baddeley, 1986; Baddeley & Hitch, 1974), it has become apparent that a role might also be played by long- term knowledge. For example, recall of words is substantially better than recall of non-words (e.g. Hulme, Maughan, & Brown, 1991; Roodenrys, Hulme, & Brown, 1993). Other phenomena reflecting a contribution of long- term knowledge include the phonotactic frequency effect (Gathercole, Frankish, Pickering, & Peaker, 1999), the word frequency effect (Gregg, Freedman, & Smith, 1989; Hulme, Roodenrys, Schweickert, Brown, Martin, & Stuart, 1997), and the imageability effect (Bourassa & Besner, 1994). Furthermore, even non- word recall may involve long- term knowledge. For example, Gathercole, Willis, Emslie, and Baddeley (1991, 1992) demonstrated that repetition of non- words was linked with rated 'word likeness', suggesting that knowledge of the structure of words may be involved. None the less, serial recall provides a convenient technique for

identifying features of the memory system specialised for storing verbal material (e.g. Baddeley et al., 1975; Conrad, 1964; Henson, Noris, Page, & Baddeley, 1996).

1.2.3: The visuo-spatial sketchpad

Tasks used to tap the visuo-spatial sketchpad component of working memory are those that require the short- term retention of visual and spatial material. Based on evidence that distinct components of the visuo-spatial sketchpad may serve the storage of visual and spatial information (e.g. Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Logie, 1995; Logie & Pearson, 1997) it is valuable to consider these separately.

Tasks requiring the storage of visual information include matrix span (Logie & Pearson, 1997; Phillips & Christie, 1977), in which participants are presented with a matrix pattern with half of the squares filled, and then asked to recall the pattern. The matrix increases in size over successive trials. One particular version of matrix span is the Visual Patterns Test (Della Sala, Gray, Baddeley, & Wilson, 1997), which is used in the study presented in Chapter 2.

Tasks measuring the storage of spatial information include tasks such as Corsi blocks (Smyth & Pendleton, 1989; Smyth & Scholey, 1994) or block recall, in which a series of blocks in a three dimensional array are tapped, and the participant then attempts to tap them in the same sequence. A more recently developed measure of spatial memory is the Mazes Memory Task (Pickering et al., 2001). In this task participants view a path traced by a finger through a two dimensional maze, and then attempt to recall it.

One problem with visuo-spatial immediate memory tasks is that they may not be as pure a measure of spatial short- term memory as previously assumed (Salway & Logie, 1995). As discussed in section 1.1, maintaining a representation of even a single visual stimulus can place demands upon the central executive (Baddeley et al., 1999). Central executive tasks can also interfere with both matrix and Corsi span tasks (Hamilton, Coates, & Heffernan, 2003) and complex working memory tasks and storage only tasks in the visuo-spatial domain are not clearly distinguishable in terms of the extent to which they call upon executive resources (Miyake et al., 2001). Some research has attempted to produce cognitive tasks that tap the known components of working memory without requiring executive intervention (Hamilton et al., 2003). However, tasks reducing executive demands may result in problems due to decreasing complexity, and any manipulation will be open to a number of different interpretations (Phillips & Hamilton, 2001). Therefore matrix span and Corsi span tasks are used in the experiments presented in this thesis.

1.2.4: The episodic buffer

As mentioned in section 1.1.4, One of the most striking limitations of the original multi- component working memory model (Baddeley & Hitch, 1974) was its difficulty in accounting for the recall of prose (Baddeley & Wilson, 2002). Short- term memory span for unrelated items is typically about five while the equivalent span for sentences can be 15 or 16 words (Baddeley et al., 1987). This, however, is unlikely to be due to the involvement of long- term memory as patients with amnesia show preserved prose recall (Baddeley & Wilson, 2002).

Prose recall would appear to involve the integration of information from short-term memory (to support the verbatim recall of individual words and their order) with the products of syntactic and semantic analysis by the language processing system. It may therefore rely upon the episodic buffer component of working memory (Alloway, Gathercole, Willis, & Adams, 2004; Baddeley & Wilson, 2002).

Prose recall is therefore the task that has been used to assess episodic buffer functioning. Alloway et al. (2004) investigated the episodic buffer in children using recall of spoken sentences. Using confirmatory factor analysis, a model in which the episodic buffer was distinct from the phonological loop and central executive, as well as phonological awareness, provided the best account of the data. Other tasks tapping the episodic buffer are yet to be developed.

1.3: Working Memory and Complex Cognitive Skills

The components of working memory have been associated with cognitive activities as diverse as reading, listening, writing, solving verbal and spatial reasoning problems, and programming a computer (Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Benton, Kraft, Glover, & Plake, 1984; Daneman & Carpenter, 1980; 1983; Daneman & Green, 1986; Gathercole & Baddeley, 1993; Jurden, 1995; Kyllonen & Christal, 1990; Kyllonen & Stephens, 1990; Masson & Miller, 1983; Shah & Miyake, 1996; Shute, 1991). However, short- term memory and working memory are differentially associated with learning abilities. For example, short- term memory is consistently a poorer predictor of scholastic and intellectual task performance than is working memory (e.g. Daneman &

Carpenter, 1980; Daneman & Merikle, 1996; Engle & Tuholski et al., 1999).

This provides strong support for the distinction between short- term memory and

working memory as suggested in the multiple component model of working

memory (Baddeley & Hitch, 1974; Baddeley, 2000). This section will review the

role that each component of working memory plays in sub-domains of skill

related to education, namely, vocabulary acquisition, language comprehension,

reading, spelling and writing, speaking, counting, mental arithmetic, and other

mathematical skills.

1.3.1: Working memory and vocabulary acquisition

The ability to retain information in the phonological loop is thought to be

associated with the acquisition of syntax (e.g. Baddeley, Gathercole, & Papagno,

1998; Gathercole et al, 1992). According to this view, stable representations of

the phonological structure of words are built by abstracting the core features

from temporary representations held in the phonological loop (Brown & Hulme,

1996).

Evidence for this role of the phonological loop comes from a number of

sources. For example, across the early and middle childhood years, vocabulary is

strongly associated with a number of verbal short- term memory measures

(Baddeley et al., 1998), even when general intelligence is partialled out. Children

with good phonological memory skills have consistently been shown to have

larger vocabulary knowledge in their native language than those with poorer

memory function (e.g. Gathercole & Adams, 1994; Gathercole & Baddeley,

1989; Gathercole, Hitch, Service, & Martin, 1997; Gathercole, Service, Hitch,

Adams, & Martin, 1999; Gathercole, Willis, & Baddeley, 1991; Michas & Henry, 1994). Gifted language learners also perform better on tests of auditory digit span and non- word repetition than controls (Papagno & Vallar, 1995). Indices of phonological memory such as non-word repetition ability can also be used to predict subsequent vocabulary one year later (Gathercole & Baddeley, 1989).

Further evidence for an association between the phonological loop and word learning comes from experimental studies. Articulatory suppression, which occupies the articulatory rehearsal mechanism, impairs the acquisition of both auditory and visually presented foreign vocabulary (Papagno, Valentine, & Baddeley, 1991). Increasing phonological similarity or the length of items to be learned is also detrimental to learning new words (Papagno & Vallar, 1992).

The relationship between working memory and vocabulary acquisition is also evident in children with learning disabilities (e.g. Hulme & Mackenzie, 1992; Hulme & Roodenrys, 1995; Jarrold & Baddeley, 1997; Jarrold, Baddeley, & Hewes, 1998; 1999; 2000; Russell, Jarrold, & Henry, 1996; Varnhagen, Das, & Varnhagen, 1987; Vicari, Carlesimo, & Caltagirone, 1995). For example, Hulme and MacKenzie (1992) found lower digit spans and word spans in children with learning difficulties than in children matched for mental age. Jarrold and Baddeley (1997) and Jarrold, Baddeley, and Hewes (1999) demonstrated that children with Down's syndrome, who commonly have poor vocabulary, also have impaired digit span. Phonological memory problems have also been implicated in specific language impairment (SLI) (Bishop, North, & Donlan, 1996; Gathercole & Baddeley 1990; Kirchner & Klatzsky, 1985; Menyuk & Looney, 1976; Montgomery, 1995; 2000a; 2000b; 2002). When

compared with aged matched controls, children with SLI perform poorly on verbal memory span tests (Locke & Scott, 1979; Raine, Hulme, Chadderton, & Bailey, 1991) and on tests of non- word repetition (Dollaghen & Campbell, 1998; Edwards & Lahey, 1998; Ellis Weismer, Tomblin, Zhang, Buckwalter, Chynoweth, & Jones, 2000; Kamhi & Catts, 1986; Taylor, Lean, & Schwartz, 1989).

As discussed in section 1.1.2, the current model of the phonological loop consists of two components, the phonological store and the sub- vocal rehearsal process. It is thought that the phonological store is the fundamental mechanism linking the phonological loop to vocabulary acquisition because sub-vocal rehearsal does not appear to emerge until about seven years of age (Cowan & Kail, 1996; Gathercole & Hitch, 1993), but there is evidence of close links between phonological memory and vocabulary learning in children as young as three years (Gathercole & Adams, 1993). This makes it unlikely that the sub-vocal rehearsal process mediates the relationship between vocabulary and phonological memory.

The relationship between phonological short- term memory and native vocabulary acquisition may, however, change throughout life. For example, Ellis and Large (1988) suggested that phonological skills are particularly critical in the first year or so after a child has started to read. Gathercole et al., (1992) found that verbal short- term memory was significantly correlated to vocabulary scores at ages four, five and six, but not at aged eight (but see Gathercole & Service et al., 1999). Relationships have been found, however, between phonological short-term memory measures and native language learning in adults (Gupta, 2003). The sub- vocal rehearsal process is also thought to play a role in second language

learning later in life, as evidenced by the effects of articulatory suppression (Papagno et al., 1991).

The possible developmental decrease in the influence of phonological working memory on native vocabulary acquisition could be due to a number of factors. There may be an increase in the use of analogies with existing vocabulary when learning new words. This would reduce phonological memory load (Gathercole, Willis, & Baddeley, 1991). Also, other constraints in vocabulary development such as acquiring the meaning of new concepts become more important. Words acquired during middle and late childhood are more abstract in nature and therefore differences in semantic and conceptual skills may impose limits on the learning of new words, with the importance of phonological memory declining. Increased exposure to reading material may also explain rapid vocabulary gains (e.g. Hayes, 1988; Nagy & Anderson, 1984), possibly due to an increase in the number of strategies used for learning new words.

1.3.2: Working memory and language comprehension

It is frequently asserted that the comprehension of both written and spoken language depends on some form of working memory (e.g. Atkinson & Shiffrin, 1968; Daneman & Merickle, 1996; Kintsch & Van Dijk, 1978). This is because comprehension demands that a sentence is held in a short- term store while it is simultaneously processed (Clark & Clark, 1987). Within the framework of the multiple component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000) it would thus appear as though the phonological loop and central executive might be involved in comprehension.

Dual task interference studies have been used to investigate the role of the phonological loop in comprehension. Baddeley, Eldridge, and Lewis (1981) demonstrated a decrease in the accuracy of detecting anomalous words and transpositions in text when participants were required to engage in concurrent articulatory suppression. There was not a decrease in accuracy, however, with concurrent tapping. Waters, Kamoda, and Arbuckle (1985) found that irrelevant articulation did not impair reading for meaning, but Waters, Caplan, and Hildebrant (1987) demonstrated that articulatory suppression significantly increased the response times for reading sentences containing two propositions, but not one proposition. A similar pattern of findings was obtained for accuracy. This finding supports the notion that the phonological loop contributes to the linguistic processing of complex sentences. Neuropsychological evidence also supports this suggestion. Saffran and Marin (1975) and Friedrich, Martin, and Kemper (1985) discussed patients with phonological loop deficits whose repetition accuracy declined as sentences increased in syntactic complexity. Subsequent work has also found an association between word span and reading comprehension (Cantor et al., 1991; Engle, Cantor, & Collins, 1991; Engle, Nations, & Cantor, 1990; LaPointe & Engle, 1990).

However, other researchers have challenged the view that phonological working memory is involved in sentence comprehension at all. Some phonological short- term memory patients, despite having very short spans, have shown good comprehension of sentences (Butterworth, Campbell, & Howard, 1986; Martin, 1993; Vallar & Baddeley, 1984; Waters, Caplan, & Hildebrandt, 1991). People with poor comprehension have also been found to possess adequate phonological skills (Oakhill & Yuill, 1986; Stothard & Hulme, 1992;

Yuill & Oakhill, 1991). Articulatory suppression has not always been found to impair sentence verification performance (Baddeley & Hitch, 1974), and digit span often fails to correlate with reading comprehension (Daneman & Carpenter, 1980; Masson & Miller, 1983; Perfetti & Lesgold, 1977; Turner & Engle, 1989). It may be the case that the phonological loop makes a more direct contribution to sentence repetition than to sentence comprehension (e.g. Hanten & Martin, 2000; Martin, Lesch, & Bartha, 1999; Martin, Shelton, & Yaffee, 1994; Willis & Gathercole, 2001). For example, Hanten and Martin (2000) discussed a child with an acquired phonological memory deficit who was impaired at repeating sentences but showed normal comprehension. Willis and Gathercole (2001) found that children with good phonological memory skills were more accurate than children with poor memory skills at repeating spoken sentences but did not differ significantly in their comprehension. Repetition accuracy was also more affected by word length when compared to comprehension, suggesting greater phonological involvement.

It may therefore be the case that during comprehension storage of information depends upon a memory system other than the phonological loop. This system may have access to lexical semantic information (Hanten & Martin, 2000; Martin & Romani, 1994; McCarthy & Warrington, 1987a; 1987b). For example, Nation, Adams, Bowyer- Crane, and Snowling (1999) stressed the semantic component of word recall by using abstract words, and demonstrated that poor comprehenders showed a selective short- term memory deficit. The short- term memory system involved in sentence comprehension might therefore be analogous to Baddeley's episodic buffer, which is capable of integrating

information from working memory and long- term memory (Willis & Gathercole, 2001).

The processing of information during comprehension is, however, likely to employ central executive resources (e.g. Gathercole & Baddeley, 1993). Daneman and Carpenter (1980; 1983) found that working memory capacity was highly correlated with both reading and listening comprehension. This was not simply a result of domain specificity as Daneman and Merikle (1996) found that a mathematics based working memory task was also a significant predictor of comprehension. Poor comprehenders have also been shown to perform significantly worse than normal comprehenders on complex span tasks (Yuill, Oakhill, & Parkin, 1989). This, however, may only be the case for verbal complex span tasks but not spatial complex span tasks (Nation et al., 1999), suggesting that comprehension difficulties may be due to a domain specific system, or to central executive processes specialised for dealing with verbal material.

1.3.3: Working memory and reading

The phonological loop, central executive, and visuo-spatial sketchpad components of working memory have each been associated with reading ability. The contribution of each component shall be considered in turn.

Performance differences between learning disabled and non- disabled readers on measures of reading are often attributed to limitations in working memory (e.g. de Jong, 1998; Siegel & Ryan, 1989), and limitations in a storage system holding and maintaining phonological codes (e.g. Shankweiler & Crain,

1986; Siegel & Ryan, 1989; Stanovich & Siegel, 1994; Swanson, Cooney, & O'Shaughnessy, 1998; Thorn & Gathercole, 1999). For example, poor readers typically perform badly on tests of verbal short- term memory (for reviews see Baddeley, 1986; Brady, 1991; Elbro, 1996; Jorm, 1983; Wagner & Torgeson, 1987), but not on tests involving non- linguistic information (e.g. Liberman, Mann, Shankweiler, & Werfelman, 1982; Mann, Cowin, & Schoenheimer, 1989; McDougall & Hulme, 1994; Snowling, 1991; Torgeson, 1985).

Reading disabled children may have problems in utilising the articulatory rehearsal process, as evidenced by findings that learning- disabled readers appear to rehearse less than skilled readers (Ackerman, Dykman, & Gardner, 1990; O'Shaughnessy & Swanson, 1998; see also Bauer, 1977; Done & Mills, 1978). Some studies, however, have found evidence to suggest that the subvocal rehearsal process functions normally in learning disabled readers (e.g. Baddeley, 1990; Kibby, Marks, Morgan, & Long, 2004), so problems could be due to the deficient utilisation of phonological storage (e.g. Mann, Liberman, & Shankweiler, 1980; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). Early studies demonstrated that poor readers exhibited weak phonological similarity effects (e.g. Shankweiler et al., 1979; Siegel & Linder, 1984), suggesting that poor performance on tests of short- term memory did result from deficiencies in the phonological store. However, when shorter lists of words are presented, or string length is determined on the basis of each participant's span, poor readers show normal phonological similarity effects (e.g. Holligan & Johnston, 1988; Johnston, 1982; Johnston, Rugg, & Scott, 1987). Evidence thus suggests that poor readers can make use of the phonological store, although given their impaired memory spans, its capacity may be reduced.

Some experimental studies also suggest a relationship between phonological abilities and reading. In skilled adult readers, rhyme judgement performance is disrupted by articulatory suppression (e.g. Besner, Davies, & Daniels, 1981; Johnston & McDermott, 1986). However, articulatory suppression does not impair performance on homophony tasks (Baddeley & Lewis, 1981; Besner et al., 1981; Daneman & Stainton, 1991). Neuropsychological studies have also described patients with deficits of immediate verbal short- term memory whose reading skills are within the normal range (e.g. Howard & Franklin, 1990; Waters et al., 1991).

Different facets of phonological ability are likely to be important in predicting reading skill. For example, McDougall, Hulme, Ellis, and Monk (1994) found differences between good, average and poor readers in phonological ability, rhyme awareness, phoneme deletion, and speech rate (but not verbal short- term memory). Accessability of phonological representations in long- term memory may also be important (Hulme et al., 1991; Katz & Shankweiler, 1985), as might the speed and ability of accessing a phonological code on the basis of a visual stimulus (Baddeley & Hitch, 1974; Hunt, Frost, & Lunneborg, 1973; Rubensten, Lewis, & Rubenstein, 1971). There is evidence that poor readers lack automaticity in retrieving verbal labels for visual information (Johnston & Anderson, 1998), and this may lead to immature rehearsal strategies including a bias to rely on visual rather than verbal processing (e.g. Swanson, 1987; see also; McNeil & Johnston, 2004).

Phonological awareness is also important in predicting reading ability, even when effects of age and IQ have been controlled for (e.g. Goswami & Bryant, 1990; Wagner & Torgeson, 1987). Phonological awareness refers to the

ability to reflect explicitly on the sound structure of spoken words. Therefore it may be difficult to say whether poor reading skills in reading disabled children could be due to phonological loop difficulties, phonological awareness difficulties, or a third common factor (Bradley & Bryant, 1983; Morais, Allegria, & Content, 1987).

Given that the phonological loop is partly controlled by the central executive system (Baddeley, 1990), deficits in phonological functioning that influence reading may also reflect deficits of the central executive system (Baddeley, 1996a; Baddeley et al., 1997; Gathercole & Baddeley, 1993; Daneman & Carpenter, 1983; Swanson & Alexander, 1997). It has been known for some time that performance on complex working memory measures is correlated with performance on tests of reading ability (e.g. Baddeley et al., 1985; Daneman & Carpenter, 1980). Furthermore, the association between reading and working memory tasks exists for working memory tasks that do not involve reading e.g. operation span and counting span (Hitch, Towse, & Hutton, 2001, see also; Swanson, Saez, Gerber, & Leafstedt, 2004). Working memory span tasks may therefore correlate with reading ability because they tap a general-purpose capacity for maintaining information (Engle, Cantor, & Carullo, 1992; Turner & Engle, 1989).

Some evidence for the link between the central executive and reading comes from children with reading disabilities. Reading disabled children perform poorly compared to normal readers on complex span tasks in both language and numerical domains (e.g. de Jong, 1998; Siegel & Ryan, 1989), and even in the visuo-spatial domain (Swanson, 1993; 2003; Swanson & Howell, 2001). Difficulties in executive processing are thought to contribute to poor working

memory performance over and beyond deficiencies in phonological processing (Bull, Johnson, & Roy, 1999; de Jong, 1998; Passolunghi & Siegel, 2001; Swanson & Ashbaker, 2000; Swanson et al., 2004), with the contributions of the central executive and phonological loop to reading ability being independent (Swanson, Ashbaker, & Lee, 1996; Swanson & Ashbaker, 2000; Swanson et al., 2004).

The central executive has also been related to reading through its ability to coordinate performance on two simultaneous tasks. For example, Towse and Houston- Price (2001) found that performance on a combination task involving both digit span and Corsi blocks was associated with reading ability. The relationship was still significant after controlling for variance in digit span and Corsi blocks separately, possibly reflecting central executive coordination capacity (Fournet, Moreaud, Roulin, Naegele, & Pellat, 2000; see also; Bayliss et al., 2003). Inhibitory skills have also been related to reading in the context of learning disabilities (e.g. Everett, Warner, Miles, & Thompson, 1997; Helland & Asbjornsen, 2000; van der Schoot, Licht, Horsley, & Sergeant, 2000; 2002; van der Sluis et al., 2004; Willcutt, Pennington, Boada, Ogline, Tunick, & Chhabildas et al., 2001) as well as in non- clinical samples (e.g. De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Gernsbacher, 1993). Children with reading disabilities might also show deficits in their ability to shift between tasks or mental sets (Willcutt et al., 2001, but see van der Sluis et al., 2004).

The visuo- spatial sketchpad may be involved in reading for maintaining an accurate spatial orientation with regard to the lines of text that are being scanned during reading (Kennedy, 1983), or for constructing spatial mental models from text to aid comprehension (Haenggi, Kintsch, & Gernsbacher,

1995). Evidence suggests that there is interference between reading and visuo-spatial tasks. For example, Brooks (1967) showed that reading interfered with the short- term storage of imaged material, presumably through the operation of the visuo-spatial sketchpad. Glass, Eddy, and Schwanenflugel (1980) also found interference between maintaining a visual pattern and verifying sentences that were imageable. Eddy and Glass (1981) further demonstrated that reading interfered with high- imagery sentences when the sentences were visually presented, but not when sentences were auditorily presented.

1.3.4: Working memory and writing

Writing is viewed as a complex activity that involves many simultaneous sub-goals and interacting processes (e.g. Bereiter, Burtis, & Scardamalia, 1988; Scardamalia & Bereiter, 1986), all or some of which may be sensitive to a limited working memory capacity (e.g. Scardamalia, 1981), particularly during childhood (e.g. Bourdin & Fayol, 1994).

An important tool for transcribing oral language in to visual language is spelling. Neuropsychological theories of spelling propose that working memory may be employed to store order and identity information of letters (Caramazza, Miceli, Villa, & Romani, 1987; Margolin, 1984; Miceli, Romani, Silveri, Villa, & Caramazza, 1985; Nolan & Caramazza, 1983). The two storage sub- systems of working memory would seem suited to this purpose. Service and Turpeinen (2001) explored the role of the phonological loop in spelling by using a backwards spelling task with articulatory suppression. Articulatory suppression did not appear to interfere with the spelling of short words, but longer words

appeared to require the use of a phonological code to monitor the process of typing. Regarding the visuo-spatial sketchpad, Caramazza and Hillis (1990) discussed patients with impaired attention who demonstrated writing deficits affecting either the beginnings or ends of words, suggesting that during writing there must be some spatial representation of a word.

The central executive may also be involved in spelling. Kreiner (1992) demonstrated a significant correlation between working memory load and spelling reaction times, suggesting that the ability to simultaneously store and process information is important in spelling ability. Ormrod and Cochran (1988) also showed that working memory capacity during the early stages of learning to spell predicted children who would subsequently have difficulty with spelling. The spelling performance of older children, however, may not be constrained by working memory (Stage & Wagner, 1992).

A number of theories accounting for other aspects of writing are also based upon working memory. McCutchen (1996) adapted the resource sharing view of working memory to account for writing ability, suggesting that more efficient writing processes require fewer resources from working memory, leaving more available for other processes such as coordinating goals. Kellogg (1996) proposed a model of writing including three aspects of the writing process; formulation processes (planning and translating), execution processes (programming and executing), and monitoring processes (reading and editing). Each aspect was linked to a component of working memory. The visuo-spatial sketchpad was linked to formulation, because in planning writers visualise images. The phonological loop was related to monitoring because processes such as reading place demands on the phonological loop. Finally, the central executive

was linked to execution. It may well be the case that different aspects of writing place different demands on the three components of working memory. Many lower- order skills such as spelling and handwriting are related to accessing a phonological code in short- term memory. However, higher order skills such as planning and text generation are more related to working memory (Swanson & Berninger, 1996a).

Performance on working memory tasks is also associated with performance on measures of writing (for a review see Berninger & Swanson, 1994; Swanson & Berninger, 1995), even when the processing component of working memory tasks is not reading or writing related (Swanson & Berninger, 1996b). It is also possible to induce errors in a writing task by increasing working memory load (Fayol, Largy, & Lemaire, 1994).

The importance of working memory in writing suggests that a breakdown of working memory may well lead to problems with written output (Fayol, 1999; Lea & Levy, 1999; Levy & Marek, 1999). McCutchen (1996) noted that poor writers typically have reduced working memory capacity when compared to expert writers. Skilled writers can also be characterised by their ability to hold information in working memory while simultaneously manipulating the same or other information (e.g. Benton et al., 1984; Swanson & Berninger, 1996a, 1996b). Hooper, Swartz, Wakely, de Kruif, and Montgomery (2002) also looked more specifically at executive functions and writing processes. It was suggested that executive functions tapping initiation and set shifting consistently separated good from poor writers.

1.3.5: Working memory and speech production

Theorists in the area of speech production identify the necessity of buffer storage (e.g. Bock, 1982), and suggest that in speech production information is retrieved from long- term memory and stored in a temporary buffer for speech output (Klapp, 1976; Morton, 1970). The phonological loop seems ideally suited to serve this purpose because it is specialised for the representation of material in the phonological domain, and it is a slave system that can be utilized without demanding limited capacity central executive resources (Gathercole & Baddeley, 1993).

Evidence for an association between the phonological loop and speech comes from a number of sources. The rehearsal component of the phonological loop is thought to be closely linked to the articulation of speech output (e.g. Baddeley et al., 1984; Baddeley et al., 1975; Levy, 1971; Murray, 1965; 1968). For example, the effects of word length indicate that articulation rate constrains the capacity of the phonological loop (Baddeley et al., 1975; Ellis & Hennelly, 1980), and articulatory suppression impairs retention of verbal information (Levy, 1971; Murray, 1965; 1968). Measures of phonological short- term memory have also been found to predict performance on a grammar-learning task involving speech (Daneman & Case, 1981), and also the length of utterances in 2 to 3- year- old children's spontaneous speech (Blake, Austin, Cannon, Lisus, & Vaughan, 1994). 3 year- old children with high short- term memory spans, classified on the basis of nonword repetition and digit span performance, have also been found to produce lengthier utterances and use a wider vocabulary than their lower span counterparts (Adams & Gathercole, 1995). This relationship continues beyond the preschool years suggesting that the association is not

restricted to the earliest stages of language development (Adams & Gathercole, 1996).

Findings of speech errors such as spoonerisms also indicate that an utterance is stored prior to output. Ellis (1979) pointed out that the maximum separation of phonemes in spoonerisms equates to the two seconds or so capacity of the phonological loop and that the exchange of phonemes is more likely to occur when they share distinctive features (e.g. Mackay, 1970), similar to the phonological similarity effect observed in the phonological loop. Neuropsychological evidence also points to a relationship between verbal short-term memory and speech production. Patients with Broca's aphasia who have non- fluent speech lacking grammatical words such as 'the' and 'is' have been shown to have impaired phonological memory skills but unimpaired visual memory (e.g. De Renzi & Nichelli, 1975; Kelter, Cohen, Engel, List, & Strohner, 1977).

However, there is some evidence against the hypothesis that the phonological loop serves as a storage buffer for speech production. In particular, experimental manipulations of phonological memory in adults appear not to effect the proposed buffering of intended speech (e.g. Klapp, Greim, & Marshburn, 1981; Sternberg, Monsell, Knowl, & Wright, 1978). There are also findings of patients with acquired phonological short- term memory deficits with normal speech production (Shallice & Butterworth, 1977; Vallar & Baddeley, 1984; Vallar & Shallice, 1990), and some patients with Broca's aphasia have no deficiencies in phonological memory (Cermak & Tarlow, 1978).

This raises the possibility that phonological memory processes support the production of spoken language in children but not in adults (e.g. Adams &

Gathercole, 1996). The speech of children is unlikely to be characterised by the automated system of skilled adult speech. For example, Bock (1982) proposed that the development of spoken language skills might constitute a progression from controlled to automated processing within a limited capacity processing system. Therefore throughout development there may a reduction in the extent to which speech is constrained by working memory.

An alternative role for working memory in speech is that it may contribute to the cognitive processing involved in speech production. The central executive system would seem to possess the power to produce the different levels of representations in speech production. It may also be responsible for retrieving information from the lexicon, constructing syntactic frames, and integrating products of these processes (Gathercole & Baddeley, 1993).

Daneman and Green (1986) found a relationship between speaking span, a complex span task, and the ability to produce synonyms for words. They concluded that the two measures reflected overlapping components of a complex working memory system. Power (1985) asked participants to generate plausible sentences to include two words provided by an experimenter, while engaging in a secondary memory task drawing upon executive resources. The semantic structure of the sentences produced was more predictable and stereotyped when participants were engaged in the concurrent task, suggesting involvement of the central executive in sentence production. The central executive has also been used to address potential associations of speech deficits and memory. For example, Howard, Binks, Moore, and Playfer (2000) found evidence that apraxic speech was associated with reduced working memory span in a subgroup of

patients with Parkinson's disease. The pattern of findings suggested that disorders of speech may have arisen from a dysfunction of the central executive.

1.3.6: Working memory and counting

Evidence suggests that in addition to knowledge of counting sequences and counting heuristics, counting requires temporary storage of a running total (Baddeley & Logie, 1999). This appears to be handled by the phonological loop (Hitch, 1978; Logie & Baddeley, 1987). For example, Logie and Baddeley (1987) asked participants to engage in articulatory suppression while counting items in stimulus arrays and counting items in event sequences. For both counting tasks articulatory suppression resulted in a substantial number of errors. Counting performance was not just disrupted by having to carry out a secondary task, however, because spatial tapping did not disrupt performance.

The central executive may also play a role in counting. Tuholski (1997) argued that counting from one to four objects is automatic because participants can subitize, whereas counting beyond four items requires controlled processing. High and low working memory span participants were found to differ in counting time of objects when there were more than four targets. It was suggested that this was because high working memory participants were better able to keep active the tags that indicate an object has already been counted. It was further demonstrated that including distracter items that shared features with target items, which according to Treisman and Gelade (1980) should cause controlled counting even within the subitizing range, resulted in counting time differences between high and low working memory participants for counting even one to

three items. This suggests a role for controlled processing. This method of varying distracter items in order to increase the amount of controlled processing required is employed in Chapter 4 of this thesis.

1.3.7: Working memory and mental arithmetic

An abundance of research has looked at the relationship between working memory and arithmetic in both normal and brain damaged individuals (e.g. Ashcraft, 1992; Ashcraft & Stszyk, 1981; Dehaene, 1992; Ellis & Henneley, 1980; Gallistel & Gelman, 1992; Geary & Widaman, 1987; Healey & Nairne, 1985; Hitch, 1978; Hitch & McAuley, 1991; Logie & Baddeley, 1987; McCloskey, Sokol, & Goodman, 1986; Sokol, McCloskey, Cohen, & Alimoniosa, 1991; Widaman, Geary, Cormier, & Little, 1989). To solve an arithmetic problem it is necessary to store problem information, perform the calculation, which may include retrieving information from memory and storing intermediate results, and then provide a response (LeFevre, 1998; LeFevre, Lei, Smith- Chant, & Mullins, 2001; McCloskey, Caramaza, & Basili, 1985; McCloskey, & Macaruso, 1995). These different aspects of arithmetic may place different demands on the phonological loop, visuo- spatial sketchpad and central executive.

Hitch (1978) demonstrated that the common sources of error in arithmetic were forgetting initial information and forgetting partial results of calculations, suggesting that the phonological loop or visuo-spatial sketchpad might be employed for storing information. The central executive, however, might be employed during arithmetic involving multi-digit numbers. Such calculations can

require the retrieval of arithmetical facts from long- term memory (Dansereau &

Gregg, 1966; Hitch, 1978; McCloskey, 1992), which is thought to be a function

of the central executive (e.g. Baddeley & Logie, 1999). Arithmetic operations

such as carrying and borrowing, that require inhibiting the tendency to continue a

sequence, would also be expected to involve the central executive system (e.g.

Furst & Hitch, 2000). The visuo- spatial sketchpad may be involved in arithmetic

tasks (Hayes, 1973; Pesenti, Tzourio, Doroux, Samson, Beaudoin, Seron, &

Mazoyer, 1998; Seron, Pesenti, Noel, Deloche, & Cornet, 1992; Zago, Pesenti,

Mellet, Bricogne, Seron, Beaudoin, Lochon, Mazoyer, & Mazoyer, 1999),

particularly when the presentation format is visual (e.g. Heathcote, 1994;

Trbovich & LeFevre, 2003), because visual images can be used to assist in the

solution of arithmetic problems (Hayes, 1973), and because some people use a

mental representation of a number line (Dehaene, 1992; Moyer & Landauer,

1967; Restle, 1970).

The association between working memory and arithmetic has been

investigated using dual- task interference studies. For example, Logie, Gilhooly,

and Wynn (1994) found that addition of numbers that were auditorily presented

was disrupted by concurrent random number generation, and to a lesser extent by

concurrent articulatory suppression. Addition was not, however, impaired by

concurrent hand movements or irrelevant visual information, although slight

decrements were observed when the numbers for addition were presented

visually. These results were interpreted as supporting the role of the central

executive in arithmetic, sub- vocal rehearsal in maintaining task information, and

the visuo-spatial sketchpad during visual presentation. The phonological loop,

however, may only be involved in single- digit problems when counting is used

to reach the solution (Hecht, 2002; Seyler, Kirk, & Ashcraft, 2003) but in multi-digit calculations may be involved in maintaining operands and interim results (Furst & Hitch, 2000; Heathcote, 1994; Noel, Desert, Aybrun, & Seron, 2001; Seitz & Schumann- Hengsteler, 2000; 2002).

Tasks loading the central executive have consistently been found to impair performance on arithmetic tasks (De Rammelaere, Stuyven, & Vandieredonck, 1999; 2001; Furst & Hitch, 2000; Hecht, 2002; Lemaire, Abdi, & Fayol, 1996; Seitz & Schumann- Hengsteler, 2000; 2002), especially as the number of digits in the operands increases (Ashcraft, Donley, Halas, & Vakali, 1992; Ashcraft & Kirk, 2001; Furst & Hitch, 2000; Noel et al., 2001; Seitz & Schumann- Hengsteler, 2000; 2002). However, even verifying simple single digit sums appears to require central executive resources (De Rammelaere et al., 1999, 2001; Hecht, 2002; Kaye, deWinstanley, Chen, & Bonnefil, 1989; Lemaire et al., 1996). This could be because the central executive is employed for retrieving numerical facts from long- term memory (De Rammelaere et al., 2001; Seitz & Schmann- Hengsteler, 2000) or because the central executive is associated with other aspects of the solution process (DeStefano & LeFevre, 2004).

A further source of evidence for the role of working memory in arithmetic comes from findings of working memory deficits in children with arithmetical learning difficulties (e.g. Hitch & McAuley, 1991; Seigel & Ryan, 1989). Such deficits, however, do not appear to be related to the phonological loop. For example, McLean and Hitch (1999) failed to find a significant impairment in digit span in children with poor arithmetic (see also: Geary, Hoard, & Hamson, 1999). Butterworth, Cipolotti, and Warrington (1996) also described a neuropsychological patient who could perform multi-digit

calculations despite having a phonological loop impairment. Children with arithmetic learning difficulties do, however, perform poorly on complex memory tasks. For example, children with both arithmetic difficulties and reading problems are impaired on speaking span and counting span tasks. Children whose learning difficulties are specific to arithmetic are impaired only on counting span, suggesting that specific arithmetical learning difficulties are associated with a low capacity working memory that is specialized for arithmetic (Siegel & Ryan, 1989).

It is also important to note, however, that arithmetical difficulties may stem from other deficits. Children with arithmetical difficulties have problems in automating basic arithmetic facts, which may stem from a speed- of- processing deficit (Bull & Johnston, 1997). Garnett and Fleischner (1983) and Geary (1993) also proposed that a major problem for children with arithmetical learning difficulties is the slow execution of operations, particularly with regard to access to long- term memory.

Mathematics ability has also been associated more specifically with executive processes. For example, a combination task involving digit span and Corsi blocks has been found to be significantly related to simple arithmetic performance even after controlling for variance on the two tasks separately, perhaps reflecting central executive coordination capacity (Towse & Houston-Price, 2001). Shifting abilities have been studied in the context of arithmetic disorders (e.g. Bull et al., 1999; Bull & Scerif, 2001; van der Sluis et al., 2004), demonstrating that arithmetic disabilities coincide with poorer performance on complex shifting tasks such as the Wisconsin Card sorting Task. Children who are poor at solving arithmetic problems may have a general deficit in inhibitory

processes (Passolunghi & Siegel, 2001; 2004, see also: Sikora, Haley, Edwards, & Butler, 2002; van der Sluis et al., 2004), and arithmetic problem solving is also likely to involve the updating of working memory (Passolunghi & Pazzaglia, 2004). Inhibition and switching, along with working memory, have also been found to predict unique variance in mathematics ability (Bull & Scerif, 2001), suggesting some diversity between executive functions. The relationships between these executive processes and their relative contribution to educational attainment in mathematics, as well as achievement in English and science, are examined in Chapter 3.

1.3.8: Working memory and other mathematical skills

A relationship may also exist between working memory and other mathematical skills. Studies using multi-component maths tests and curriculum-based measures of general school mathematics have demonstrated that mathematics skills are independent of phonological loop capacity (Reuhkala, 2001) and that children of high and low mathematics ability do not differ on measures of phonological short- term memory (Bull & Johnson, 1997). Mathematics skills do, however, appear to be related to central executive functioning (e.g. Bull et al., 1999; Lehto, 1995). Maybery and Do (2003) demonstrated that both verbal and visual working memory scores were associated with number abilities (primarily arithmetic), measurement abilities (concerning perimeter, area and time) and also with space abilities (manipulation or evaluation of geometric forms). Miller and Bichsel (2004) demonstrated that verbal and visuo-spatial complex memory spans both predicted basic and applied

mathematics i.e. the ability to carry out arithmetic and the ability to apply mathematical principles e.g. to calculate how many miles have been travelled given speed and length of time.

1.4: Working Memory and School Assessments

The evidence presented in section 1.3 shows that the components of working memory have been linked with a number of complex cognitive skills including vocabulary learning, comprehension, reading, spelling and writing, speech, counting, arithmetic, and other mathematical skills. All of these abilities are likely to be vital for children to reach attainment targets in schools in key subject areas such as English and mathematics.

Working memory skills have been found to be closely associated with performance on national curriculum tests in England, in which all children in state schools are classified according to nationally expected standards in terms of their academic achievement. Children are assessed at three Key Stages, at 7, 11, and 14 years of age. At Key Stage 1 (aged 7 years) children are assessed on tests of English and mathematics, and at key Stages 2 and 3 (ages 11 and 14) children are formally assessed on tests of English, mathematics, and science. Gathercole and Pickering (2000) found that children with low levels of performance on national curriculum tests at 7 years of age showed marked impairments on measures of central executive functioning and of visuo-spatial memory. Gathercole et al., (2004) also found strong links between working memory and attainment levels in English and mathematics at 7 years of age, and links between working memory and mathematics and science at 14 years of age. Gathercole et

al., (2003) further demonstrated that working memory at school entry (at aged 4 or 5 years) accounted for unique variance in spelling and writing at 7 years of age, beyond that explained by baseline assessments administered by local education authorities.

Other aspects of working memory may also be important for predicting scholastic skills. For example, Hitch et al., (2001) found that processing speeds during working memory span tasks accounted for unique variance in word reading scores when controlling for spans. Processing speed did not, however, account for unique variance in predicting number skills. Cowan, Towse, Hamilton, and Saults et al. (2003) also found that response durations in complex memory tasks helped to predict academic skills and achievement, independent from the contribution of memory spans themselves. These findings have implications for models of working memory. For example, the resource sharing account of working memory predicts that spans and speeds should predict only shared variance in any cognitive ability.

The relationship between working memory and educational attainment is explored further in Chapters 2 and 3 of this thesis. In the light of evidence that verbal and visuo-spatial complex span tasks tap distinct resources (e.g. Jurden, 1995; Shah & Miyake, 1996), Chapter 2 examines the relationships between both verbal and nonverbal complex span tasks and school achievements. Based on suggestions that there are multiple executive processes (e.g. Miyake et al., 2000), Chapter 3 explores the relationships between a number of executive abilities including working memory, and scholastic performance. Chapter 4 of the thesis also explores the relative contributions of working memory scores, processing

speeds (see Hitch et al., 2001) and response durations (see Cowan et al., 2003) to educational attainment measures.

1.5: Summary

The evidence presented in this chapter suggests that the phonological loop plays an important role in vocabulary acquisition (e.g. Baddeley, Gathercole, & Papagno, 1998) language comprehension (e.g. Martin & Romani, 1994), reading (e.g. Brady, Mann, & Schmidt, 1987), and spelling (e.g. Service & Turpeinen, 2001). The central executive may also be involved in language comprehension (e.g. Daneman & Carpenter, 1980), and reading (e.g. Baddeley, 1993). Counting, mental arithmetic, and other mathematical skills may also employ the phonological loop (e.g. Logie & Baddeley, 1987), the visuo- spatial sketchpad (e.g. Hayes, 1973) and the central executive (e.g. Logie et al., 1994). Working memory has thus been related to educational achievement in key areas such as English and mathematics (Gathercole & Pickering, 2000; Gathercole et al., 2004; Gathercole et al., 2003).

The primary aim of this thesis is to further examine whether there are specific associations between the components of working memory and scholastic attainment. Chapter 2 is an investigation of the relationships between verbal and nonverbal working memory and educational attainment at 11 and 14 years of age, and also looks at the utility of working memory as a predictor of later scholastic attainment at 15 and 16 years of age. Chapter 3 aims to explore more specific links between the central executive and scholastic attainment by distinguishing between the executive skills of shifting, inhibition, and working

memory. Chapter 4 involves manipulating the cognitive demand of complex span tasks and looks at the relative contributions of span scores, response durations, and speeds of processing to attainment. Chapter 5 examines the relationships between temporal duration and processing activities in a range of working memory tasks in order to examine a hypothesis of cognitive load. Chapter 6 draws together these findings and discusses them in relation to theories of working memory and implications for educational practice.

Chapter 2

Verbal and Nonverbal Working Memory and Achievements on National Curriculum Tests

Section 1.1 described how the resources proposed to underlie performance on working memory tasks differ widely across alternative models. According to the most widely accepted model (Baddeley & Hitch, 1974; Baddeley, 2000) working memory consists of four components. At the heart of working memory is the central executive system, a domain general limited capacity system capable of controlling resources and monitoring information processing (e.g. Baddeley, 1986; 1996a; 1996b; Baddeley & Hitch, 1974; Baddeley & Emslie et al., 1998). The central executive system is supported by two domain specific storage components: the phonological loop that is responsible for the maintenance of auditory information, and the visuo-spatial sketchpad that is specialised for dealing with visual and spatial information. Baddeley (2000) recently identified the episodic buffer as a further subcomponent of working memory, responsible for integrating information from the subcomponents of working memory and long- term memory. According to this view, working memory tasks rely upon a combination of domain specific and domain general resources: the phonological loop and visuo-spatial sketchpad supporting domain- specific storage, with processing drawing upon domain-general executive resources (Baddeley & Logie, 1999).

Other theorists, however, have conceptualised working memory as a limited capacity system where processing and storage operations compete for a limited pool of resources (e.g. Case et al., 1982; Daneman & Carpenter, 1980;

Just & Carpenter, 1992). Consistent with this view, performance on complex span tasks with different processing requirements, for example involving either language or numbers, are highly correlated with one another (e.g. Engle et al., 1992; Kyllonen, 1993; Shute, 1991; Turner & Engle, 1989). Other studies, however, have found marked dissociations between verbal and spatial complex span tasks (e.g. Jurden, 1995; Shah & Miyake, 1996). For example, Shah and Miyake (1996) found no significant correlation between verbal and spatial complex span measures. They used the reading span task (Daneman & Carpenter, 1980) in which participants read aloud sentences while remembering the last word of each sentence, and a spatial task involving performing a spatial transformation while keeping track of spatial locations. The spatial measure significantly correlated with spatial abilities but not with verbal abilities. Correspondingly, the verbal complex span measure was correlated with verbal ability, but not spatial abilities, suggesting separate pools of resources for the two domains (see also: Friedman & Miyake, 2000; Handley et al., 2002; Kane et al., 2004).

As discussed in section 1.3, within the Baddeley and Hitch (1974) model of working memory, phonological loop skills have been associated with vocabulary acquisition in children with learning difficulties (e.g. Hulme & Mackenzie, 1992; Hulme & Roodenrys, 1995; Jarrold & Baddeley, 1997; Jarrold et al., 1999; Russell et al., 1996), children with specific language impairment (e.g. Gathercole & Baddeley, 1990), and also within typically developing children (Gathercole & Adams, 1994; Gathercole & Baddeley, 1989; Michas & Henry, 1994). Scores on measures on central executive functioning have also been associated with vocabulary acquisition (e.g. Henry, 2001), language

comprehension (e.g. Swanson & Ashbaker, 2000; Yuill et al., 1989), and reading (Siegel & Ryan, 1989; Swanson & Ashbaker, 2000). Furthermore, all three of the main components of working memory have been associated with mental arithmetic (e.g. Dark & Benbow, 1990; De Rammelaere et al., 2001; Furst & Hitch, 2000; Hitch, 1978; Reuhkala, 2001; Seitz & Schumann- Hengsteler, 2000).

Working memory skills are also closely associated with performance on national curriculum tests in England. As discussed in section 1.4, Gathercole and Pickering (2000) found that children with low levels of performance on national curriculum tests at 7 years of age showed marked impairments on measures of central executive functioning and of visuo-spatial memory. Gathercole et al. (2004) also found strong links between working memory and attainment levels in English and mathematics at 7 years of age, and links between working memory and mathematics and science at 14 years of age. At 14 years working memory showed little association with English assessments. Gathercole et al. (2003) further demonstrated that working memory measures taken at school entry (aged 4 or 5 years) were important predictors of performance at 7 years of age.

However, each of the complex span tasks employed by Gathercole and colleagues (Gathercole et al., 2004; Gathercole & Pickering, 2000; Gathercole et al., 2003) to tap central executive capacity was predominantly verbal in nature, involving for example the recall of the final words in sentences or sequences of digits in reverse order. An outstanding issue is whether in the light of evidence that verbal and spatial complex span tasks tap distinct resources (e.g. Shah & Miyake, 1996), nonverbal complex span tasks are uniquely related to school achievements. The present study therefore employed measures of both verbal and

nonverbal working memory. The verbal complex span tasks were backwards digit recall and listening recall (Working Memory Test Battery for Children, Pickering & Gathercole, 2001). Analogous tasks involving the processing and storage of nonverbal information included the odd- one- out task (based on Russell et al., 1996) and the spatial span task (based on Shah & Miyake, 1996). These tasks required participants to make judgements about the appearance of visual stimuli, while simultaneously remembering spatial locations (see also: Bayliss et al., 2003; Kane et al., 2004).

The primary aim of study 1 was to examine whether verbal and nonverbal working memory have distinguishable dissociations with performance on national curriculum tests. A further aim was to establish whether previous findings of links between working memory and national curriculum test scores (Gathercole & Pickering, 2000; Gathercole et al., 2004) could be extended to Key Stage 2 (11 years of age) of the national curriculum as well as Key Stage 3 (14 years of age). The aim of study 2 was to examine the utility of working memory as a predictor of later academic attainment. Thus, relationships between working memory at 14 years of age and academic attainment at 16 years of age were explored.

2.1: Study 1

2.1.1: Method

Participants. The participants were 55 children (23 boys and 32 girls) with a mean age of 11 years and 6 months (S.D. = 3.24 months, range 10 years 11 months to 11 years and 9 months) and 73 children (35 boys and 38 girls) with

a mean age of 14 years and 5 months (S.D. = 3.00 months, range 13 years 10 months to 14 years 9 months). The two groups of children were from two different local education authority schools in a suburban area of a city in North East England. The socio-economic background of the pupils at both the schools was mixed, but well above average. Percentages of pupils achieving level 4 or above on national curriculum tests at 11 years of age were 81% in English, 61% in mathematics, and 74% in science, higher than percentages achieved nationally (65%, 59% and 68% respectively). The percentages of pupils at 14 years of age achieving level 5 or above were 62% in English, 67% in mathematics, and 68% in science, in excess of the national percentages of 56%, 59% and 60%, respectively. Both the working memory assessments and the national curriculum tests were conducted during the summer term of the school year.

Materials and procedure. All children took part in one testing session in which eight working memory tasks were administered. Digit recall and word recall, taken from the Working Memory Test Battery for Children (Pickering & Gathercole, 2001), were used as measures of the phonological loop. The Visual Patterns Test (Della Sala et al., 1999) and the dynamic matrices task were employed as measures of the visuo-spatial sketchpad. Two verbal complex span tasks, listening recall and backwards digit recall, were used along with two nonverbal complex span tasks, the spatial span task (based on Shah & Miyake, 1996) and the odd- one- out task (based on Russell et al., 1996), to tap the central executive component of working memory. Each child was tested individually in a quiet area of the classroom. The order of presentation of the tasks was held constant with phonological loop tasks administered first. Visuo-spatial sketchpad tasks were administered second, followed by verbal and then nonverbal central

executive tasks. A fixed order of testing across all children was employed in order to minimise individual variation due to differences in testing sequences.

In the digit recall test, participants were asked to recall, in the same order, sequences of digits spoken aloud by the experimenter. The digits were presented at the rate of one per second. Testing began with three trials at a list length of two digits. The number of digits was then increased by one every three trials until two lists of a particular length were recalled incorrectly. The score given was the maximum list length at which three sequences were recalled correctly. Test-retest reliability for digit recall is .82 for children aged 9- 11 years (Pickering & Gathercole, 2001).

In the word recall test participants were asked to recall, in the same order, sequences of monosyllabic words spoken aloud by the experimenter. The structure of testing was identical to that for the digit recall task, but the score given was the maximum list length at which at least two out of three trials were recalled correctly, with an extra half a point if one out of three was correct at the next list length. Test- retest reliability for word recall is .64 for children aged 9- 11 years (Pickering & Gathercole, 2001).

The Visual Patterns Test (Della Sala et al., 1999) was originally developed for use with adults, but is suitable for use with children and can be normed alongside the Working Memory Test Battery for Children (Pickering & Gathercole, 2001). Participants are required to remember and recall checkerboard patterns. Each pattern is created by filling in half of the squares in a given grid. Following a practice trial, there are three trials at each grid size, from a 2x2 matrix to a 5x6 matrix. Each pattern is presented for three seconds, but there is no time limit for responding. The score given is the level of complexity (the

number of filled squares contained by the grid) at which at least one of the three patterns is recalled correctly.

The dynamic matrices task was a computerised version of the Corsi blocks task, developed for the purpose of this study. The test was presented using Microsoft PowerPoint on a personal computer with a 33 cm monitor. Matrices increasing in size in the same manner as for the visual patterns test were presented in the centre of the screen. Squares within the matrices changed from white to black for one second in sequence. The participant was then asked to recall the sequence. The sequences were random with no location being highlighted more than once within a trial. The level of difficulty was increased by increasing the number of squares that went from white to black in a trial. Following a practice trial there were three trials at each level of difficulty. The score given was the longest sequence at which at least two of the three sequences were correctly reproduced.

In the listening recall task (Working Memory Test Battery for Children, Pickering & Gathercole, 2001) participants hear a series of sentences and are asked to judge the veracity of each. At the end of each trial they are asked to recall the final word from each sentence. After two practice trials, each participant is given four trials with two sentences. After each four trials the number of sentences is increased by one. When two trials at any list length are incorrectly recalled, then the test ends. Each participant is given a score of the maximum list length at which they are correct on at least three out of four trials, and an additional half a point if correct on two trials at the next list length. Test-retest reliability for listening recall is .38 for 9-11 year old children (Pickering & Gathercole, 2001).

The backwards digit recall test (Working Memory Test Battery for Children, Pickering & Gathercole, 2001) requires each participant to recall a sequence of spoken digits (between one and nine) in reverse order. The structure of the testing includes discontinuation and scoring criteria the same as for the digit recall test outlined above. Test- retest reliability for backwards digit recall is .71 for children aged 9- 11 years (Pickering & Gathercole, 2001).

The odd- one- out task (based on the procedure used by Russell et al., 1996) consisted of sets of three shapes. Two of the shapes were identical and one was different. The participant's task was to indicate the odd- one- out. Each set of three shapes was shown for only two seconds (in which all children did identify the odd shape), then immediately followed by another set, to minimize the possibility that participants delayed the judgement of the odd- one- out to rehearse the spatial locations. Following each trial (in list lengths of two to seven) the participant was asked to recall the spatial locations of all the odd- one-out shapes, in their original order. An example of the odd- one- out task at a list length of 2 can be seen in Appendix *I*. The participant was given a score of the longest list length at which they were correct on at least two out of three trials. An extra half a point was awarded if the child made a correct response on one out of the three trials at the next list length. Test- retest reliability for one version of the odd- one- out task is .81 (Alloway, Gathercole, & Pickering, 2004).

The spatial span task (Shah & Miyake, 1996) was modified for the purposes of the present study in order to eliminate any involvement of long- term memory or verbal working memory. The test stimuli were thus nonsense shapes presented either in a normal view or as a mirror image, in one of eight spatial orientations. Each participant was required to state whether each shape presented

was 'normal' or a 'mirror image' of an original shape which remained present on one side of the computer screen, while keeping track of the orientation of each shape. After each trial at list lengths of two to seven shapes, the participant was asked to recall the position of the top of each shape by pointing to one of eight given locations. Each shape was shown for only two seconds to minimize the possibility that participants delay the mental rotation in order to rehearse the orientations. An example of the spatial span task at a list length of 2 can be seen in Appendix *II*. The participant was given a score of the longest list length at which they were correct on at least two out of the three trials. They were given half a point extra if they were correct on one out of three trials at the next list length. Test- retest reliability for a simplified version of spatial span is .82 (Alloway, Gathercole, & Pickering, 2004).

The schools supplied attainment levels in English, mathematics and science for each pupil. These levels were based on standardised tests taken in the summer term, and were independent of teacher assessments of ability. At Key Stage 2, English test scores incorporate measures of reading, writing, spelling and handwriting. Two mathematics papers and a mental arithmetic test are used to generate a mathematics score, and there are two science papers. Each test has high reliability, with Cronbach's alpha for each subtest ranging from .86 to .89 (Qualifications and Curriculum Authority, 2001). Attainment levels provided for each child range from 3 to 5, with level 4 indicating nationally expected standards. At Key Stage 3 English assessments differ somewhat from at Key Stage 2, assessing more complex abilities. For example, within the 'reading' subtest of English, children have to demonstrate their understanding of literature and make comments on reader- writer relationships within text. Again, a

mathematics score is generated from mathematics and mental arithmetic tests, and there are two science papers. Cronbach's alpha for subtests range from .85 to .94 (Qualifications and Curriculum Authority, 2001). The levels of attainment at this Key Stage range from 3 to 8, with levels 5 and 6 indicating nationally expected standards.

2.1.2: Results

Descriptive statistics. Descriptive statistics for all the working memory measures and national curriculum test levels at Key Stages 2 and 3 are presented in Table 2.1. Within both age groups skew and kurtosis for all measures met criteria for multivariate normality (Kline, 1998). No univariate or multivariate outliers were identified.

Correlational analyses. The correlation matrix of the working memory tasks and the national curriculum attainment levels is presented in Table 2.2. Age is also included. The upper triangle displays correlation coefficients at age 11, and the lower triangle displays correlation coefficients at age 14.

Table 2.1 *Descriptive Statistics of Working Memory Measures and National Curriculum Test Levels for English, Mathematics and Science*

Measures	Key Stage 2		Key Stage 3	
	Mean	*SD*	Mean	*SD*
Working memory measures				
Digit recall	4.82	0.92	5.21	0.93
Word recall	3.28	0.64	3.75	0.72
Visual Patterns	7.24	1.32	8.41	1.31
Dynamic matrices	3.29	0.92	3.56	0.76
Listening recall	2.81	0.74	3.12	1.60
Backwards digit recall	4.00	0.92	4.56	0.85
Spatial span	2.50	0.59	3.08	0.40
Odd- one- out	3.48	0.80	3.60	0.77
National curriculum tests				
English level	4.44	0.74	5.89	1.14
Mathematics level	4.20	0.78	5.88	1.46
Science level	4.53	0.60	5.42	1.10

Table 2.2 *Correlation Coefficients between Working Memory Measures and National Curriculum Attainment Levels; Upper Triangle Displaying Coefficients for Key Stage 2, Lower Triangle Displaying Coefficients for Key Stage 3*

	1	2	3	4	5	6	7	8	9	10	11	12
1 Age	-	.32*	.36**	.14	.40**	.26	.21	.37**	.20	.06	.19	.26
2 Digit recall	.45**	-	.49**	.76**	.63**	.22	.37**	.40**	.31*	.34*	.44**	.21
3 Word recall	.34**	.53**	-	.47*	.64**	.30*	.46**	.32*	.36**	.40**	.53**	.37**
4 Backwards digit recall	.36**	.56**	.39**	-	.61**	.32*	.35**	.26	.38**	.35**	.49**	.27*
5 Listening recall	.27*	.46**	.34**	.43**	-	.47**	.59**	.51**	.47**	.46**	.58**	.46**
6 Visual Patterns	.18	.30*	.37**	.42**	.37**	-	.56**	.51**	.72**	.29*	.46**	.42**
7 Dynamic matrices	.08	.19	.20	.35**	.17	.56**	-	.55**	.62**	.33*	.57**	.39**
8 Odd- one- out	.19	.43**	.37**	.57**	.27*	.33**	.25*	-	.50**	.42**	.54**	.46**
9 Spatial span	.19	.18	.28*	.33**	.26*	.41**	.44**	.35**	-	.26	.47**	.47**
10 English level	.17	.36**	.47**	.50**	.52**	.36**	.25*	.45**	.37**	-	.71**	.60**
11 Mathematics level	.05	.23*	.40**	.47**	.31**	.42**	.32**	.48**	.47**	.73**	-	.68**
12 Science level	.09	.21	.44**	.50**	.24*	.34**	.22	.48**	.41**	.65**	.85**	-

*p < .05   **p < .01

At 11 years of age, age was significantly correlated with digit recall, r (53) = .32, $p < .05$, word recall, r (53) = .36, $p < .01$, listening recall, r (53) = .40, $p < .01$, and odd- one- out scores, r (53) = .37, $p < .01$. At 14 years of age, age was significantly correlated to digit recall, r (71) = .45, $p < .01$, word recall, r (71) = .34, $p < .05$, listening recall, r (71) = .27, $p < .05$, and backwards digit recall, r (71) = .36, $p < .01$.

The majority of the scores on the working memory measures were also significantly correlated with each other. The correlation coefficients between scores on the two tasks aimed at tapping the phonological loop were significant at age 11, r (53) = .49, $p < .01$, and age 14, r (71) = .53, $p < .01$, as were those between the two tasks aimed at tapping the visuo-spatial sketchpad, r (53) = .56, $p < .01$, r (71) = .56, $p < .01$. Scores on the two verbal central executive tasks were also significantly correlated in both age groups, r (53) = .61, $p < .01$, r (72) = .43, $p < .01$, as were those on the two nonverbal central executive tasks, r (53) = .50, $p < .01$, r (71) = .35, $p < .01$.

The correlation coefficients between scores on phonological loop and verbal central executive tasks were also highly significant in both age groups, the highest correlation being between digit recall and backwards digit recall, r (53) = .76, $p < .01$, r (71) = .56, $p < .01$. Scores on visuo-spatial sketchpad and nonverbal central executive tasks were also significantly correlated in both age groups, the highest correlations being between scores on the Visual Patterns Test and spatial span, r (53) = .72, $p < .01$, r (71) = .41, $p < .01$.

At 11 years of age, odd- one- out scores correlated highly with scores on nonverbal tasks such as dynamic matrices, r (53) = .55, $p < .01$, and the Visual Patterns Test, r (53) = .51, $p < .01$. However, at 14 years of age, the odd- one-

out task correlated more highly with tasks within the verbal domain, such as backwards digit span, r (71) = .57, p < .01.

Highly significant correlations were found between a number of the working memory measures and national curriculum attainment levels. At Key Stage 2 the strongest associations were found between English levels and listening recall, r (53) = .46, p < .01, and mathematics levels and listening recall, r (53) = .58, p < .01. Science scores were highly correlated with listening recall, r (53) = .46, p < .01 as well as odd- one- out scores, r (53) = .46, p < .01, and spatial span, r (53) = .47, p < .01. At Key Stage 3 the strongest associations were found between English levels and backwards digit recall, r (71) = .50, p < .01, and listening recall, r (71) = .52, p < .01. Mathematics levels were most strongly associated with odd- one- out scores, r (71) = .48, p < .01, and spatial span, r (71) = .47, p < .01, as well as backwards digit recall, r (71) = .47, p < .01. Science levels were most highly correlated with backwards digit recall, r (71) = .50, p < .01, and odd- one- out scores, r (71) = .48, p < .01.

In order to evaluate the extent to which unique associations were obtained between working memory tasks and national curriculum attainment levels, composite scores were calculated for the phonological loop, visuo-spatial sketchpad, verbal central executive and nonverbal central executive by averaging the Z scores on the associated tasks. Partial correlations between each construct and English, mathematics and science scores were calculated, eliminating variance related to age and the other working memory constructs in each case. Corresponding correlational analyses were conducted partialling out variance associated with age and the constructs in the opposite domain, for example, in the partial correlations involving the phonological loop the visuo-spatial

constructs (visuo-spatial sketchpad and nonverbal executive) were partialled out. However, the high correlations between the odd- one- out task and tasks in the verbal domain at age 14 suggested that the task tapped a verbal rather than a nonverbal construct. Scores on the odd- one- out task were therefore excluded from further analysis of the data at 14 years of age, with the spatial span task used as a single measure of nonverbal executive processes. This procedure is highly conservative given the high degree of inter-correlations between the variables but does provide a very stringent test of the specificity of the relationships between the components of working memory and attainment. The partial correlation coefficients are presented in Table 2.3.

The partial correlations revealed that when the other three working memory constructs were taken in to account, the only unique link between working memory and national curriculum attainment levels at Key Stage 2 was that between nonverbal central executive scores and science, r (49) = .29, p < .05. The few significant partial correlations, however, were likely to be a result of the high inter-correlations between simple and complex span tasks within the same domain. When partialling out only the constructs in the opposite domain i.e. verbal or nonverbal as appropriate, a stronger pattern of associations emerged. The verbal constructs (phonological loop and verbal central executive) were highly correlated with English levels, r (50) = .33, p < .01, r (50) = .33, p < .01, and mathematics levels, r (50) = .41, p < .01, r (50) = .39, p < .01. The visuo-spatial constructs (the visuo-spatial sketchpad and nonverbal central executive) were significantly related to mathematics levels, r (50) = .39, p < .01, r (50) = .44, p < .01, and science levels, r (50) = .30, p < .01, r (50) = .40, p < .01. At Key Stage 3, even when all other working memory constructs were

Table 2.3 *Partial Correlation Coefficients between Working Memory Constructs and Attainment Levels in English, Mathematics and Science*

Assessment	Working Memory construct						Working Memory construct				
	PL	VSSP	VCE	NVCE	SS		PL	VSSP	VCE	NVCE	SS
Constructs partialled out:	VSSP VCE NVCE/SS	PL VCE NVCE/SS	PL VSSP NVCE/SS	PL VSSP VCE	PL VSSP VCE		VSSP NVCE/SS	PL VCE	VSSP NVCE/SS	PL VCE	PL VCE
Key Stage 2											
English	.14	-.00	.13	.17	-		.33**	.16	.33**	.23	-
Mathematics	.19	.17	.15	.20	-		.41**	.39**	.39**	.44**	-
Science	-.03	.02	.12	.29*	-		.09	.30**	.15	.40**	-
Key Stage 3											
English	.21	.00	.41**	-	.20		.39**	.09	.51**	-	.21
Mathematics	.17	.13	.25*	-	.32**		.29*	.26*	.34**	-	.38**
Science	.19	.02	.23	-	.28*		.31*	.14	.33**	-	.31*

Note. PL = Phonological loop. VSSP = Visuo-spatial sketchpad. VCE = Verbal central executive. NVCE = Nonverbal central executive. SS = Spatial span.

p < .05 ** *p* < .01

partialled out, verbal central executive scores were significantly correlated with levels in English, $r(67) = .41, p < .01$, and mathematics, $r(67) = .25, p < .05$, and nonverbal central executive scores were significantly correlated with mathematics levels, $r(67) = .32, p < .01$, and science levels, $r(67) = .28, p < .05$. When controlling for constructs in the other domain phonological loop scores were also significantly correlated with levels in English, $r(68) = .39, p < .01$, mathematics, $r(68) = .29, p < .05$, and science, $r(68) = .31, p < .05$, and visuo-spatial sketchpad scores were correlated with mathematics levels, $r(68) = .26, p < .05$.

Factor analysis and structural equation modelling. Factor analysis and structural equation modelling were then conducted using the EQS 6 structural equation package (Bentler, 2001). The purpose of this approach was to test, formally, different theoretical models of the relationships between latent constructs tapped by a number of measures. Each model assessed in structural equation modelling generates coefficients for the paths between constructs and variables, indicating the strength of relationships. A number of statistics are produced that indicate the goodness of fit of the model to the input correlation matrix. By comparing the fit indices across competing models it is possible to find the best theoretical account of the data. In the present study, the input matrix was the partial correlation matrix controlling for age.

Consider first the data from the children at 11 years of age. Four models of the structure of working memory were tested. The first model (CFA1a) corresponded to the standard Baddeley and Hitch (1974) working memory model with 3 factors representing the central executive, phonological loop and visuo-spatial sketchpad. The second model (CFA2a) fractionated the central executive

in to distinct verbal and nonverbal components, and was therefore composed of both verbal and nonverbal central executive components in addition to the phonological loop and visuo-spatial sketchpad. The third model (CFA3a) eliminated the distinction between the central executive and the two domain specific storage systems (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) and consisted of one verbal factor incorporating the phonological loop and verbal complex span measures, and one nonverbal factor including both the visuo-spatial sketchpad and nonverbal complex span measures. In the final model (CFA4a), all of the working memory tasks were associated with a single common factor (e.g. see Kail, 2002). A diagrammatic representation of these models is shown in Figure 2.1.

Figure 2.1 *Diagramatic Representation of the Confirmatory Factor Analysis Models at Key Stage 2*

CFA1a

Listening Recall	Central Executive	Spatial Span
Backwards Digit Recall		Odd- One- Out
Digit Recall	Phonological Loop	Visual Patterns
Word Recall	Visuo-spatial Sketchpad	Dynamic Matrices

CFA2a

Listening Recall	Verbal Central Executive	Nonverbal Central Executive	Spatial Span
Backwards Digit Recall			Odd- One- Out
Digit Recall	Phonological Loop	Visuo-spatial Sketchpad	Visual Patterns
Word Recall			Dynamic Matrices

CFA3a

Verbal Working Memory
- Digit Recall
- Word Recall
- Listening Recall
- Backwards Digit Recall

Nonverbal Working Memory
- Visual Patterns
- Dynamic Matrices
- Spatial Span
- Odd- One- Out

CFA4a

- Digit Recall
- Word Recall
- Listening Recall
- Backwards Digit Recall

Working Memory

- Visual Patterns
- Dynamic Matrices
- Spatial Span
- Odd- One- Out

The fit statistics for these models for the Key Stage 2 data are presented in Table 4. The fit statistics used are chi squared (χ^2), the comparative fit index (CFI) (Bentler, 1990), Bollen's incremental fit index (IFI), the standardised root mean square of the model residuals (SRMR), and the root mean square error of approximation (RMSEA). The most well known index of fit is χ^2, which measures the degree to which the covariances predicted by the model differ from the observed covariances. Small and non-significant χ^2 values indicate good fit. CFI and IFI indicate the extent to which the model is better than a baseline model with all covariances set to zero. Values should equal or exceed .90 for adequate fit of model to the data. The SRMR is the square root of the averaged squared residuals i.e. differences between observed and predicted covariances. A value of 0.08 or less represents acceptable goodness of fit (Hu & Bentler, 1999). The RMSEA is also a measure of the discrepancies between observed and predicted covariances, and values less than .05 correspond to a good fit and values less than .08 correspond to an acceptable fit.

Model 1, the standard three factor working memory model, did not provide satisfactory fit to the data (both fit indices < .90). The model that yielded fit indices (CFI and IFI) in excess of .90 was the two- factor domain specific model composed of one verbal and one nonverbal factor (CFA3a). It should, however, be noted that the fit of this model was not ideal. The χ^2 value was significant (p = .03) and the RMSEA value was .11. The factor loadings and item error terms for this model are presented in Figure 2.2a. All loadings and variances are significant at the .05 probability level.

Table 2.4 *Goodness of Fit Statistics for the Estimated Models*

Model	df	$\chi 2$	p	CFI	IFI	SRMR	RMSEA
Key Stage 2							
CFA1a	17	55.5	.00	.80	.81	.11	.21
CFA2a	16	41.3	.00	.87	.88	.24	.17
CFA3a	19	32.0	.03	.93	.94	.09	.11
CFA4a	20	72.9	.00	.72	.73	.12	.22
SEM	49	56.3	.21	.97	.97	.09	.05
Key Stage 3							
CFA1b	11	14.7	.20	.96	.98	.07	.07
CFA2b	9	22.8	.01	.86	.88	.16	.15
CFA3b	13	11.4	.58	1.0	1.0	.05	.00
CFA4b	14	28.5	.01	.85	.86	.09	.12
SEM	39	47.2	.17	.97	.97	.08	.05

Note. CFI = Bentler's comparative fit index. IFI = Bollens incremental fit index.

SRMR = standardised root- mean squared residual. RMSEA = root mean square

error of approximation

Figure 2.2 *Factor Loadings and Factor Correlations for the Confirmatory Factor Analyses and Structural Equation Models at Aged 11*

a) Confirmatory factor analysis model
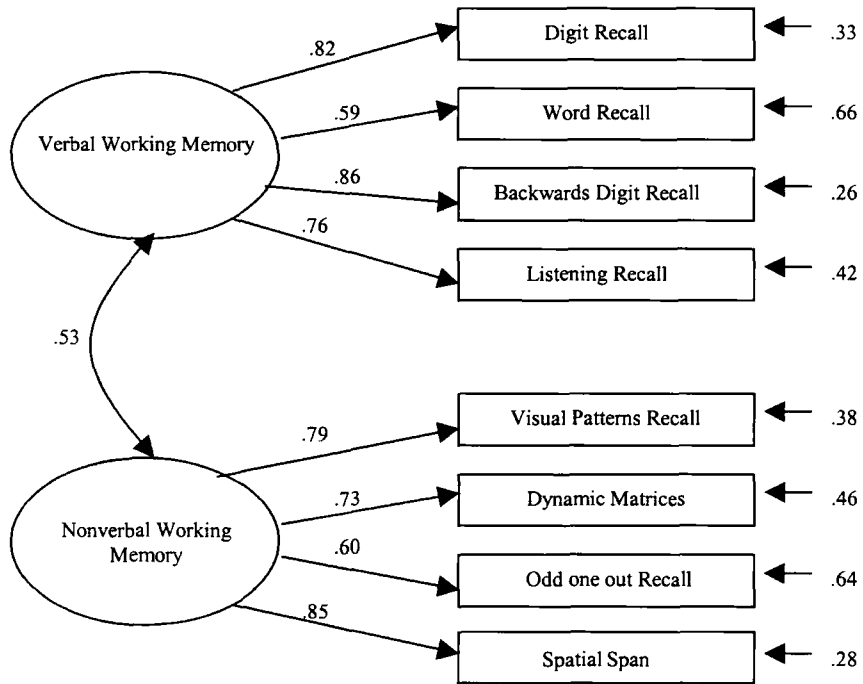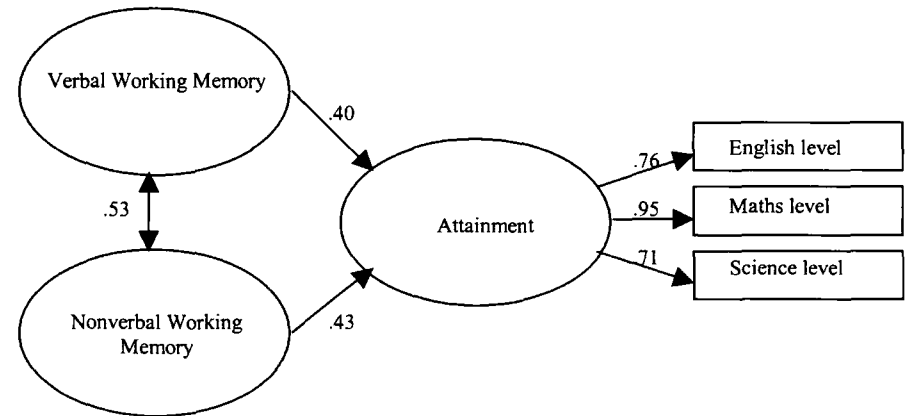
b) Structural equation model

The factor loadings produced in the best fitting, two- factor confirmatory factor analysis model (CFA3) were then incorporated into a structural equation model (SEM) in which verbal and nonverbal working memory predicted English, mathematics and science scores. In the model, both verbal and nonverbal factors were causally linked with a single attainment factor associated with English, mathematics and science attainment levels. The fit indices produced for this model are shown in Table 2.4. Alternative models in which verbal and nonverbal working memory differentially predicted English, mathematics and science were also tested, but failed to satisfy statistical criteria for a good fit.

This model provided an excellent fit to the data, with a CFI of .97, a RMSEA value of .05, and a non-significant χ^2 value (p = .21). In this model highly significant paths existed between each working memory domain and attainment: for verbal working memory the standardised path coefficient was .40, p < .05, and for nonverbal working memory the standardised path coefficient was .43, p < .05. A structural equation model diagram of this model is presented in Figure 2.2b.

Corresponding analyses were then performed on the data from the 14 year- old children. As with the younger children, four confirmatory factor analysis models of the structure of the working memory assessments were tested. The models differed in one respect. As a result of the high correlations between the odd- one- out task and the verbal measures at Key Stage 3, the odd- one- out task was not included during modelling. Thus in CFA2b spatial span was used as a single indicator of nonverbal central executive capacity and in CFA3b only Visual Patterns, dynamic matrices and spatial span were used as nonverbal working memory indicators. For a diagrammatic representation of the models

assessed for children aged 14 see Figure 2.3. The fit statistics for these models are presented in Table 2.4.

Model 1, with separate phonological loop, visuo-spatial sketchpad and central executive factors produced fit statistics indicative of a satisfactory fit (both fit indices > .90). However, all the fit statistics for Model 3b with one verbal and one nonverbal working memory factor indicated improved fit from model 1. The fit indices (CFI and IFI) were both 1.0 and the RMSEA value was .00. Factor loadings and item error terms for this model are shown in Figure 2.4a. All loadings and variances are significant at the .05 probability level.

The factor loadings from the two-factor confirmatory factor analysis model were then incorporated into a structural equation model (SEM) in which the verbal and nonverbal factors predicted national curriculum scores. In the model, the two working memory factors were both specified as predictors of a single attainment factor that was associated with English, mathematics and science. The fit indices for this model are shown in Table 2.4. Alternative models in which verbal and nonverbal working memory differentially predicted English, mathematics and science were also tested, but failed to satisfy statistical criteria for a good fit.

This model provided an excellent fit to the data, with a CFI of .97, an RMSEA of .05, and a non- significant χ^2 value ($p = .17$). In this model highly significant paths existed between each working memory domain and attainment: for verbal working memory the standardised path coefficient was .46, $p < .05$, and for nonverbal working memory the standardised path coefficient was .29, $p < .05$. A structural equation model diagram of this model is presented in Figure 2.4b.

Figure 2.3 *Diagramatic Representation of the Confirmatory Factor Analysis Models at Key Stage 3*
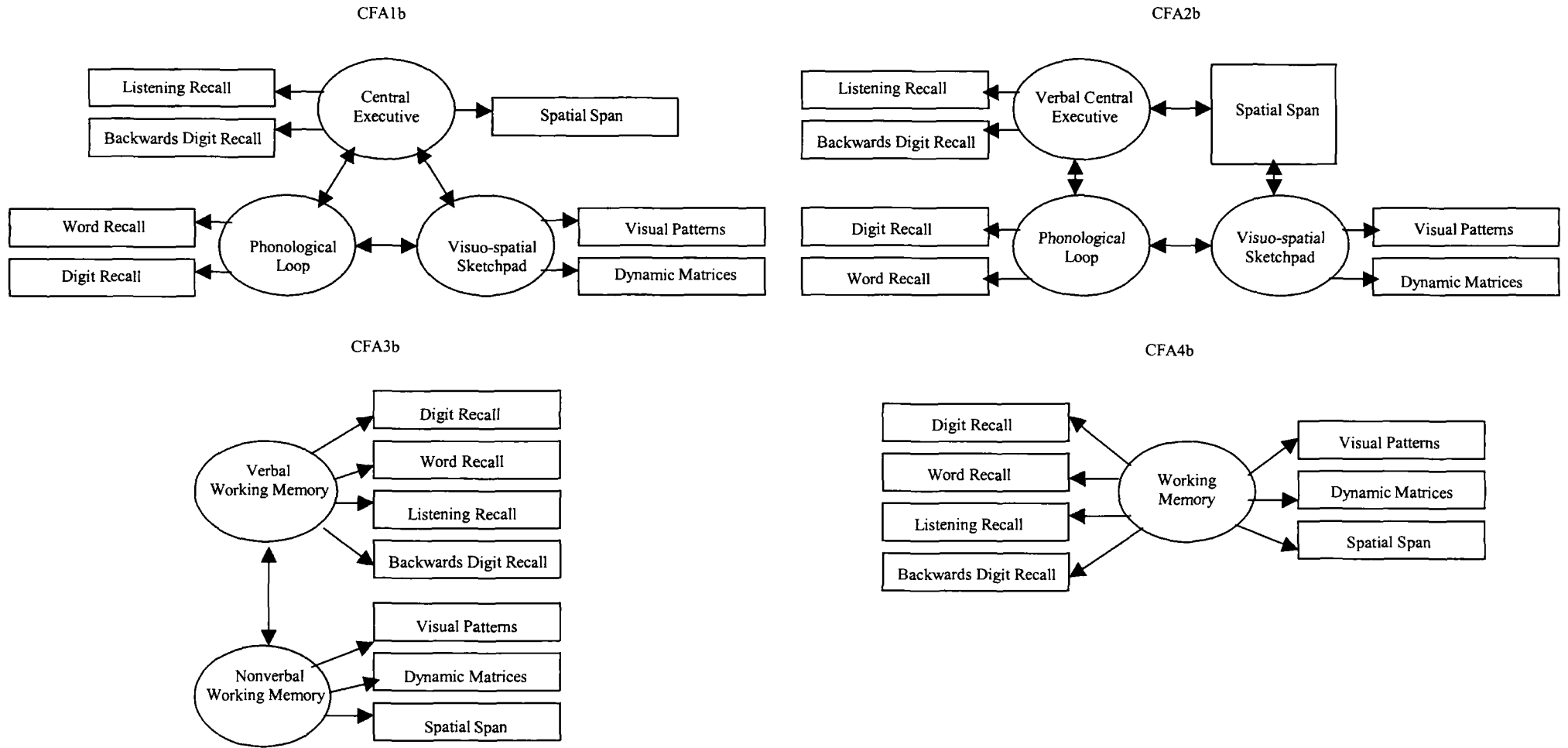
Figure 2.4 *Factor Loadings and Factor Correlations for the Confirmatory Factor Analyses and Structural Equation Models at Aged 14*

a) Confirmatory factor analysis model
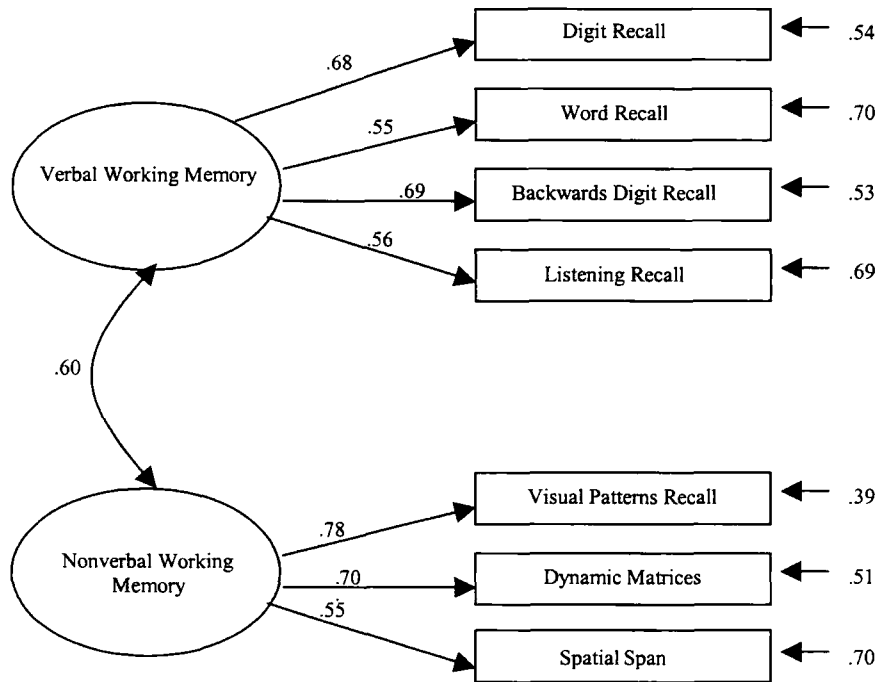
b) Structural equation model
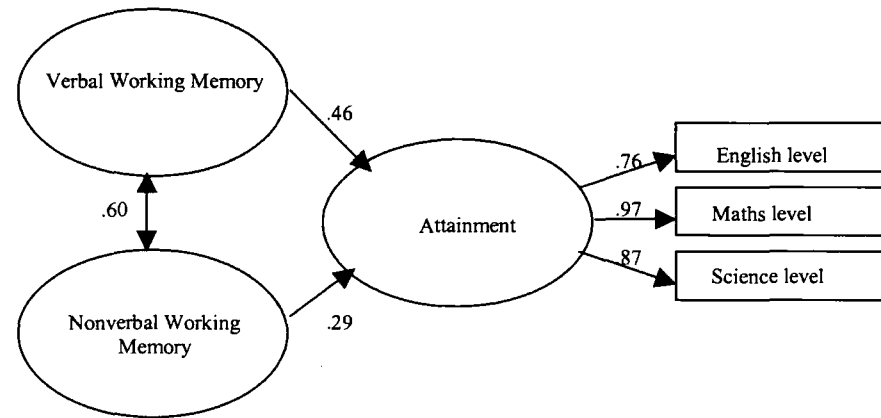
2.2: Study 2

Research into the role of working memory in complex cognitive skills has largely focused on the development of sub- domains of skill during the early and middle childhood years (e.g. Bull & Johnston, 1997; Bull et al., 1999; de Jong, 1998; Gathercole & Baddeley, 1989; 1990; Gathercole et al., 1997; McLean & Hitch, 1999; Michas & Henry, 1994; Siegel & Ryan, 1989; Willis & Gathercole, 2001). However, associations between working memory and scholastic measures may also extend throughout later childhood and in to adulthood, as indicated by relationships between working memory, literacy, and numeracy in adults (e.g. Bayliss et al., 2003; De Rammelaere et al., 2001; Gupta, 2003; Jurden, 1995; Lee & Kang, 2002; Noel et al., 2001; Papagno et al., 1991).

Investigations in to the relationship between working memory and standardised school assessments have been limited to children between 7 and 14 years of age (Gathercole et al., 2003; Gathercole & Pickering, 2000; Gathercole et al., 2003), and studies into longitudinal links have been limited to children aged 4 to 7 years (Gathercole et al., 2003). However, in the light of evidence that working memory is related to scholastic skills even in adulthood, it is reasonable to predict that a relationship exists between working memory and educational attainment during later childhood years.

The aim of study 2 was to establish whether longitudinal relationships exist between working memory at 14 years of age and performance on standardised tests of school attainment at 16 years of age. At 7, 11, and 14 years of age children are formally assessed on national curriculum tests. At 16 years of

age, however, children complete GCSE assessments in up to 11 subject areas, with English, mathematics, and science being compulsory.

2.2.1: Method

A school provided the GCSE attainment scores in English, mathematics and science for 69 of the 73 children who contributed data to the Key Stage 3 analyses presented in section 2.1. Each score was in the range of 0 to 8, with 0 corresponding to a grade of U (unclassified) and 8 corresponding to a grade of A* (A star). In English the scores were for English language only. In science, the maximum score was 16 because the pupils all completed double science, a programme of study in which two GCSE's are awarded for performance across biology, chemistry and physics. The associations between the working memory measures administered at aged 14 and the GCSE scores were analysed.

2.2.2: Results

Descriptive statistics. Table 2.5 shows the descriptive statistics of the working memory measures for the 69 children whose attainment scores were available. Descriptive statistics for GCSE scores in English, mathematics, and science at 16 years of age are also shown. Skew and kurtosis for all measures met criteria for multivariate normality (Kline, 1998). No outliers were identified.

Table 2.5 *Descriptive Statistics of Working Memory Measures and GCSE Scores*

Measures	Mean	*SD*
Working memory measures		
Digit recall	5.21	0.92
Word recall	3.73	0.72
Visual Patterns	8.43	1.33
Dynamic matrices	3.59	0.75
Listening recall	3.10	0.60
Backwards digit	4.59	0.85
Spatial span	2.08	0.41
Odd- one- out	3.62	0.77
GCSE scores		
English (max 8)	5.78	1.76
Mathematics (max = 8)	5.33	2.04
Science (max = 16)	10.17	4.21

Correlational analyses. The correlation matrix of the working memory measures and the scholastic attainment scores is presented in Table 2.6. Age is also included.

Table 2.6 *Correlation Coefficients between the Working Memory Measures and GCSE Scores*

	1	2	3	4	5	6	7	8	9	10	11	12
1 Age	-	.48**	.38**	.38**	.27*	.20	.09	.18	.19	.06	.03	-.08
2 Digit recall		-	.57**	.62**	.50**	.31*	.24	.45**	.18	.28*	.24*	.13
3 Word recall			-	.40**	.32**	.36**	.20	.39**	.29*	.41**	.37**	.34**
4 Backwards digit recall				-	.44**	.41**	.29*	.56**	.34**	.38**	.37**	.27*
5 Listening recall					-	.37**	.17	.27*	.28*	.41**	.27*	.20
6 Visual Patterns						-	.56**	.32**	.41**	.35**	.39**	.30*
7 Dynamic matrices							-	.22	.45**	.20	.17	.17
8 Odd- one- out								-	.35**	.47**	.40**	.34**
9 Spatial span									-	.44**	.37**	.41**
10 English										-	.76**	.77**
11 Mathematics											-	.89**
12 Science												-

*$p < .05$ **$p < .01$

Scores on the two phonological loop tasks were significantly related, r (67) = .57, p < .01, as were those on the two visuo-spatial sketchpad tasks, r (67) = .56, p < .01, the two verbal central executive tasks, r (67) = .44, p < .01, and the two nonverbal central executive tasks, r (67) = .35, p < .01. Scores on the phonological loop and verbal central executive tasks were also highly correlated, with the highest correlation being between digit recall and backwards digit recall, r (67) = .62, p < .01. The visuo-spatial sketchpad and nonverbal central executive tasks were also significantly related, with the exception of the dynamic matrices task and the odd- one- out task, r (67) = .22, p > .05. As reported earlier, scores on the odd- one- out task correlated more highly with scores on tasks in the verbal domain such as backwards digit recall, r (67) = .56, p < .01.

A number of the working memory measures were also significantly related to attainment in English, mathematics and science at 16 years of age. The strongest associations were between English scores and scores on the odd- one- out task, r (67) = .47, p < .01, and the spatial span task, r (67) = .44, p < .01, between mathematics scores and performance on the odd- one- out task, r (67) = .40, p < .01, and the Visual Patterns Test, r (67) = .39, p < .01, and between science scores and spatial span scores, r (67) = .41, p < .01.

In order to evaluate whether unique relationships were obtained between the working memory tasks and GCSE scores, as with the data presented in section 2.1, composite scores were calculated for the phonological loop, visuo-spatial sketchpad, verbal central executive, and nonverbal central executive by averaging the Z scores on the associated tasks. Due to the high correlations between the odd- one- out task and tasks in the verbal domain (see section 2.1), spatial span scores were used as a single indicator of nonverbal central executive

processes. Partial correlations between each working memory construct and attainment in each academic subject were calculated, eliminating the variance associated with age and the other working memory constructs in each case. Corresponding analyses were performed eliminating the variance associated with age and the working memory tasks in the opposite domain. The partial correlation coefficients are presented in Table 2.7.

When the other working memory constructs were taken in to account unique links existed between verbal central executive scores and attainment in English, $r (64) = .27, p < .05$, and nonverbal central executive scores and attainment in English, $r (64) = .33, p < .01$, and science, $r (64) = .34, p < .01$. When partialing out only the constructs in the opposite domain, the phonological loop was associated with attainment in English, $r (65) = .35, p < .01$, mathematics, $r (65) = .30, p < .01$, and science, $r (65) = .28, p < .05$, but the visuo-spatial sketchpad was not uniquely related to attainment $(p > .05$ in each case). Verbal central executive scores were significantly related to attainment in English, $r (65) = .38, p < .01$, and mathematics, $r (65) = .28, p < .05$. Nonverbal central executive scores were significantly associated with attainment in English, $r (65) = .35, p < .01$, mathematics, $r (65) = .28, p < .05$, and science, $r (65) = .37, p < .01$.

Table 2.7 *Partial Correlation Coefficients between Working Memory Constructs and Attainment in English, Mathematics and Science*

Assessment	Working Memory construct					Working Memory construct			
	PL	VSSP	VCE	SS		PL	VSSP	VCE	SS
Constructs partialled out:	VSSP VCE SS	PL VCE SS	PL VSSP SS	PL VSSP VCE		VSSP SS	PL VCE	VSSP SS	PL VCE
English	.21	-.02	.27*	.33**		.35**	.12	.38**	.35**
Mathematics	.20	.08	.16	.23		.30*	.17	.28*	.28*
Science	.21	.01	.10	.34**		.28*	.15	.21	.37**

Note. PL = Phonological loop. VSSP = Visuo-spatial sketchpad. VCE = Verbal central executive. SS = Spatial span.

*p < .05 ** p < .01

Factor analyses and structural equation modelling. Factor analysis and structural equation modelling were then conducted using the EQS 6 structural equation package (Bentler, 2001). As with the data in section 2.1, four models of the structure of working memory were tested. The first model corresponded to the Baddeley and Hitch (1974) model of working memory, with separate central executive, phonological loop, and visuo-spatial sketchpad factors. The second model fractionated the central executive into verbal and nonverbal components in addition to consisting of phonological loop and visuo-spatial sketchpad factors. The third model consisted of one verbal factor incorporating the phonological loop and verbal central executive tasks, and one nonverbal factor incorporating the visuo-spatial sketchpad tasks and the spatial span task. In the fourth model all of the working memory tasks were associated with a single factor. For a diagrammatic representation of the models see Figure 2.3. The fit statistics for these models are presented in Table 2.8. Again, the fit statistics used are chi squared (χ^2), the comparative fit index (CFI) (Bentler, 1990), Bollen's incremental fit index (IFI), the standardised root mean square of the model residuals (SRMR), and the root mean square error of approximation (RMSEA).

Table 2.8 *Goodness of Fit Statistics for the Estimated Models*

Model	df	$\chi 2$	p	CFI	IFI	SRMR	RMSEA
CFA1b	11	20.6	.04	.91	.92	.08	.11
CFA2b	9	10.5	.31	.99	.99	06	.05
CFA3b	13	15.9	.26	.97	.98	.06	.06
CFA4b	14	38.1	.00	.77	.79	10	.16
SEM1	39	48.6	.14	.97	.97	.09	.06

Note. CFI = Bentler's comparative fit index. IFI = Bollens incremental fit index. SRMR = standardised root- mean squared residual. RMSEA = root mean square error of approximation.

Model 2, with the fractionated central executive, and Model 3, with one verbal and one nonverbal working memory factor, both yielded fit indices indicative of an excellent fit to the data, with CFI and IFI in excess of .95 and non-significant χ^2 values. To examine whether one of these models provided a significantly better fit than the other, a χ^2 difference test was conducted by subtracting the χ^2 value for model 2 from that for model 3 (degrees of freedom are calculated with an analogous subtraction). The finding of a statistically significant value would indicate that model 2 provided a better fit. There was no significant difference between the models, $\chi^2 (4) = 5.4, p > .05$. On grounds of parsimony, the model that was endorsed was therefore the two- factor model,

with one verbal and one nonverbal working memory factor. This model is shown in Figure 2.5a. All factor loading and correlations are significant at the .05 probability level.

The factor loadings produced in the best fitting, two- factor confirmatory factor analysis model (CFA3b) were then incorporated into a structural equation model (SEM) in which verbal and nonverbal working memory predicted scholastic attainment scores. In the model, both verbal and nonverbal factors were causally linked with a single attainment factor associated with English, mathematics, and science scores. The fit indices produced for this model are shown in Table 2.8. Alternative models in which verbal and nonverbal working memory differentially predicted English, mathematics, and science were also tested, but failed to satisfy statistical criteria for a good fit.

This model provided an excellent fit to the data, with a CFI of .97, a RMSEA value of .06, and a non-significant χ^2 value ($p = .14$). In this model significant paths existed between each working memory domain and attainment: for verbal working memory the standardised path coefficient was .33, $p < .05$, and for nonverbal working memory the standardised path coefficient was .28, $p < .05$. A structural equation model diagram of this model is presented in Figure 2.5b.

Figure 2.5 *Factor Loadings and Factor Correlations for the Confirmatory Factor Analyses and Structural Equation Models*

a) Confirmatory factor analysis model
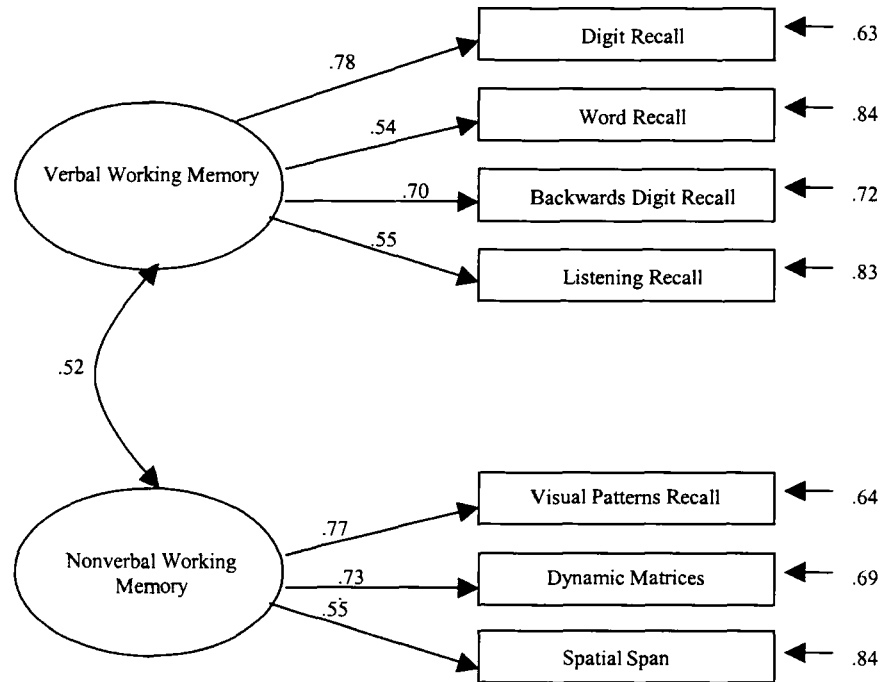
b) Structural equation model
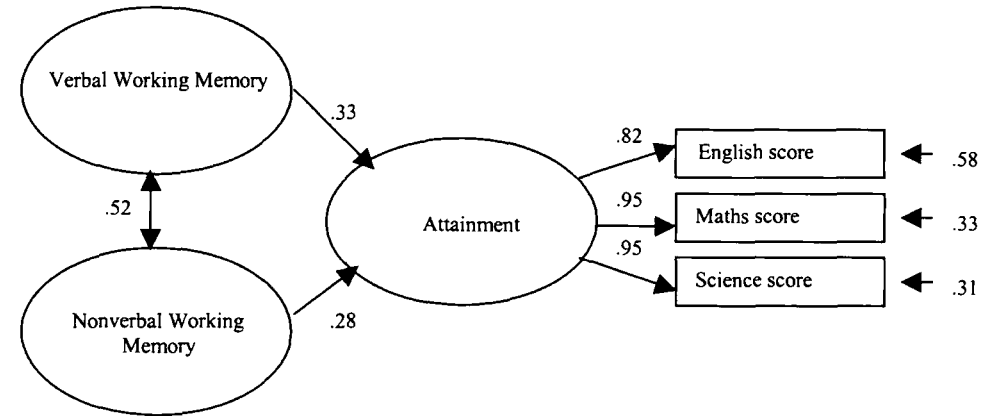
2.3: Discussion

Study 1 provided direct evidence for links between working memory and performance on national curriculum tests at 11 and 14 years of age. Both verbal and nonverbal working memory predicted attainment at both ages. Study 2 provided evidence for the utility of working memory as a predictor of later academic achievement.

The results build upon previous evidence of relationships between national curriculum test scores and working memory at 7 years of age and at 14 years of age (Gathercole & Pickering, 2000; Gathercole et al., 2004) and findings of the involvement of the phonological loop, visuo-spatial sketchpad, and central executive components of working memory in domains of skill related to education (e.g. Gathercole & Baddeley, 1993; Seitz & Schumann- Hengsteler, 2000; Reuhkala, 2001). The results also build upon the findings of Gathercole et al., (2003) who suggested that working memory can serve as a predictor of later educational attainment, and extends these findings to measures taken at 14 years of age. It should, however, be noted that the present findings of close associations between working memory and attainment in English at Key Stage 3 are inconsistent with previous reports (Gathercole et al., 2004) and provide little evidence for developmental changes in the contribution of working memory to the acquisition of knowledge and skill in language.

Detailed analysis of interrelations between specific working memory tasks and attainment indicated that complex span tasks that are associated with the central executive in the Baddeley and Hitch (1974) model of working memory were most closely related to attainment in all curricular areas. In study

1, at Key Stage 3, scores on verbal complex span tasks were significantly correlated with attainment levels in English and mathematics. Performance on spatial span, a nonverbal complex task, was significantly correlated with mathematics and science levels. Tasks tapping the two slave systems, however, were not uniquely related to levels in English, mathematics or science. In study 2, verbal complex span scores at 14 years of age predicted unique variance in English at 16 years of age, and spatial span scores predicted unique variance in English and science. This supports previous evidence that the central executive in particular plays a crucial role in the acquisition of complex cognitive abilities and skills such as literacy, comprehension and arithmetic (e.g. Bull et al., 1999; Swanson, 1994; Yuill et al., 1989).

It should, however, be noted that the data did not provide strong support for the specific Baddeley and Hitch (1974) model of working memory incorporating a domain general central executive and subsidiary domain specific storage systems. The findings of a dissociation between verbal and nonverbal working memory however, are consistent with those of Shah and Miyake (1996) who found evidence for separate pools of resources for verbal and spatial working memory, and further extend these findings to 11 and 14 year old children (see also: Friedman & Miyake, 2000; Handley et al., 2002; Kane et al., 2004).

Detailed analysis also revealed that the predictive relationships between verbal and nonverbal working memory abilities and school achievements reveal a marked degree of domain specificity (e.g. see also: Bayliss et al., 2003; Daneman & Carpenter, 1980; Daneman & Tardiff, 1987; Shah & Miyake, 1996). Partial correlations revealed that at 11 and 14 years of age, verbal working memory

tasks were uniquely associated with English and mathematics performance, whereas visuo-spatial tasks shared unique links with mathematics and science.

In study 2, associations between working memory scores and attainment at 16 years of age, however, showed a slightly different pattern. There was evidence for a domain specific link between verbal constructs and attainment in English and mathematics. However, spatial span predicted unique variance in attainment in each curricular domain. At present, it is not clear how this link between spatial span and attainment arose. One possibility is that visuo-spatial working memory is genuinely important in supporting learning across all curricular domains during later childhood. Another possibility is that visuo-spatial working memory measures are more dependent on general executive resources then verbal working memory measures (see Miyake et al., 2001; Oberauer et al., 2000; Shah & Miyake, 1996), and that these processes become particularly important for attainment during later years.

One apparent developmental change in the associations between working memory and attainment concerns science. Verbal complex span tasks were uniquely correlated with science scores at 14 years of age, but not at 11 years of age. In addition, it is notable that nonverbal working memory contributed rather less to attainment at Key Stage 3 than at Key Stage 2, although there was no direct statistical comparison. Although nonverbal working memory appeared to contribute rather less to attainment at Key Stage 3 than at Key Stage 2, there was no further developmental decrease in its contribution to learning achievements between 14 and 16 years of age. It is possible that the decrease observed between 11 and 14 years of age was a consequence of variations in the scholastic attainment measures employed with the different age groups. For example, as

discussed in section 2.1, in the English tests at 14 years of age children must demonstrate their understanding of literature and comment on reader- writer relationships, where as at 11 years of age assessments are more concerned with things like spelling and handwriting. GSCE assessments, however, are likely to have similar requirements to the national curriculum tests at 14 years of age.

A further difference between the age groups concerns the correlations between the odd- one- out task and the other working memory measures. At aged 11, odd- one- out scores correlated highly with other nonverbal measures but at aged 14 it correlated highly with verbal measures. In considering the demands made by the odd- one- out task it is plausible to suggest that in the older age group, where speed of processing is likely to be more efficient (e.g. Carella & Hale, 1994), participants were able to recode the spatial locations within the task in to a verbal format, such as 'left, middle and right'. In the younger age group, the time constraints imposed during the task may have prevented this recoding, resulting in visuo-spatial working memory being used to complete the task. None the less, the lack of validity of the odd- one- out task as a nonverbal complex span task has implications for its further use.

In conclusion, these studies provide further evidence for a distinction between verbal and spatial working memory resources. They also demonstrate that working memory is a strong predictor of educational attainment, as measured by national curriculum attainment levels. The impact of working memory capacities on performance on national curriculum tests is likely to be a result of working memory being employed for storage, processing and integration of information during complex and demanding activities (Just & Carpenter, 1992). Such activities are common in the school classroom, for

example writing while formulating the next part of a text, or engaging in mental arithmetic.

The strong links found here between working memory capacities and children's scholastic attainments have important practical implications for educational practice as well as cognitive theory. Firstly, using measures of working memory in addition to more commonly used knowledge- based assessments may provide better estimates of a child's chance of future academic success. Secondly, one reason why children may fail to achieve expected levels in key curricular domains is that their performance on learning tasks in the classroom is constrained by their working memory capacities. There may be significant benefits from creating structured learning activities that reduce opportunity for failure due to inadequate working memory resources. One way of achieving this may be to decompose complex task sequences involving intermediate storage and concurrent processes in to component stages, supported where possible by external memory prompts rather than working memory.

Chapter 3

Executive Functions and Achievements in School

Studies 1 and 2 demonstrated that working memory is an important predictor of educational attainment between 11 and 16 years of age. Detailed analyses of the interrelationships between specific working memory tasks and attainment revealed that complex span tasks associated with the central executive in the Baddeley and Hitch (1974) model of working memory were most closely associated with attainment. This supports previous evidence suggesting that executive functioning plays an important role in learning during childhood (e.g. Bull et al., 1999; Bull & Scerif, 2001; Lehto, 1995; Lorsbach, Wilson, & Reimer, 1996; McLean & Hitch, 1999; Ozonoff & Jensen, 1999; Russell et al., 1996; Swanson, 1993; 1999; Swanson et al., 1996), and evidence that the impact of working memory on academic achievement is considerable. Between the ages of 7 and 14 years, children who score poorly on working memory measures linked with executive skills typically perform below expected standards in national curriculum assessments of English, mathematics and science in England (Gathercole et al., 2003; Gathercole & Pickering, 2000; Gathercole et al., 2004).

The first step towards understanding the nature of the contribution made by executive aspects of working memory to the acquisition of complex skills and knowledge during childhood is to identify the component processes involved in relevant working memory measures. In 1986, Baddeley suggested that the model of the supervisory attentional system developed by Norman & Shallice (1980), a limited capacity system responsible for the control of action and attention, provides a useful account of some of the regulatory functions of the central

executive. Baddeley has subsequently identified further functions of the central executive. These include the capacity for the temporary activation of long-term memory (Baddeley, 1998), coordination of multiple tasks (e.g. Baddeley et al., 1997), shifting between tasks or retrieval strategies (Baddeley, 1996a), and the capacity to attend and inhibit in a selective manner (Baddeley & Emslie et al., 1998).

In a parallel analysis of executive functioning, Miyake et al. (2000) identified three key executive functions: shifting, updating, and inhibition. Shifting involves moving back and forwards between multiple tasks, operations or mental sets (e.g. Monsell, 1996). Updating requires monitoring and coding of incoming information and appropriately revising the items held in working memory by replacing no longer relevant information with new, more relevant information (e.g. Morris & Jones, 1990). Inhibition in this context refers to the ability to deliberately inhibit dominant, automatic, or pre-potent responses (e.g. Stroop, 1935). In an individual differences study of adult participants, Miyake et al. presented evidence that these three executive functions were separable (see also; Lehto et al., 2003; Oberauer et al., 2003).

Miyake et al. (2000) also tested participants on a measure of working memory, operation span, in which participants read aloud and verified arithmetic calculations, and then attempted to recall unrelated words presented after the verification of each sum. Operation span scores were highly related to updating skills, but not to measures of either shifting or inhibitory control. On this basis it was concluded that there is a common working memory factor underlying operation span and updating. Other researchers, however, have identified shifting between the processing and storage components of working memory tasks as a

crucial determinant of performance (e.g. Conway & Engle, 1996; Towse et al., 1998), and some have focussed on inhibitory processes (e.g. Cataldo & Cornoldi, 1998).

The purpose of the present study was to investigate the organisation of executive functions including working memory in children. There is some evidence for discrete executive functions in children although both the number and nature of these functions have differed widely across studies (e.g. Lehto et al., 2003; Levin, Fletcher, Kufera, & Harward et al., 1996; Welsh, Pennington, & Goisser, 1991). There is also some evidence to suggest that there may be developmental differences in the organisation of executive functions (e.g. Senn, Espy, & Kaufmann, 2004).

Multiple measures were taken of working memory, including listening recall (Daneman & Carpenter, 1980), and backwards digit recall (e.g., Morra, 1994). In addition, because verbal and visuo-spatial working memory skills have been found to be dissociated in both children (see Chapter 2) and adults (e.g. Jurden, 1995; Shah & Miyake, 1996), measures of visuo-spatial as well as verbal working memory were included. A major goal of the present study was to investigate whether the two domains of complex memory span task share common or distinct links with other executive functions.

The study was also designed to assess the extent to which the executive processes of shifting, working memory and inhibition relate to learning abilities and achievements in childhood. As well as suggesting the importance of working memory in scholastic attainment, research has suggested links between specific executive functions and sub- domains of skill related to education. Inhibitory processes have been implicated in reading (e.g. De Beni et al., 1998;

Gernsbacher, 1993), comprehension (Dempster & Corkill, 1999), vocabulary

learning (Dempster & Cooney, 1982) and mathematics (e.g. Espy, McDiarmid,

Cwik, Stalets, Hamby, & Senn, 2004). Shifting abilities have been associated

with both writing skills (Hooper et al., 2002) and arithmetic (e.g. Bull et al.,

1999; Bull & Scerif, 2001). Furthermore, shifting, working memory and

inhibition each account for unique variance in mathematics scores (Bull & Scerif,

2001). The present study extended the approach taken by Bull and Scerif (2001)

in order to explore whether distinct executive processes are uniquely linked with

children's attainments in school-based assessments of English, mathematics and

science.

To reiterate, the study had three main goals. The first goal was to

investigate the extent to which the three target executive functions of shifting,

updating, and inhibition are unitary or separable in children. This was examined

by looking at the factor structure of the executive tasks. The second major goal

was to investigate the executive functions underlying performance on working

memory span tasks. Miyake et al. (2000) found evidence suggesting that a

common working memory factor underlies performance on updating tasks and

the operation span task. In the present study, measures of both verbal and visuo-

spatial working memory were included. The factor structure of the executive and

working memory tasks was explored. The final goal of the study was to assess

the extent to which executive functions contribute to children's learning

achievements. This was investigated by analysing the relationships between

executive factors and educational attainment in English, mathematics and

science. The domain- specificity of links between working memory and

attainment was also explored by examining associations between verbal versus nonverbal working memory and attainment.

3.1: Method

3.1.1: Participants

The participants were 51 children (27 boys and 24 girls) with a mean age of 11 years and nine months (SD = 3 months, range = 11 years 4 months to 12 years 3 months), attending a local education authority school in the North East of England. The pupils completed the executive tasks and working memory assessments during the first term of secondary school. The national curriculum tests (tests of academic achievement) had been completed approximately three months earlier during the final term of primary school.

3.1.2: Materials and procedure

All participants completed a set of six executive tasks, composed of two tasks designed to tap each of the three functions of shifting, updating, and inhibition. The tasks were based on those employed by Miyake et al. (2000). All participants were also tested on four working memory span tasks, two of each requiring the storage and processing of verbal and visuo-spatial information. The schools supplied the attainment scores of each child on national curriculum tests in English, mathematics and science.

Each child was tested in three sessions. Testing took place in a quiet room in school. The order of test administration was held constant. The shifting, updating, and inhibition tasks were administered first, followed by the two verbal, and finally two visuo-spatial working memory span tasks.

Executive Tasks. The following shifting tasks were administered. The plus-minus task (adapted from Jersild, 1927) consisted of three lists of 30 two- digit numbers. The numbers were pre-randomised without replacement. On the first list participants were instructed to add 3 to each number. They were told to complete as many as possible within 2 minutes. Within the same time limit, on the second list the participants were instructed to subtract 3 from each number, and on the third list the participants were required to alternate between adding and subtracting 3 from the numbers. The cost of shifting was then calculated as the difference between the number of correct answers given in the alternating list, and the average of those in the addition and subtraction lists.

The local- global task consisted of sets of figures in which the lines of a global figure, e.g. a triangle, are composed of smaller local figures, e.g. squares (Navon, 1977). On one list, participants were instructed to record the number of lines in the global figure, i.e. one for a circle, two for an X, three for a triangle, and four for a square. They were instructed to complete as many as possible within 2 minutes. Within the same time limit, on the second list participants were instructed to record the number of lines in the local figure, and on the third list participants were required to alternate between recording the number of lines in the local figure and the global figure. The cost of shifting was then calculated as the difference between the number of correct answers given in the alternating list, and the average of those in the local and global lists.

The updating tasks were letter memory and the keep track task. In the letter memory task (adapted from Moris & Jones, 1990) letters were presented serially, for 2000 ms each in the centre of the computer screen. The number of letters presented (either 5, 7, 9 or 11) was varied randomly across trials. The task was to recall the last four letters presented in each list. Following the procedure used by Miyake et al. (2000), to ensure that the task required continuous updating, the instructions required the participants to rehearse the last four letters out loud throughout the task. After two practice trials participants performed 15 trials. The score given was the number of letters recalled incorrectly (so that consistent with the other executive tasks higher scores denoted worse performance). Split- half reliability for this task was calculated as .47.

In the keep track task (adapted from Yntema, 1963) participants were shown a number of target categories at the bottom of a computer screen. The target categories used here were animals, colours, clothes, countries and sports. Fifteen words, including three exemplars from each category were then presented serially in random order in the centre of the computer screen for 2000 ms each. Participants were required to remember the last word presented in each of the target categories, and then write these down at the end of each trial. Participants were not informed of the number of items in each category in order to minimise the possibility that they would monitor the number of instances rather than continuously updating information. Participants performed five trials with three target categories and five trials with four target categories. The score given was the number of words recalled incorrectly (again so that higher scores denoted worse performance). The split- half reliability estimate for this task was .43.

Stop signal and Stroop measures were used as inhibition tasks. The stop signal task (based on Logan, 1994) consisted of two blocks of trials. The first block was used to build up a pre-potent categorisation response. Participants were presented with a series of 24 monosyllabic words matched for length and frequency one at a time in the centre of the computer screen, for 1000 ms each. They were instructed to verbally categorise each as an animal or non- animal. They were given 2000 ms to do so. In the second block of 48 trials the procedure was the same with the exception that participants were instructed not to respond i.e. to inhibit the categorisation response when given a particular signal. The signal consisted of three asterisks presented below the word. Asterisks were presented on 16 of the trials. As recommended by Logan (1994) the instructions emphasised that participants should not slow down to wait for possible signals, and if slowing was detected the experimenter reminded them to continue responding as quickly as possible. The score given was the number of categorisation responses given to the 'stop' trials. Split- half reliability for the stop- signal task was .81.

In the Stroop task (Stroop, 1935) participants were presented with strings of asterisks, each printed in one of five colours (red, green, blue, orange and yellow). Participants were asked to name the colours. They were given 2 minutes to complete as many as possible. Participants were then presented with colour words in incongruent colours, e.g. BLUE in yellow ink, or RED in green ink. Again, participants were required to name the colour of the stimuli and complete as many as possible within 2 minutes. The score given was the difference between the numbers of colours correctly named for the two types of stimuli.

Working Memory Span Tasks. Each child completed the listening recall task and the backwards digit recall test from the Working Memory Test Battery for Children, (Pickering & Gathercole, 2001). They were also tested on the odd-one- out task (based on Russell et al., 1996), and the spatial span task (based on Shah & Miyake, 1996). Details of each of these tasks, their administration, and their scoring criteria were described in section 2.1.

Scholastic Attainment Tests. Attainment scores on national curriculum tests in English, mathematics and science were obtained for each pupil. Details about the attainment tests at 11 years of age were provided in Chapter 2. However, in the present study, rather than using the attainment levels which result in a restricted range of scores, schools were asked to supply children's actual scores on the scholastic tests.

3.2: Results

3.2.1: Descriptive statistics

Descriptive statistics for the executive measures, working memory tasks and children's attainment in school are provided in Table 3.1. No univariate or multivariate outliers were identified.

Table 3.1 *Descriptive Statistics for Executive Measures, Working Memory Span Tasks and Scholastic Attainment Scores*

Measure	Mean	*SD*
Shifting		
Plus minus task	11.51	4.15
Local global task	21.74	8.55
Updating		
Letter memory (max. 60)	27.63	9.53
Keep track task (max. 35)	15.12	5.96
Inhibition		
Stroop task	12.06	6.77
Stop signal task	5.78	4.60
Working memory tasks		
Listening recall	2.84	0.42
Backwards digit recall	3.73	0.85
Odd- one- out task	3.54	0.56
Spatial span task	2.57	0.47
Scholastic attainment score		
English	59.70	14.22
Mathematics	70.57	18.12
Science	61.39	11.19

Table 3.2 *Correlations between Executive Measures, Working Memory Tasks and Attainment, Upper Triangle Displaying First Order Correlations and Lower Triangle Displaying Correlations Controlling for Age*

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Age	-	-.07	-.10	.05	.12	-.29*	.01	-.21	-.09	-.03	.12	.08	.12	.07
2. Plus minus task	-	-	.13	.16	.24	.25	.19	-.03	-.11	-.17	-.29*	-.28*	-.42**	-.34*
3. Local global task	-	.12	-	.32*	.32*	.11	.19	-.20	-.13	-.26	-.27	-.20	-.26	-.16
4. Letter memory	-	.16	.33*	-	.38**	-.08	.06	-.51**	-.49**	-.66**	-.52**	-.43**	-.33*	-.08
5. Keep track task	-	.25	.33*	.37**	-	-.03	.24	-.37**	-.37**	-.58**	-.51**	-.46**	-.51**	-.39**
6. Stroop task	-	.24	.08	-.07	.00	-	.47**	-.03	-.06	-.03	-.20	-.24	-.17	-.18
7. Stop signal task	-	.19	.19	.06	.24	.49**	-	-.04	.01	-.19	-.31*	-.24	-.31*	-.28*
8. Listening recall	-	-.04	-.23	-.51**	-.36*	-.10	-.04	-	.52**	.46**	.26	.50**	.21	.06
9. Backwards digit recall	-	-.12	-.14	-.48*	-.36*	-.09	-.01	.52**	-	.40**	.37**	.39**	.08	-.10
10. Odd-one-out	-	-.18	-.26	-.66**	-.58**	-.04	-.19	.46**	.40**	-	.60**	.56**	.47**	.22
11. Spatial span	-	-.28*	-.26	-.53**	-.53**	-.18	-.32*	.29*	.39**	.61**	-	.45**	.44**	.31*
12. English score	-	-.28	-.19	-.43**	-.47**	-.23	-.24	.53**	.40**	.56**	.44**	-	.53**	.35*
13. Maths score	-	-.42**	-.25	-.34*	-.54**	-.15	-.31*	.25	.09	.48**	.44**	.52**	-	.79**
14. Science score	-	-.34*	-.15	-.08	-.40**	-.17	-.28*	.08	-.09	.22	.31*	.34*	.79**	-

*$p < .05$ **$p < .01$

3.2.2: Correlational analyses

The correlation matrix including the executive measures, working memory tasks and scholastic attainment scores is presented in Table 3.2. The upper triangle shows zero- order correlations, and the lower triangle shows partial correlations controlling for age in months. Only small reductions in correlation coefficients were observed when age was partialed out.

Several of the executive tasks were significantly correlated with one another. The highest correlations were between the two inhibitory tasks, Stroop and stop signal, r (49) = .47, p < .01, and the two updating tasks, letter memory and keep track, r (49) = .38, p < .01. The two shifting measures were not significantly correlated with one another, r (49) = .13, p > .05.

All four working memory span tasks were significantly correlated with one another. The highest correlations were between the pairs of verbal tasks, listening recall and backwards digit recall, r (49) = .52, p < .01, and visuo-spatial tasks, the odd- one- out task and spatial span, r (49) = .60, p < .01.

Several executive measures correlated significantly with the working memory span tasks. The highest correlation coefficients were found between the updating and working memory span tasks, ranging from -.37 to -.66. Note that these coefficients have negative valences because higher scores reflect poorer performance on the executive tasks, but not on the working memory tasks.

Significant correlations were found between some of the executive tasks and attainment scores. The strongest associations were between the keep track scores and attainments in English, r (49) = -.46, p < .01, and mathematics, r (49) = -.51, p < .01. Several working memory measures were also significantly

correlated with attainment scores. Both listening recall and backwards digit recall were associated with English scores, $r (49) = .50, p < .01$, and $r (49) = .39$, $p < .01$, respectively. The odd- one- out task was significantly correlated with both English, $r (49) = .56, p < .01$, and mathematics attainment, $r (49) = .47, p < .01$. Spatial span was significantly correlated with English scores, $r (49) = .45, p < .01$, mathematics scores, $r (49) = .44, p < .01$, and science scores, $r (49) = .31$, $p < .05$.

3.2.3: Factor structure of executive and working memory measures

In order to explore relations between the shifting, updating and inhibition tasks, scores on the executive measures were entered in to a principal components analysis with varimax rotation. Following Kaiser's criterion, factors with eigenvalues in excess of one were retained. Factor loadings of .45 and above were used to guide the interpretation of factor structure (Tabachnick & Fidell, 1996). The factor loading scores for this analysis, PCA1, are shown in Table 3.3. Two factors were identified, accounting for 56.7 % of the variance in total. Both updating tasks (letter memory and keep track) and one shifting measure (local- global task) loaded highly on Factor 1. Factor loadings for Factor 2 were high for both inhibition tasks (Stroop task, stop signal task), with an additional moderate loading of the plus minus shifting task.

Table 3.3 *Factor Loading Scores from Principal Component Analysis of Executive Measures*

	PCA1		PCA2	
	Factor 1	Factor 2	Factor 1	Factor 2
Plus Minus task	.32	**.48**		
Local Global task	**.65**	.19		
Letter Memory	**.78**	-.01	**.81**	-.08
Keep Track task	**.77**	.12	**.83**	.13
Stroop task	-.15	**.86**	-.16	**.86**
Stop Signal task	.16	**.79**	.22	**.85**

Note. Values in bold are in excess of .45

As the two shifting measures failed to load on a single distinct factor they were excluded from further analysis. A further principal components analysis (PCA2) was performed on the reduced set of two updating and two inhibition measures, in order to gain purer estimates of each factor. The solution yielded two factors corresponding to updating and inhibition, and accounted for 72.6 % of the variance in total.

The relationships between updating and inhibition and the two domains of working memory were then explored. All eight measures (two each of updating, inhibition, verbal working memory, and visuo-spatial working memory) were entered in to a principal components analysis, PCA3. Again factors with

eigenvalues in excess of one were retained. The resulting factor loadings are shown in Table 3.4. Two factors were identified, accounting for 61.8 % of the variance in total. A clear split between executive functions was apparent in the factor structure, with the updating and working memory measures loading onto Factor 1, and the inhibition tasks onto Factor 2. In addition, the spatial span task scores showed a lower but moderate association with this factor (-.41). Using factor scores produced by this solution, a general working memory score (updating and both verbal and visuo-spatial working memory) and an inhibition score were calculated for each participant.

Table 3.4 *Factor Loading Scores from Principal Component Analysis of Executive tasks and Working Memory Measures*

	Factor 1	Factor 2
Letter memory	**-.82**	-.07
Keep track task	**-.70**	.18
Stroop task	.06	**.81**
Stop signal task	-.11	**.85**
Listening recall	**.71**	.08
Backwards digit recall	**.71**	.07
Odd- one- out task	**.83**	-.15
Spatial span	**.68**	-.41

Note. Values in bold are in excess of .45

3.2.4: Relationships between executive functions, working memory,

and scholastic attainment

In order to identify unique associations between the executive factors and scholastic attainment scores, a series of partial correlation coefficients were computed using the factor scores from PCA3. The resulting coefficients are shown in Table 3.5. In the first set of analyses, correlations between the executive constructs and attainment were computed in which the other construct was partialed out in each case. Working memory was associated with unique variance in attainment in English scores, r (49) = .62, $p < .01$, and mathematics scores, r (49) = .45, $p < .01$. Inhibition accounted for a small amount of unique variance in each curricular domain, for English r (49) = .31, $p < .05$, for mathematics r (49) = .36, $p < .05$, and for science r (49) = .34, $p < .05$.

A further set of analyses was performed in order to examine possible links between domain- specific aspects of working memory and the attainment measures. Composite scores were calculated for verbal working memory and for visuo-spatial working memory by averaging the z scores on the associated tasks. The verbal and visuo-spatial composite scores were significantly correlated with one another, r (49) = .48, $p < .01$. Partial correlations between each working memory score and attainment measures were then computed, eliminating the variance associated with the other working memory score in each case. Significant partial correlations were found between verbal working memory and English scores, r (49) = .33, $p < .05$, and between visuo-spatial working memory and scores in all areas of assessment: English, r (49) = .42, $p < .01$, mathematics, r (49) = .50, $p < .01$, and science, r (49) = .35, $p < .05$.

Table 3.5: *Partial Correlation Coefficients between Executive Functions, Working Memory and Scholastic Attainment*

| | Executive Function | | Working Memory Domain | |
| | Working Memory | Inhibition | Verbal | Visuo-spatial |
Function partialed out:	Inhibition	Working Memory	Visuo-spatial	Verbal
English	.62**	.31*	.33*	.42**
Mathematics	.45**	.36*	-.10	.50**
Science	.19	.34*	-.19	.35*

* *p*<.05 ** *p*<.01

3.3: Discussion

This study casts further light on the relationship between executive functions and learning achievements in children, with three principal findings. First, abilities to update the contents of working memory and to inhibit information were unrelated in this sample of 11 and 12- year- old children. This extends previous evidence from studies of adults that inhibition is dissociable from other executive functions to children, and is consistent with the view that there are several diverse executive functions (e.g. Espy, 1997; Klenberg, Korkman, & Lahti- Nuuttila, 2001; Miyake et al., 2000). Unlike the Miyake et al. study with adult participants, the present study failed to identify a third distinct executive factor, shifting. This disparity across the two studies may reflect a fundamental difference in the organisation of executive function between children and adults. Consistent with this view, Senn et al. (2004) suggested that mental flexibility may be less differentiated from working memory and inhibition in young children than in older participants. Alternatively, the disparity could result from limitations associated with the paradigm used for the shifting tasks (see Emerson & Miyake, 2003; Rogers & Monsell, 1995). Contrasting conditions in which the same task is repeated with a condition in which it is necessary to switch between two tasks confounds switch costs and mixing costs i.e. costs associated with switching from one task to another and costs of mixing two tasks in a trial sequence rather than always performing the same task (Miyake, Emerson, Padilla, & Ahn, 2004). Furthermore, the reliability of the shifting measures is unknown. For these reasons, no strong conclusions concerning the

relationships between shifting and either other executive functions or learning can be drawn from the present data.

A second finding was that verbal and visuo-spatial measures of complex working memory share a common association with updating skills, but are not linked with inhibitory processes. This finding reinforces Miyake et al.'s (2000) report of strong and specific links between updating and one verbal working memory measure, operation span. The present results establish that the association between updating and complex memory span extends both to other verbal measures and also to visuo-spatial working memory assessments, and are consistent with claims that performance on these tasks is constrained by the ability to monitor incoming information and update the contents of working memory (Conway & Engle, 1996; Engle & Tuholski et al., 1999; Lehto, 1996; Miyake et al., 2000; Towse et al., 1998). It is worthy of note that updating was closely linked with nonverbal working memory measures even though the stimulus demands of the updating tasks were largely verbal in nature. Updating therefore appears to reflect a genuinely domain-general facility crucial for both verbal and visuo-spatial complex memory tasks. Dissociability of verbal and visuo-spatial memory factors must therefore arise from additional domain-specific components to the tasks, possibly reflecting in part at least the contributions of modality-specific storage systems (Baddeley & Logie, 1999).

The third aim of the present study was to explore links between executive functioning and learning achievements at 11 years of age. The results are consistent with findings of independent contributions of discrete executive functions to children's attainment in mathematics (Bull & Scerif, 2001) and extend these findings to standardised assessments in English, mathematics and

science. The results are also consistent with previous findings of associations between working memory span tasks and national curriculum test scores at 7, 11, and 14 years of age (Gathercole & Pickering, 2000; Gathercole et al., 2004). It is notable that when controlling for inhibition, working memory remained closely associated with English scores. This provides support for the view that working memory plays a causal role in children's developing skills and knowledge, particularly in the domain of literacy (see also; de Jong, 1998, Gathercole & Pickering, 2000; Siegel & Ryan, 1989; Swanson & Alexander, 1997). This finding may have emerged due to working memory being employed for all or some of the skills assessed by the English tests; reading (e.g. Swanson et al., 2004), writing (see Berninger & Swanson, 1994; Swanson & Berninger, 1995 for a review), and spelling (e.g. Carramazza, Miceli, Villa, & Romani, 1987; Margolin, 1984). Working memory was also closely related to achievement in mathematics, consistent with the view that working memory capacity constrains mental arithmetic and mathematics performance (see DeStefano & LeFevre, 2004 for review). Competence in curriculum based mathematics tests involves mastering a number of skills such as counting and mental arithmetic, measurement abilities (e.g. perimeter, area, and time) and space abilities (manipulation or evaluation of geometric forms), all of which may require working memory resources (e.g. Geary, 2004; Maybery & Do, 2003; Swanson, 2004).

When controlling for working memory, inhibition was significantly associated with attainment in each curricular area, indicating that inhibitory skills support general academic learning rather than the acquisition of skills and knowledge in specific domains (e.g. Dempster & Corkill, 1999). It should,

however, be noted that the magnitude of the associations between attainments and working memory was considerably higher than the links found between attainments and inhibitory skills.

Although verbal and visuo-spatial working memory scores were highly associated with one another they did account for unique variance in academic attainments. Verbal working memory was found to account for a small but significant amount of unique variance in English scores whereas visuo-spatial working memory was closely related to attainment in English, mathematics, and science. This latter finding contrasts with a previous study with the same age group (see Chapter 2), in which visuo- spatial working memory was found to be uniquely linked with achievements in mathematics and science only. It is possible that the present findings of more pervasive links between visuo-spatial working memory and attainments may arise from the greater dependency of this component of working memory on general executive resources than verbal working memory (see Miyake et al., 2001; Oberauer et al., 2000; Shah & Miyake, 1996, for related arguments). At present it is sufficient to note that in English and mathematics at least, the strongest associations with scholastic attainment are found with domain- general rather than domain- specific aspects of working memory.

This study adds to existing evidence that executive functions of working memory and inhibition play a role in learning. There are a number of possible reasons why this is the case. Children with poor working memory function (as indexed by poor verbal complex memory span performance) have been found to make frequent errors in a range of learning activities including remembering and carrying out instructions, keeping track of places in tasks, writing while

formulating text, and carrying out mental arithmetic, (Gathercole, Lamont, & Alloway, in press). Several of these common classroom activities require the simultaneous processing and storage of information. Several also clearly involve processes such as shifting, updating, and inhibition. For example, a task such as writing a sentence has a complex hierarchical structure that requires shifting between lower levels of processing (identifying the component letters in individual words and writing them) and higher levels of activity such as maintaining the surface form of the planned sentence and identifying the next word in the sequence. Keeping track of place in the sentence requires updating of previous representations of how far the child has progressed in the task. Reading a sentence also requires inhibition of irrelevant information (Gernsbacher, 1993). This theoretical analysis has potentially important implications for educational practice. In particular it predicts that structuring learning activities in ways that prevent working memory overload, for example by reducing processing difficulty and storage loads as appropriate and encouraging the use of external memory aids, will enhance learning activities in children with poor working memory function.

Chapter 4

Exploring Complex Span Tasks as Predictors of Educational Attainment

Studies 1 to 3 suggested that complex working memory tasks are important predictors of scholastic skills (see also; Gathercole et al., 2003; Gathercole & Pickering, 2000; Gathercole et al., 2004). This predictive power, however, has increased the need to address theoretical issues related to the tasks. Despite their popularity, there is still some debate as to what working memory tasks really measure (e.g. Miyake, 2001). The study in Chapter 3 demonstrated that complex span performance relies on the ability to monitor and update the contents of working memory (see also; Conway & Engle, 1996; Engle & Tuholski et al., 1999; Lehto, 1996; Miyake et al., 2000; Towse et al., 1998). However, there is a continuing debate as to whether the demands of the tasks are met by a single system (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) or a number of interacting subsystems (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000). One reason why this issue is difficult to address is that it is common practice to measure performance only in terms of final item recall (for a critique see Waters & Caplan, 1996). Thus it is possible that participants neglect processing activities in order to focus on the items to be remembered. The study presented in this chapter focuses on the counting span task (Case et al., 1982) and had three main goals; to explore the influence of the difficulty of processing on working memory task performance, to investigate the relative contributions of processing speed and memory span to scholastic skills,

and to explore relationships between processing and storage abilities. The findings are discussed in terms of theories of working memory.

Chapter 1 discussed how approaches to working memory differ in terms of the resources proposed to underlie performance on working memory measures. The resource switching hypothesis (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) assumes that the storage demands of tasks are met by the phonological loop or visuo-spatial sketchpad whereas processing requires domain- general executive resources (e.g. Baddeley & Logie, 1999). This account of working memory proposes that working memory tasks should be distinguishable from, but related to, tasks that measure short- term memory capacity. Evidence from studies using individual differences approaches does suggest that this is the case (e.g. Cantor et al., 1991; Conway et al., 2002; Engle & Tuholski et al., 1999; Kail & Hall, 2001).

In the studies presented in Chapter 2, however, close relationships were found between short- term memory tasks and working memory tasks within the same domain, either verbal or nonverbal. This finding did not provide strong support for the multiple- component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000) in which the central executive, which is assessed by using complex span tasks, is separable from domain- specific storage systems. One possible reason for the finding is that short- term memory tasks and working memory tasks rely upon a single system, as suggested by the resource sharing approach to working memory (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992).

However, there is also an alternative explanation, which is concerned with the difficulty of processing within complex memory tasks. The idea

underlying working memory tasks is that more controlled and complex processing activities provide better working memory measures because complex abilities sufficiently tap cognitive resources and therefore disrupt maintenance of memory items (Barrouillet et al., 2004; Lepine, Barrouillet, & Camos, in press). If the processing requirements of a working memory task place too small a load upon participants then the task may not employ executive resources and therefore not provide an index of working memory capacity. For example, Baddeley et al. (1985) argued that both the processing and storage requirements of the counting span task are not attentionally demanding, and could be met by the phonological loop. The absence of executive involvement was used to explain the finding that counting span was a worse predictor of language comprehension than a reading span task. Bayliss et al. (2003) demonstrated that individual differences in both storage capacity and processing efficiency placed constraints on complex span performance, but that those imposed by processing efficiency were dependent on the level of processing demand. When processing was not effortful its influence on complex memory span was minimal, allowing performance to be constrained by storage capacity only. Therefore findings of close relationships between short-term memory and working memory could be consistent with the resource switching approach to working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) if it assumed that processing activities with low complexity do not place sufficient demands upon the central executive. A major goal of the present study was to explore the possibility that the previous findings of close relationships between short- term memory and working memory measures were a result of the processing elements of working memory tasks having a low level of complexity (e.g. Baddeley et al., 1985).

It is worthy of note, however, that a recent conceptualisation of working memory suggests that the cognitive cost of a task cannot be equated with the difficulty of processing. As discussed in section 1.2, Barrouillet and Camos (2001) and Barrouillet et al. (2004) suggested that a critical factor constraining complex span performance is the extent to which a processing task is demanding of attention over a set period of time. For a given duration the cognitive cost of a task is a function of the time during which it captures attention in such a way that the refreshing of memory traces is prevented. The longer this time, the fewer and shorter the periods of time that can be allocated to retrieving the information to be recalled. However, complex processing activities are not necessarily required and even adding or subtracting one can suffice (e.g. Gavens & Barrouillet, 2004) as long as the number of calculations is sufficient to distract attention away from the memory items. Thus this view proposes that working memory is constrained by both attentional sharing and temporal duration, and that when performing a working memory task there is a rapid switching between processing and refreshing memory traces *during* processing intervals. It is important to note, however, that because this approach assumes resource sharing it is not consistent with findings that working memory tasks are distinguishable from tasks that measure short- term memory capacity (e.g. Cantor et al., 1991; Conway et al., 2002; Engle & Tuholski et al., 1999; Kail & Hall, 2001).

The task used in the present study was counting span (Case et al., 1982). One manipulation that has been used to increase the cognitive demand of this task involves varying the similarity between targets and non- targets (Towse & Hitch, 1995). Studies of visual search have shown that the identification of targets among non targets is more demanding if targets must be distinguished

using a conjunction of two featural attributes rather than a single featural cue (e.g. Duncan, 1987; Treisman, 1991; Treisman & Gelade, 1980; Treisman & Sato, 1990).

An alternative approach to increasing cognitive demand was used by Case et al. (1982), who asked participants to count using an unfamiliar sequence of numbers. Participants first repeated the list of numbers until they could do so without error. They then used the nonsense numbers to count a series of practice arrays until they were able to count at a predetermined rate. This increase in demand resulted in the counting speeds of adults becoming equivalent to those of six- year- old children. The counting spans of adults also became comparable to those of children, suggesting that developmental differences in span are a result of differences in the efficiency of processing.

The present study used three counting span tasks, two of which differed in terms of target- non target similarity, and one of which involved counting using unfamiliar numbers. It was expected that counting using unfamiliar numbers would be the most complex task because the numbers would first have to be retrieved from long- term memory. It was also expected that a counting span task requiring a conjunction search would be more complex than a task requiring a feature search (e.g. Duncan, 1987; Treisman, 1991; Treisman & Gelade, 1980; Treisman & Sato, 1990), leading to a lower working memory span score.

Performance on each version of the counting span task was related to performance on measures of short- term memory capacity. If the previous findings of strong associations between simple and complex span tasks were a result of short- term memory and working memory tasks employing a limited

pool of resources (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992), it was assumed that performance on each version of the counting span task would be highly associated with scores on short- term memory measures. Alternatively, if working memory tasks involve resource switching (Towse & Hitch, 1995; Towse et al., 1998; 2000), and the associations between short- term memory and working memory were a result of working memory tasks having a low level of complexity (e.g. Baddeley et al., 1985), it was assumed that more demanding versions of the counting span task would be less closely associated with short- term memory measures than the less demanding versions. Manipulating cognitive demand could therefore provide evidence addressing the resources underlying performance on working memory tasks.

In addition to examining span scores on the variations of counting span and comparing these scores to performance on short- term memory tasks, as an indicator of complexity of processing, speeds of processing and response durations were recorded. Speed of processing refers to the time taken to count the targets in an array, with a decreased attentional load resulting in an increased speed of processing (Logan, 1976; Shiffrin & Schneider, 1977). According to both resource sharing (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992), and resource switching (see Towse & Hitch, 1995; Towse et al., 1998; 2000) memory span is determined by this speed of processing.

Response durations refer to the length of time taken at the end of each trial for a participant to recall all of the count totals. Response durations may reflect a general speed of processing (e.g. Kail & Salthouse, 1994) but may also be influenced by rehearsal, response planning, memory search, and

redintegration (Cowan, 1992; Cowan, Keller, Hulme, & Roodenrys et al., 1994; Cowan, Wood, Wood, & Keller et al., 1998; Hulme, Newton, Cowan, Stuart, & Brown, 1999; Sternberg et al., 1978; Sternberg, Wright, Knoll, & Monsell, 1980). Although additional research is needed to fully understand timing in complex span tasks, the duration of responses serves as a useful index of the difficulty or duration of processing in a span task (see Cowan et al., 2003).

The second goal of the present study was to assess the relative contributions of working memory span scores and processing speed measures to academic attainment. Studies 1 to 3 demonstrated close relationships between working memory span tasks and achievement on national curriculum tests at 11, 14, and 16 years of age (see also; Gathercole & Pickering, 2000, Gathercole et al., 2003, Gathercole et al., 2004). However, processing efficiency and storage capacity independently constrain complex span performance (e.g. Bayliss et al., 2003). Processing and storage may also make independent contributions to academic skills. For example, Bayliss et al. (2003) demonstrated that processing efficiency was related to reading and mathematics scores when statistically controlling for storage capacity. Visuo-spatial storage capacity was also associated with mathematics when controlling for speed of processing. Hitch et al. (2001) further demonstrated that the speed of processing during working memory span tasks predicted unique variance in attainment measures when controlling for working memory span scores. Friedman and Miyake (2004b) found that controlling for speed in the reading span task resulted in only small decreases in the correlation between working memory and comprehension.

Researchers have also explored the relationships between response durations and scholastic skills. Cowan et al. (2003) found that response durations

helped to predict academic skills and achievement, independently from the contributions of memory spans themselves. This was particularly true in young children, with response durations being better predictors of word reading than the corresponding memory span scores. In older children and adults, however, more of the predictive power appeared to shift to spans.

The findings that speed measures are not behind the predictive power of working memory span tasks are of interest because according to both resource sharing and task switching approaches to working memory, span is determined by speed. Span and speed should therefore explain common variance in educational attainment (e.g. Friedman & Miyake, 2004b; Hitch et al., 2001). Exploring the relative contributions of processing speeds and spans to attainment could therefore provide further insights in to the resources underlying performance on working memory tasks.

The relationships between processing and storage requirements in each of the three working memory tasks were also explored in the interest of further understanding what the counting span task actually measures. Both the resource sharing and task switching approaches to working memory assume that there is a linear relationship between counting time and counting span. The two approaches, however, could make different predictions about the relationships between speed and span across different working memory tasks. Hitch et al. (2001) suggested that the resource sharing assumption predicts that different working memory tasks will conform to the same speed- span relationships. In contrast, they claimed that because the task switching approach to working memory explains the effect of processing time in terms of forgetting, span- speed relationships could depend upon the dynamics of activation loss in different task

contexts. Hitch et al. demonstrated that both reading span and operation span increased linearly with the time taken to perform the processing operations, but that the quantitative relationship was different in each case, ruling out a simple resource sharing model.

In summary, the present study centred on the counting span task (Case et al., 1982) and addressed three specific goals. The first goal was to ascertain whether working memory tasks with more complex processing requirements are less closely associated with short- term memory measures than less complex tasks. The second goal was to explore the relative contributions of speed measures and span scores to scholastic skills. The third goal was to investigate the relationships between processing and storage requirements in order to provide insights in to what counting span actually measures. The results are discussed in terms of implications for models of working memory.

4.1: Method

4.1.1: Participants

The participants were 70 children with a mean age of 11 years and 11 months (S.D 4 months). All children attended a local education authority school in the North East of England. All children had completed national curriculum tests (tests of scholastic achievement) in English, mathematics and science approximately 5 months prior to being testing on the experimental measures.

4.1.2: Materials and procedure

All children took part in a single testing session in which three short-term memory tasks and three working memory tasks were administered. The three measures of short- term memory were taken from The WMTB-C (Pickering & Gathercole, 2001). The working memory tasks used were modified versions of the counting span task (Case et al., 1982). Each child was tested individually in a quiet area of the classroom. The order of presentation of the counting span tasks was fully counterbalanced.

Short- term memory tasks. Each participant completed the digit recall test from The WMTB-C (Pickering & Gathercole, 2001). Participants were asked to recall, in the same order, sequences of digits spoken aloud by the experimenter. The digits were presented at the rate of one per second. Testing began with three trials at a list length of two digits. The number of digits was then increased by one every three trials until two lists of a particular length were recalled incorrectly. The score given was the total number of trials on which the digits were recalled correctly.

In the word recall test (WMTB-C, Pickering & Gatercole, 2001) participants were asked to recall, in the same order, sequences of monosyllabic words spoken aloud by the experimenter. The structure of testing was identical to that for the digit recall task. The score given was the total number of trials on which the words were recalled correctly.

In nonword list recall (WMTB-C, Pickering & Gathercole, 2001) participants were asked to recall, in the same order, sequences of monosyllabic nonwords spoken aloud by the experimenter. The nonsense words were created using the same phonemes as the words in the word recall test. The structure of

testing was identical to that for the digit recall and word recall tasks. The score given was the total number of trials on which the nonwords were recalled correctly.

Feature search counting span task. Count arrays consisting of targets (blue squares) and non-targets (red circles) were presented on a computer screen, with targets to be counted. The number of target items appearing in each array varied between 3 and 7. There were twice as many non-targets as targets, and the target non- target positions were varied across presentations. After several such displays were counted, the printed word RECALL served as a cue to recall the count totals.

Following two practice trials, testing began with a list length of two (i.e. two counting arrays within a trial). Each count array was presented and participants were required to count and say aloud the number of targets. As soon as the participant gave a count total the experimenter pressed the space bar on the computer to record the processing time. The next array was then presented. At the end of each trial, upon pressing the space bar, the participant was cued to sequentially recall the number of targets in each array. After the participant recalled the number of targets the experimenter pressed the space bar and the computer recorded the response duration. A maximum of six trials were administered at any one list length, with the number of arrays being increased by one after successful completion of any four trials at each list length. When three or more trials were recalled incorrectly within a list length testing was terminated. The score given was the total numbers of trials in which the totals were recalled correctly. Thus each participant generated a counting span score, a mean processing time, and a mean response duration.

Conjunction search counting span task. Count arrays consisted of targets (blue squares), and non- targets that shared a feature with the targets (blue circles and red squares). The procedure, scoring and discontinuation criteria were identical to those for the feature search counting span task presented above. Again, each participant generated a counting span score, a mean processing time, and a mean response duration.

Counting span with nonsense numbers. The count arrays, procedure, scoring, and discontinuation criteria were identical to those for the feature search counting span task. However, following Case et al. (1982) participants were required to count using the following nonsense numbers; rab, slif, dak, leet, roak, taid, fap. To learn these nonsense numbers participants had repeated the list until they could do so without error and then counted a series of practice arrays until they were able to count without error at the rate of two items per second. Again, each participant generated a counting span score, a mean processing time, and a mean response duration.

Scholastic attainment measures. The school supplied national curriculum test levels for each child in English, mathematics and science. Details about national curriculum tests can be seen in section 2.1.

4.2: Results

4.2.1: Descriptive statistics

Preliminary analyses identified a number of univariate outliers (i.e. Z scores in excess of 2.5). These scores were generated by two participants who

were unable to complete the counting span tasks at list lengths in excess of 1 and were unable to learn the nonsense numbers. These data were therefore excluded from analysis. The descriptive statistics for the remaining 68 participants for the short- term memory and working memory measures are presented in Table 4.1.

4.2.2: Correlational analyses

The correlation matrix of the short- term memory and working memory task scores is presented in Table 4.2. Scores on the three phonological loop measures, digit recall, word recall, and nonword recall were significantly correlated with one another, with coefficients ranging from .35 to .74. Scores on the three versions of the counting span task were also significantly related, with coefficients ranging from .52 to .62. There were also significant associations between performance on the phonological loop tasks and the counting span tasks, with the highest coefficients between scores on the digit recall task and all three versions of the counting span task, r (67) = .60, p < .01, r (67) = .42, p < .01, and r (67) = .43, p < .01 respectively.

Scores on digit recall, word recall, and nonword recall were each moderately associated with performance in English, mathematics, and science, with correlations ranging from .28 to .40. Performance on the three versions of the counting span task also showed associations with scholastic attainment in each curricular domain. Scores on each version of the task were highly associated with English scores, r (67) = .45, p < .01, r (67) = .40, p < .01, and r (67) = .38, p < .01. Performance on each version was also significantly related to

Table 4.1 *Descriptive Statistics for the Memory Measures*

Measure	Mean	SD
Short- term memory tasks		
Digit recall	29.54	4.40
Word recall	23.07	3.05
Nonword list recall	22.82	3.43
Counting span tasks		
Feature Search		
Counting score	19.93	3.98
Processing time (in ms)	2571.83	530.06
Response duration (in ms)	2012.57	343.87
Conjunction Search		
Counting score	17.82	4.12
Processing time (in ms)	3031.61	576.38
Response duration (in ms)	2158.44	332.47
Nonsense numbers		
Counting score	16.91	4.14
Processing time (in ms)	4069.37	1202.65
Response duration (in ms)	2602.56	370.02
Scholastic attainment		
English level	3.84	.88
Mathematics level	3.96	.79
Science level	4.13	.76

Table 4.2 *Correlation Coefficients between Short- Term Memory and Working Memory Measures*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Age	-	.21	.39**	.30*	.17	-.29*	-.15	.00	-.20	-.26*	.08	-.18	-.07	.30*	.14	.30*
2. Digit recall		-	.50**	.35**	.60**	-.18	-.10	.42**	-.10	-.10	.43**	.11	-.03	.32**	.39**	.29*
3. Word recall			-	.74**	.37**	-.26*	-.17	.08	-.10	-.28*	.27*	-.10	-20	.40**	.37**	.37**
4. Nonword recall				-	.24*	-.12	-.08	.12	-.02	-.11	-.29*	-.00	-.04	.28*	.29*	-.35**
5. Feature search score					-	-.41**	-.30*	.58**	-.20	-.21	.62**	-.06	-.20	.42**	.35**	.20
6. Processing time						-	.38**	-.29**	.57**	.40**	-.38**	.26*	.34**	-.37**	-.41**	-.25*
7. Response duration							-	-.29*	.47**	.29*	-.16	.29*	.41**	-.25*	-.18	-.11
8. Conjunction search score								-	-.42**	-.34**	.52**	-.02	-.20	.40**	.43**	.26*
9. Processing time									-	.47**	-.34**	.43**	.36**	-.34**	-.39**	-.40**
10. Response duration										-	-.41**	.45**	.54**	-.38**	-.43**	-.34**
11. Nonsense numbers score											-	-.33**	-.26	.38**	.51**	.40**
12. Processing time												-	.66**	-.20	-.32**	-.32**
13. Response duration													-	.38**	-.38**	-.32**
14. English level														-	.69**	.74**
15. Maths level															-	.80**
16.Science level																-

* *p* <.05 ** *p* <.01

mathematics and science scores, with the strongest associations between scores on the nonsense numbers task and performance in both subject areas, r (67) = .51, p < .01, and r (67) = .40, p < .01.

Response durations were also related to scholastic attainment, with durations in the feature search task being moderately related to English levels, r (67) = -.25, p < .05, durations in the conjunction search being significantly associated with English levels, r (67) = -.38, p < .01, mathematics levels, r (67) = -.43, p < .01, and science levels, r (67) = -.34, p < .01, and durations in the nonsense numbers task also being significantly related to attainment in each subject area, r (67) = -.38, p < .01, r (67) = -.38, p < .01, and r (67) = -.32, p < .01 respectively.

There were also significant relationships between processing times and scholastic achievement, with processing times on the feature search task and the conjunction search task being significantly related to achievement in each curricular domain, with coefficients ranging from -.25 to -.41. Processing time on the nonsense numbers task was significantly associated with achievement in mathematics, r (67) = -.27, p < .05, and science, r (67) = -.25, p < .05.

Counting span scores and response durations for each task were moderately correlated, for the feature search task, r (67) = -.30, p < .05, for the conjunction search task, r (67) = -.34, p < .01, and for the nonsense numbers task, r (67) = -.26, p < .05. For each version of the counting span task, the scores and the processing times were also significantly associated, for the feature search task, r (67) = -.41, p < .01, for the conjunction search task, r (67) = -.42, p < .01, and for the nonsense numbers task, r (67) = -.33, p < .01.

4.2.3: Cognitive demand of the counting span tasks

A repeated measures analysis of variance revealed a significant difference in response durations during the three counting span tasks, F (2, 134) = 90.03, *p* < .01. Bonferroni post hoc multiple pairwise comparisons revealed a significant difference between durations in each task with *p* < .05 in each case. Durations were shortest for the feature search task, followed by the conjunction search task, with durations being longest for the nonsense numbers task (means 2013, 2158, and 2603ms respectively). A repeated measures analysis of variance (using the Greenhouse- Geisser correction for a violation of sphericity) also revealed a significant difference in processing times during the three versions of the counting span task, F (1, 134) = 84.36, *p* < .01. Bonferroni comparisons revealed a significant difference in times during each task with *p* < .01 in each case. Processing times were shortest for the feature search task, followed by the conjunction search task, with times being longest for the nonsense numbers task (means 2572, 3032, and 4069ms respectively). Taken together, these findings suggest that the feature search task was the least cognitively demanding, and the nonsense numbers task was the most demanding. Consistent with this view, the mean scores on the counting span tasks decreased from the feature search task to the nonsense numbers task (mean scores of 19.93, 17.82, and 16.91 respectively). A repeated measures analysis of variance revealed a significant difference in these scores, F (2, 134) = 22.79, *p* < .01. Bonferroni post hoc multiple pairwise comparisons revealed a significant difference in scores on the feature search task and the conjunction search task and the feature search task and the nonsense numbers task, with *p* < .01. There was no significant difference, however,

between scores on the conjunction search task and the nonsense number task ($p >$ .05).

4.2.4: Factor structure of counting span tasks and short- term memory tasks

In order to explore relations between the phonological loop tasks and the counting span tasks, a principal components analysis with oblique rotation was conducted on the data. Following Kaiser's criteria, factors with eigenvalues in excess of 1 were retained. The outcomes of the factor analysis are presented in Table 4.3. Two factors were identified, accounting for 74.2 % of the variance in total. Factor loadings of .45 were used to guide the interpretation of the factor structure (Tabachnick & Fidell, 1996). The first factor appeared to represent a phonological loop factor, with high loadings from the word recall and nonword recall tasks, and an additional moderate loading from the digit recall task. The second factor showed high loadings from all three versions of the counting span tasks, indicating that it represented a working memory factor. However, it also showed a significant loading from the digit recall task.

Table 4.3 *Rotated Component Matrices*

	Factor 1	Factor 2
Digit recall	.38	**.59**
Word recall	**.93**	.03
Nonword recall	**.91**	-.02
Feature search task	.10	**.84**
Conjunction search task	-.23	**.89**
Nonsense numbers task	.06	**.78**

Note: values in bold are in excess of .45

4.2.5: Factor structure of speed measures and span scores

In order to explore relations between the speed and span measures a principal components analysis with oblique rotation was conducted on the response durations, processing speeds, and span scores for each version of the counting span task. Adopting Kaiser's criteria, factors with eigenvalues in excess of 1 were retained. The outcomes of the factor analysis are presented in Table 4.4. Two factors were identified, accounting for 59.4 % of the variance in total. Again, factor loadings of .45 were used to guide the interpretation of the factor structure (Tabachnick & Fidell, 1996). The first factor appeared to represent a speed factor, with significant loadings from processing times and response durations in all three counting span tasks. The second factor appeared to

represent a memory span factor, with significant loadings from scores on each of the counting span tasks.

Table 4.4 *Rotated Component Matrices*

	Factor 1	Factor 2
Feature search score	.08	**.90**
Feature search processing time	**.47**	-.38
Feature search response duration	**.56**	-.13
Conjunction search score	-.00	**.83**
Conjunction search processing time	**.65**	-.22
Conjunction search response duration	**.71**	-.09
Nonsense numbers score	-.11	**.74**
Nonsense numbers processing time	**.85**	.22
Nonsense numbers response duration	**.83**	.10

Note: values in bold are in excess of .45

4.2.6: Relationships between counting span measures and school achievement

A major goal of the present study was to explore the relationships between speed measures, working memory span scores, and scholastic attainment. Speed scores and memory span scores were computed for each

participant using the factor solution produced in the principal components

analysis presented in Table 4.4. A series of forced- order multiple regressions

was performed. The thrust of these analyses was to identify measures that

accounted for unique variance in scholastic attainment. Age was always entered

in to the regressions first, as it is known to be an important general factor (e.g.

Gathercole et al., 1997; Kail & Park, 1994). To address questions about the span

and speed measures, their entry was rotated. By this means it was possible to

identify shared and unique variance associated with the two categories of

measure.

The results are summarised in Table 4.5. With English as the dependent

variable age accounted for a modest 9 % of the variance, whereas span and speed

together explained a further 24 %. Speeds accounted for only 4 % when entered

after spans, whereas spans accounted for 13 % when entered after speeds. Thus

spans and speeds accounted for both shared (7%) and unique variance, with

spans accounting for more unique variance than speeds. With mathematics as the

dependent variable age accounted for only 2 % of the variance, with span and

speed together accounting for 32 %. Speed accounted for 8 % of the variance

when entered after span and span accounted for 13 % when entered after speed.

Therefore again spans and speeds accounted for both shared (11%) and unique

variance, with spans accounting for more unique variance than speeds. With

science as the outcome variable age explained a modest 9 % of the variance, with

spans and speeds together accounting for a modest 14 %. Speed accounted for 6

% when entered after spans where as spans only accounted for 3 % when entered

after speeds. Thus spans and speeds accounted for both shared (5%) and unique

variance. However, unlike the case with English and mathematics, more unique variance was associated with speed rather than span.

Table 4.5 *Outcomes of Hierarchical Multiple Regression Analyses*

|	Span entered before speed		Speed entered before span	
Step	Variable	ΔR^2	Variable	ΔR^2
	English level as outcome measure			
1	Age	.09*	Age	.09*
2	Span	.20**	Speed	.11**
3	Speed	.04	Span	.13**
	Mathematics level as outcome measure			
1	Age	.02	Age	.02
2	Span	.24**	Speed	.19**
3	Speed	.08**	Span	.13**
	Science level as outcome measure			
1	Age	.09*	Age	.09*
2	Span	.08*	Speed	.10**
3	Speed	.06*	Span	.03

*$p < .05$ **$p < .01$

4.2.7: Span- speed relationships

The final goal of the study was to explore relationships between speeds of processing and memory span scores. Figure 4.1 shows the relationships between processing time and memory span for each of the counting span tasks. The best fitting regression line is included for each task. It can be seen that in each case there is a linear relationship between speed and span, with a faster speed of processing associated with a higher score on the task. For the feature search task the correlation between speed and span was -.41, with speed accounting for approximately 17 % of the variance in span. For the conjunction search task the correlation between speed and span was -.42, with speed accounting for 18 % of the variance in span. For the nonsense numbers task, the correlation between speed and span was -.33, with speed accounting for approximately 11 % of the variance in span.

Although speed and span in each task showed a significant linear relationship, the regression equation for the nonsense numbers task differed from that for the feature search and conjunction search tasks (although no direct statistical comparison was possible). The intercept value for the nonsense numbers task was 21.77, compared to 27.85 for the feature search and 26.87 for the conjunction search task. The slope for the nonsense numbers task was -1.19, compared to -3.08 for the feature search and -2.98 for the conjunction search task. The regression line for the nonsense numbers task crossed over the lines for the feature search and conjunction search tasks.

Figure 4.1 *Span- Speed Relationships for the Three Versions of the Counting Span Task*
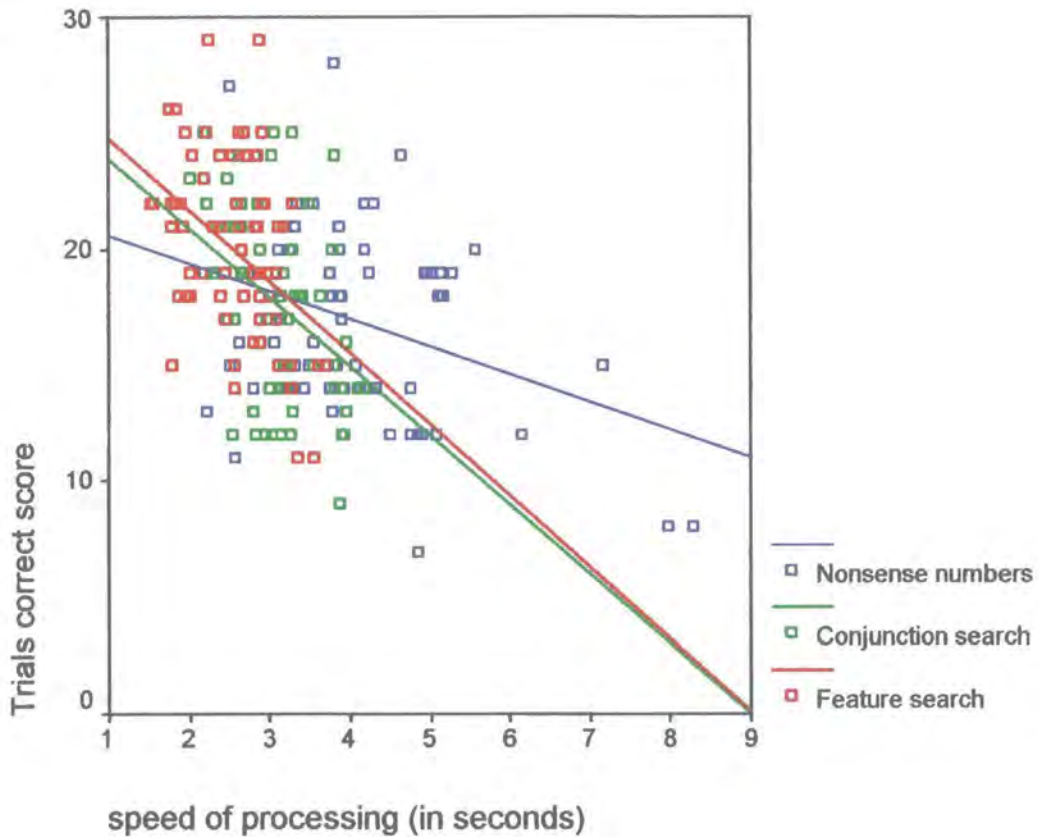
4.3: Discussion

The results demonstrated that the three versions of counting span did differ significantly in terms of the difficulty of processing with the nonsense numbers task being most demanding, and the feature search task being least demanding. Scores on the feature search task were significantly higher than scores on the conjunction search and nonsense numbers tasks, and speed of processing was fastest in the feature search task and slowest in the nonsense

numbers task. This supports evidence from studies of visual search that have shown that the identification of target objects among non- targets is more demanding if targets must be distinguished using a conjunction of two featural attributes rather than a single featural cue (e.g. Duncan, 1987; Treisman, 1991; Treisman & Gelade, 1980; Treisman & Sato, 1990). The findings also provide evidence that participants find counting with unfamiliar numbers significantly more difficult than counting with a familiar sequence (see also; Case et al., 1982). There was also a significant difference between response durations in each of the three counting span tasks, with durations being shortest in the feature search task and longest in the nonsense numbers task. This may be because response durations reflect a general speed of processing (e.g. Cowan, 2003). Consistent with this view, processing time and response duration measures loaded on to a single factor during factor analysis.

A major goal of the present study, however, was to examine the relationships between short- term memory tasks and working memory measures varying in cognitive demand. Analyses revealed that although the counting span tasks and short- term memory tasks were moderately correlated, they loaded on to distinct factors during factor analysis. The digit recall task showed a moderate loading on to the working memory factor but it is likely that this was due to a contribution of domain- specific numerical processes because digit recall and each of the counting span tasks were all numerically based. The results therefore support previous evidence of dissociations between short- term memory and working memory measures (e.g. Cantor et al., 1991; Conway et al., 2002; Engle & Tuholski et al., 1999; Kail & Hall, 2001), supporting the resource switching view of working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000).

Contrary to the suggestions of Baddeley et al., (1985), even the least demanding counting span task, involving only a feature search, still appeared to require executive involvement.

The findings of a distinction between short- term memory and working memory are inconsistent with the findings presented in Chapter 2 of this thesis, which suggested that short- term memory tasks and working memory tasks within the verbal domain were not distinguishable. It is possible that this discrepancy is a result of differences between the counting span tasks used in the present study and the backwards digit recall and listening span tasks used in Studies 1 and 2. For example, the assumption that backwards recall requires executive intervention has been questioned by some authors (e.g. Farrand & Jones, 1996; Hutton & Towse, 2001; Isaacs & Vargha- Khadem, 1989), and it has previously been found to be closely related to phonological loop measures (e.g. Engle et al., 1999).

The study was also designed to explore the contributions of speed measures and span scores to scholastic attainment. Analyses revealed that speed measures and span scores loaded on to separate factors during factor analysis (see also; Bayliss et al., 2003). This presents difficulties for resource sharing accounts of working memory that claim that individual differences in storage capacity are directly related to differences in processing efficiency (Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992). Rather, the results suggest that processing and storage are met by separate subsystems, consistent with the resource switching account of working memory task performance (e.g. Towse & Hitch, 1995; Towse et al., 1998, 2000) and the multiple component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000).

In terms of the contributions of speeds of processing and working memory spans to children's scholastic skills, working memory spans were significantly related to national curriculum test scores (see also; Gathercole et al., 2003; Gathercole & Pickering, 2000; Gathercole et al., 2004). However, analyses also revealed that speeds accounted for unique variance in attainment. These findings support those of Hitch et al. (2001) who found that processing speeds and span scores each accounted for unique variance in scholastic skills (see also; Bayliss et al., 2003; Friedman & Miyake, 2004b), and also those of Cowan et al. (2003) who found that response durations predicted unique variance when controlling for span scores. Cowan et al. (2003) suggested that there were at least two ways to interpret the difference between accuracy and response duration measures. Speed measures could allow more detailed information, revealing differences where spans do not. This interpretation accounts for why speeds explain unique variance. However, it does not account for the finding that span scores also predict a considerable amount of unique variance. An alternative possibility is that spans and response durations may reflect different processes. For example, as discussed in Chapter 3, working memory spans may reflect the ability to update the contents of working memory (see also; Miyake et al., 2000). Response times, however, may reflect retrieval speeds (e.g. Kail & Salthouse, 1994) and/ or the efficiency of memory organisation (Ericsson & Kintsch, 1995).

The finding that speed and span predict unique variance in attainment has important theoretical implications. According to both resource sharing and task switching approaches to working memory, memory span is determined by speed. Span and speed should therefore explain common variance in educational attainment. The observation that spans and speeds predict unique variance

indicates that the influence of processing on performance is not simply a consequence its effects on storage. This suggests that accounts of working memory that are based upon both resource sharing (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) and time based forgetting (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) do not provide a complete account of working memory limitations (see also: Friedman & Miyake, 2004b; Hitch et al., 2001). Thus, it is not just processing time *per se* that it is important in determining memory span.

The finding that spans and speeds predict unique variance in scholastic attainment measures also has important practical implications. To the extent that the purpose of using working memory span tasks is to predict scholastic performance, the purpose appears to be much better served if timing measures are used along with span scores (see also; Cowan et al., 2003; Friedman & Miyake, 2004b; Waters & Caplan, 1996).

The third goal of the present study was to explore relationships between speeds and spans for the three versions of the counting span task. The results showed that the linear relationship between counting span and counting speed demonstrated by Case et al. (1982) generalises to manipulations of the counting span task requiring feature searches, conjunction searches, and counting using unfamiliar sequences. Thus, scores on each version of the counting span task decreased linearly with the time taken to perform the counting. It is worthy of note, however, that for each task speed predicted only a moderate amount of variance in span scores, consistent with the view that no single ability underlies complex span performance (Halford, Maybery, O'Hare, & Grant, 1994; Miyake & Shah, 1999; Ransdell & Hecht, 2003; Towse & Houston- Price, 2001).

The relationship between speed and task scores was, however, different in the nonsense numbers task when compared with the feature search and conjunction search tasks. This finding supports those of Hitch et al. (2001) who demonstrated different relationships between speed and span when comparing operation span and reading span. This would appear to rule out a simple resource sharing explanation in which processing and storage access a common pool of resources and processing time reflects the amount of resources available for storage. However, as suggested by Hitch et al. (2001) the resource sharing model could come close to accounting for the data if it was assumed that different tasks consume resources in working memory at different rates, for example because different amounts of time are taken up in processes outside of working memory. In the case of the nonsense numbers task used in the present study, more time could have been taken up retrieving the unfamiliar words from long- term memory.

The task- switching view of working memory also predicts that span will vary with speed because faster processing allows less time over which items can be forgotten. This model is therefore also consistent with a linear relationship between speed and span. Also, given similar forgetting curves for different types of verbal information (e.g. see Murdock, 1961), task switching would also predict similar relationships between span and processing rates in different working memory tasks. However, Hitch et al. (2001) suggested that because the task switching approach to working memory explains the effect of processing time in terms of forgetting, span- speed relationships could depend upon the dynamics of activation loss in different task contexts. They then, acknowledged, however, that the model is not sufficiently well specified to make predictions as

it would need to account for things such as interference effects and redintegration processes (Hulme et al., 1997). Advocates of the task switching approach have also been careful to point out that task switching is unlikely to provide a complete explanation of working memory span and that other mechanisms may also be involved (Towse & Hitch, 1995; Towse et al., 1998). For example, working memory could also be constrained by individual differences in memory decay and the activation of memory traces (Byrne, 1998), or the ability to resist interference (e.g. Stolzfus, Hasher, & Zacks, 1996, but see study 3).

Therefore neither the resource sharing (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) nor resource switching (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) approach to working memory offers a complete account of the present findings. The results suggest that working memory task performance is determined by both temporal duration and the nature of processing activities. It would be premature, however, to conclude that it is the complexity of processing activities that influences performance because cognitive demand cannot necessarily be equated with complexity. Barrouillet et al. (2004) proposed that performance on complex span tasks is determined by cognitive cost. For a given period of time the cognitive cost of a task depends upon the number of retrievals required and the time during which they capture attention in such a way that the refreshing of memory traces is prevented. The longer this time, the fewer and shorter the periods of time that can be allocated to retrieving the information to be recalled. For the nonsense numbers task, retrievals are required to retrieve unfamiliar numbers form long- term memory. According to Barrouillet et al. (2004), this would capture attention so that memory traces could not be refreshed, leading to a lower working memory score.

In terms of the number of retrievals, the feature search and conjunction search tasks did not differ, and the relationship between speed and span in the two tasks was also very similar.

It is, however, difficult to interpret the findings of the present study based on the time- based resource- sharing approach (Barrouillet et al., 2004) because while cognitive demand was manipulated, processing durations were not equated. The observed durations were therefore likely to have been influenced by participants strategy use. For example, participants could have rehearsed memory items before or after each processing segment (e.g. Engle et al., 1992), and participants were also permitted to pause before processing or responding to the processing task (Daneman & Carpenter, 1980). It is also worthy of note that there were a number of strategies participants could have used to complete the nonsense numbers task. For example, participants could have counted each item using the nonsense numbers, or alternatively they could have counted using the familiar number sequence and then produced the corresponding nonsense number. What is needed to explore the time- based resource- sharing view is a method of administering complex span tasks which allows for careful control over both processing activities and temporal duration, thus minimising differences in strategy use. The following study presented in Chapter 5 employs such a method to investigate complex span performance (see also; Barrouillet & Camos, 2001; Barrouillet et al., 2004; Gavens & Barrouillet, 2004).

Chapter 5

Evidence for the Time- Based Resource- Sharing Model?

The study presented in Chapter 4 showed that speed measures and working memory span scores each explained unique variance in children's educational attainment. Span- speed relationships also varied across different versions of the counting span task. In particular, the span speed relationship for a task involving counting using unfamiliar numbers was different from the span speed relationships for tasks requiring feature searches and conjunction searches. Taken together, these findings suggest that it is not just speed *per se* that determines memory span. Neither the resource sharing (e.g. Case et al., 1982; Daneman & Carpenter, 1980, Just & Carpenter, 1992) nor resource switching (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) account of working memory can fully account for these findings (see also; Hitch et al., 2001).

Case et al. (1982) suggested that working memory is a limited capacity system that can be flexibly allocated to support both processing and storage. By this view, more efficient and faster processing leads to additional resources being available to support storage. Case et al. (1982) found that in a study of 6- to 12-year old children counting spans were highly predictable from counting speeds. Adults' counting spans were also reduced to those of 6- year old children when counting efficiency was reduced by requiring the use of nonsense numbers rather than digits to count arrays. The authors concluded that decreased spans resulted from greater processing demands leading to a processing/ storage trade off (see also; Daneman & Carpenter, 1980, Just & Carpenter, 1992).

However, Towse and Hitch (1995) argued that higher working memory spans might be due to more efficient processing reducing the temporal duration

over which information can be forgotten. They proposed that instead of simultaneously storing and processing information, people switch between processing and item retention. Towse and Hitch (1995) manipulated the difficulty and duration of counting in the counting span task. A more difficult counting activity (reduced discriminability between targets and distracters) did not result in lower spans, whereas longer counting durations (counting a higher number of targets) did. Towse and Hitch concluded that counting span did not depend upon the workspace required for counting, but on the duration of the counting activity. According to this hypothesis, there is no active maintenance of memory items during processing (Hitch et al., 2001; Towse, Hitch, & Hutton, 2002), so in the counting span task children would operate in serial fashion, first counting each array, then committing the total to memory, and then counting the next array. Thus as soon as a participant is involved in processing there is a time-related decay of memory items.

Towse et al. (1998; 2000) further tested this task switching hypothesis in a series of experiments in which they used an adaptation of a paradigm used by Cowan, Day, Saults, & Keller et al., (1992). In the counting span task, children were presented with sequences of cards in which the array numerosity of the first card was small (and that of the last card large) or the numerosity of the first card was large (and the last card small). The authors claimed that the processing demands in the two tasks were identical, with only the duration for which representations were to be held in working memory being manipulated. Because only the count total had to be retained, it was assumed that the duration of the first card did not influence the retention period, whereas the duration of the last card did. Performance was poorer in the large- final condition which involved a

longer retention period, providing support for the memory decay hypothesis. Similar results were observed in reading span and operation span tasks in which the length of sentences and operations were manipulated.

However, Barrouillet and Camos (2001) argued that when Towse and Hitch (1995) manipulated the duration of counting, the cognitive cost of activities might also have been altered. Counting a larger number of items may constitute a more difficult task than counting a smaller number of items in terms of the verbal production of the series of numbers (Dehaene & Mehler, 1992). Since the sequence of numbers is learned starting with the lowest it is possible that the more objects there are to count, the higher the cognitive demand of the production of each successive number (Fuson, 1988; Fuson & Hall, 1983; Fuson, Richards, & Briars, 1982). Counting a larger number of items could also be a more difficult task due to the activities which distinguish between objects that have already been counted and those remaining to be counted (Beckwith & Restle, 1996; Potter & Levy, 1986; Tuholski, Engle, & Baylis, 2001). Several developmental studies have demonstrated that counting performance is influenced by the number of objects present (Camos, Barrouillet, & Fayol, 2001; Camos, Fayol, & Barrouillet, 1999; Gelman & Meck, 1983; Potter & Levy, 1986). In a similar way, reading long sentences involves complex syntactic structures that are often more difficult to process than shorter sentences, and longer arithmetic operations often involve larger numbers and thus require less automatized and more complex calculations (Ashcraft & Battaglia, 1978; Lebiere & Anderson, 1998; Siegler & Shrager, 1984).

As far as Towse et al's further experiments (1998; 2000) are concerned, the same argument could be applied. Towse et al. reasoned that in the counting

span task, the cognitive demand of large- final and small- final conditions was identical because the same set of cards had to be processed in each case. However, the working memory task i.e. simultaneous processing and storage, only begins at the end of the first card. If it is more demanding to count large arrays than small arrays (e.g. Beckwith & Restle, 1996; Fuson, 1988; Fuson & Hall, 1983; Fuson et al., 1982; Potter & Levy, 1968; Tuholski et al., 2001) then large- final conditions could involve a greater cognitive demand than small- final conditions. The same argument could be used for reading span and operation span tasks.

Consistent with this suggestion, Saito and Miyake (2004) explored the sentence order effect in the reading span task by using a computer- paced paradigm to independently manipulate both the amount and duration of processing. In one experiment they manipulated the amount of processing required for the last sentence presented in a trial, while holding the duration of processing constant. In a further experiment they manipulated the duration while holding constant the amount of processing. A sentence order effect was not observed when duration was manipulated but the amount of processing was held constant, suggesting that the critical factor behind the sentence order effect is not the length of the retention interval *per se,* but rather the amount of processing one has to perform during that retention interval.

Barrouillet and Camos (2001) suggested comparing performance on tasks in which the processing activity retained the same duration but varied in cognitive cost. They administered to children a counting span task and an operation span task. Children were asked to remember letters presented at the end of each array to be counted or operation to be solved, and then subsequently

recall these letters. In a further task, children were asked to suppress articulation for a corresponding duration as counting dots or solving operations in the other two tasks. Complex span was significantly poorer when the intervening activity involved arithmetic operations than when it involved articulatory suppression, despite being matched for time. Barrouillet and Camos suggested that the critical factor underlying performance on complex span tasks is the extent to which the processing task captures attention over a set period of time. They further integrated both time and resource constraints into a time- based resource- sharing model. In contrast to the resource switching approach to working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000), which assumes that there is no attempt to maintain memory items during processing, the time- based resource-sharing approach assumes that participants switch their attention from processing to storage *during* processing intervals (see also; Barrouillet et al., 2004; Gavens & Barrouillet, 2004).

Towse et al. (2002), however, proposed an alternative account of the Barrouillet and Camos (2001) findings. They pointed out that mental arithmetic and articulatory suppression differ not only the extent to which they are demanding of attention, but also in the extent to which they require storage. Storage of interim products is necessary in mental arithmetic whereas articulatory suppression has no storage requirements. Lower spans associated with arithmetic in comparison to ariculatory suppression could therefore be due to storage related interference processes. However, Gavens and Barrouillet (2004) provided clear evidence of the effect of cognitive load in working memory span tasks when tasks did not differ in any dimension except the order of presentation of items, a manipulation that only modified the attentional

demand of the activity. Conlin, Gathercole, and Adams (in press) also compared performance on a complex span task in which the intervening activity imposed storage demands, to performance on a task requiring no intrinsic storage. There was no difference in scores on the two tasks. These findings are contrary to the suggestion that lower spans on an arithmetic task can be explained in terms of storage demands.

The time- based resource- sharing model of working memory (Barrouillet & Camos, 2001; Barrouillet et al., 2004) is based on four main proposals. Firstly it is assumed that attention must be shared between both processing and storage requirements. Secondly it is assumed that when attention is switched away from items to be stored there is a time- related decay of information, and refreshing items requires the focus of attention. Thirdly, processing tasks all occupy the retrieval process needed to refresh memory because of a central bottleneck constraining retrieval activities. A working memory span task that does not require retrievals still involves attentional demand. Fourthly, processing that involves retrievals (e.g. solving arithmetic problems can require retrieving answers from long- term memory), should be the most disruptive for refreshing items to be remembered because the bottleneck only allows one retrieval at a time. Thus, there is rapid and frequent switching between processing and maintenance that occurs during completion of a task. This approach to working memory span tasks allows for a calculation of cognitive cost. For a given period of time, the cognitive cost that a task involves is a function of the time during which it captures attention in such a way that the refreshing of memory traces is impeded. The longer this time, the fewer and shorter the periods of time that can be allocated to retrieving information to be recalled (Barrouillet et al., 2004).

Barrouillet et al. (2004) tested this model of working memory using span tasks that enabled them to carefully control for both the nature and duration of tasks. They claimed that the self- paced nature of standard working memory tasks was a major shortcoming when comparisons of duration were needed. For example, many participants would not have time to perform a processing task if major time constraints were imposed. On the other hand, allowing long durations for processing tasks could leave faster participants time to covertly rehearse memory items, undermining the rationale of the tasks. They therefore designed externally- paced working memory tasks in which the processing activities are relatively simple, resulting in lower interindividual variation, and durations which can be fixed by the experimenter. For example, in a variation of the operation span task (Turner & Engle, 1989), instead of presenting participants with complex problems after each memory item was presented, participants were presented with small operations whose operands appeared successively on the screen. Performance on this task was compared to that on a task matched for duration, in which instead of solving operations, participants simply read aloud the operations and their solutions which were both presented on the screen. The tasks were therefore matched for duration, but also involved the pronunciation of exactly the same numbers. This was in contrast to the earlier studies of Towse and Hitch (1995; Towse et al., 1998; 2000) who manipulated duration, but may also have unavoidably varied cognitive cost.

Barrouillet et al. (2004) demonstrated that even when tasks were matched for duration, more demanding processing resulted in lower spans, presumably because less time could be allocated to refreshing the information to be remembered. In a second series of experiments, they focused on two specific

predictions about time- related effects within the time- based resources-sharing theory. The metric of cognitive load imposed by the theory assumes that the load can be increased by altering two parameters; increasing the number of retrievals while keeping time constant, and decreasing the time allowed to perform a constant number of retrievals. Barrouillet et al. demonstrated that both of these manipulations resulted in reduced working memory spans. In a final experiment Barrouillet et al. progressively increased the ratio of the number of retrievals to time in two working memory tasks, one requiring concurrent articulation and one requiring the reading of digits. A smooth linear decrease in memory span was observed. The specific effect of difficulty was also observed by comparing the slopes for the two tasks. The slope was steeper for the task involving reading compared to the task involving concurrent articulation, suggesting articulation to be less demanding.

The present study employed four tasks; the articulation and reading digits tasks used by Barrouillet et al. (2004), and two new tasks in which the processing element involved a visual search (one a feature search and one a conjunction search), allowing the tasks to be comparable to the counting span task (Case et al., 1982). The first aim of the experiment was to explore two predictions of the time- based resource- sharing theory. This included examining the effects of increasing the number of retrievals during the processing interval while holding the duration of processing constant, and the effects of manipulating the duration of processing while leaving the number of retrievals unchanged. The second goal was to ascertain whether a linear relationship exists between the number of retrievals to time ratio and memory span. The final aim was to explore differences between the four tasks in terms of the difficulty of the processing

operations, which according to Barrouillet et al. (2004) would be reflected in the slopes of the number of retrievals to time ratio against memory span. The results are discussed in terms of the metric of cognitive load proposed by Barrouillet et al. (2004) and also in terms of implications for models of working memory.

5.1: Method

5.1.1: Participants

The participants were 76 undergraduate students with a mean age of 18 years and 10 months (SD 6 months). They were separated into two groups of 20 and two groups of 18 participants. One group completed a 'ba-ba' span task at seven number of retrievals: time ratios. The second group completed a 'reading digits' span task, the third group completed a 'feature search' span task, and the fourth group completed a 'conjunction search' span task, each at the seven number of retrievals: time ratios.

5.1.2: Materials and procedure

In the ba-ba span task consonants to be remembered were presented on the computer screen one at a time for 1500 ms each. Following the series of consonants, 0, 4, 8, or 12 syllables, alternating between 'BA' and 'ba' were presented on the screen for a total period of 0, 6, or 8 seconds, thus resulting in seven different values of the numbers of retrievals: time ratio (0, 0.5, 0.67, 1.0, 1.33, 1.5, 2.0). Participants were asked to repeat aloud the syllable 'ba' each time

it appeared. The word 'Recall' then appeared on the screen and participants were asked to recall the series of consonants in their original order. Testing began with two practice trials at a list length of two (i.e. two consonants were presented) and there were then three trials at each list length of 1 to 8. When a participant failed to correctly recall the consonants in all three trials at any one list length testing was terminated. Following the procedure used by Daneman and Carpenter (1980) and Barrouillet et al. (2004) each correctly recalled series of consonants counted as one third. The total number of thirds was then added up to provide a span score (Kemps, De Rammelaere, & Desmat, 2000; Smith & Scholey, 1992). For example, the correct recall of all the series of one, two and three letters, of two series of four letters, and one series of five letters, resulted in a span of $(3 + 3 + 3 + 2 + 1) \times 1/3 = 4$.

In the reading digits span task consonants were presented on the computer screen one at a time for 1500 ms each. Following the series of consonants, during the 0, 6, or 8 second period, 0, 4, 8, or 12 single digit numerals were presented one at a time. Participants were asked to read the numerals aloud. The word 'Recall' then appeared on the screen and participants were asked to recall the series of consonants in their original order. The discontinuation criteria and scoring method were the same as for the ba-ba span task presented above.

In the feature search span task the consonants to be remembered were presented on the screen in the same manner as for the two tasks described above. A series of 0, 4, 8, or 12 visual search displays were then presented over the 0, 6, or 8 seconds. Each visual search display consisted of between 10 and 15 non-targets (red circles), with positions varied across presentations. 50% of the

displays also contained a target (a blue square). For each visual search participants were asked to respond 'yes' or 'no' as to whether a blue square was present, by pressing the 'M' or 'C' key respectively. The word 'Recall' then appeared on the screen and participants were asked to recall the series of consonants in their original order. As for the tasks described above, when a participant failed to correctly recall the consonants in all three trials at any one list length testing was terminated. Each correctly recalled series of consonants counted as one third and the total number of thirds was then added up to provide a span score.

In the conjunction search task the procedure, discontinuation criteria, and scoring were the same as for the feature search task with the exception of the visual search stimuli. Each visual search display consisted of 10- 15 non-targets which shared one feature with the target (red squares and blue circles). 50% of the displays contained the target (a blue square). As in the feature search task, for each visual search the participant was asked to respond 'yes' or 'no' as to whether a blue square was present, by pressing the 'M' or 'C' key respectively. The word 'Recall' then appeared on the screen and participants were asked to recall the series of consonants in their original order.

For both the feature search and conjunction search tasks the responses as to whether a target was present or not in each visual search array were also recorded, allowing for an examination of participant's compliance to the visual search tasks.

5.2: Results

5.2.1: Descriptive statistics

The descriptive statistics for each of the four working memory tasks at each number of retrievals: time ratio is presented in Table 5.1. Skew and kurtosis for all measures met criteria for normality (Kline, 1998) and no outliers were identified. The mean span for each task at each number of retrievals: time ratio is also presented in Figure 5.1. As the number of retrievals: time ratio was increased there was a decrease in memory span for each of the four tasks.

Table 5.1 *Mean Spans for the Four Working Memory Tasks at Each Number of Retrievals: Time Ratio (Standard Deviations are Shown in Parentheses)*

Task	Ba-ba task	Reading digits	Feature search	Conjunction search
Ratio				
0	5.40 (.37)	5.34 (.89)	5.35 (.43)	5.31 (.71)
0.50	5.13 (.31)	4.55 (.27)	4.74 (.44)	4.50 (.56)
0.67	4.93 (.30)	4.25 (.36)	4.50 (.47)	4.22 (.62)
1.00	4.85 (.28)	4.02 (.53)	4.29 (.70)	4.22 (.62)
1.33	4.60 (.30)	3.85 (.45)	4.13 (.64)	3.82 (.80)
1.50	4.41 (.43)	3.80 (.23)	4.00 (.70)	3.76 (.89)
2.00	4.20 (.20)	3.55 (.23)	3.81 (.69)	3.48 (.94)

Figure 5.1 *Mean Spans for the Four Working Memory Tasks at Each Number of*

Retrievals: Time Ratio

Ba- Ba task

Reading digits task

Feature search task

Conjunction search task
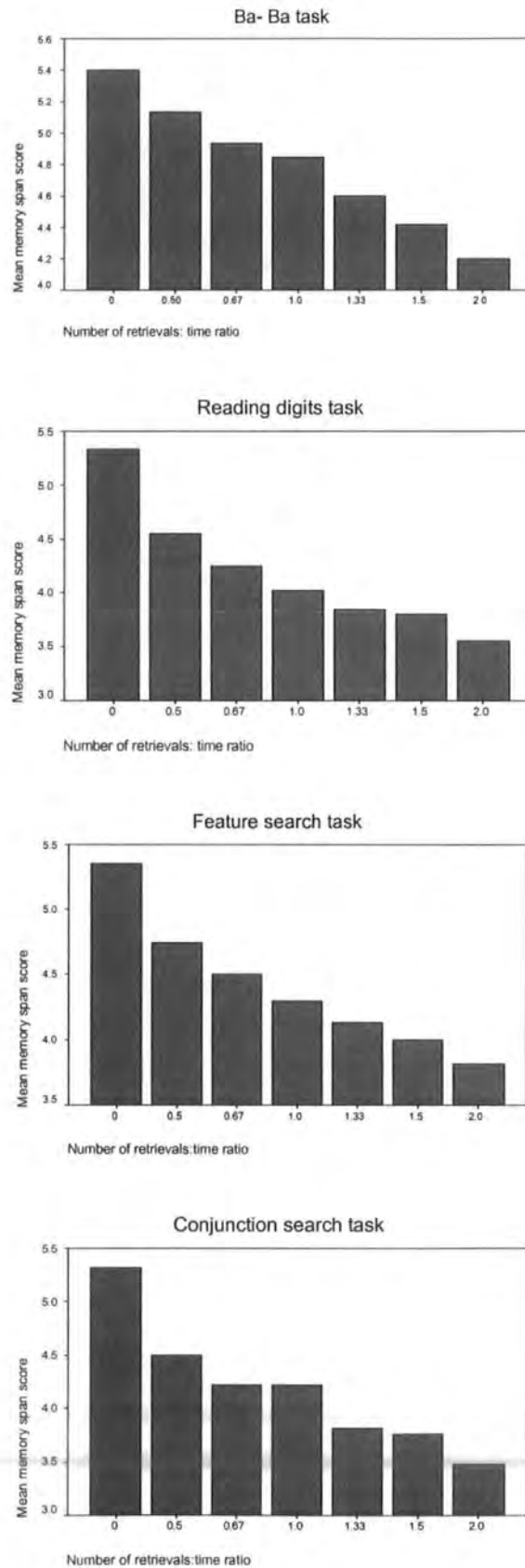
5.2.2: Manipulating the number of retrievals and time

For the ba-ba task, a 3 (number of syllables: 4, 8, or 12) x 2 (time: 6s, or 8s) analysis of variance revealed that spans decreased as the number of syllables increased (means 5.03, 4.73, and 4.31 respectively), $F_{(2, 38)} = 57.29, p < .001$. Bonferoni multiple pairwise comparisons revealed significant differences in spans between each number of syllables ($p < .001$ in each case). Shorter durations also resulted in lower spans (4.58 compared to 4.80), $F_{(1, 19)} = 42.27$, $p < .001$, without any interaction between number of syllables and duration, $F_{(1, 25)} = .10, p > .05$.

For the reading digits span task, a 3 (number of numerals: 4, 8, or 12) x 2 (time: 6s, or 8s) analysis of variance revealed that spans decreased as the number of numerals increased (means 4.40, 3.93, and 3.68 respectively), $F_{(1, 24)} = 27.42, p < .001$. Bonferoni multiple pairwise comparisons revealed significant differences between spans when there were 4 and 8 numerals, and 4 and 12 numerals ($p < .001$ in each case) but not 8 and 12 numerals ($p > .05$). Shorter durations also resulted in lower spans (3.89 compared to 4.12), $F_{(1, 19)} = 95.37$, $p < .001$, without any interaction between number and duration, $F_{(2, 38)} = .84, p > .05$.

For the feature search task, a 3 (number of displays: 4, 8, or 12) x 2 (time: 6s, or 8s) analysis of variance revealed that spans decreased as the number of displays increased (means 4.62, 4.21, and 3.91 respectively), $F_{(2, 34)} = 22.99, p < .001$. Bonferoni multiple pairwise comparisons revealed significant differences in spans between each number of displays ($p < .001$ in each case). Shorter durations also resulted in lower spans (4.15 compared to 4.35), $F_{(1, 17)}$

= 18.11, $p < .01$, without any interaction between the number of displays and time, F (2, 34) = .30 $p > .05$.

For the conjunction search task, a 3 (number of displays: 4, 8, or 12) x 2 (time: 6s, or 8s) analysis of variance revealed that spans decreased as the number of displays increased (means 4.36, 4.02, and 3.62 respectively), F (2, 34) = 11.29, $p < .001$. Bonferoni multiple pairwise comparisons revealed significant differences between spans when there were 4 and 12 displays, and 8 and 12 displays ($p < .05$ in each case) but not 4 and 8 displays ($p > .05$). Shorter durations also resulted in lower spans (3.84 compared to 4.16), F (1, 17) = 56.21, $p < .01$, again, without any interaction between the number and duration, F (2, 34) = .88 $p > .05$.

5.2.3: The difficulty of operations

Regarding differences between the four tasks, a 4 (task: ba-ba, reading digits, feature search or conjunction search) x 7 (number of retrievals: time ratio: 0, 0.5, 0.67, 1.0, 1.33, 1.50, 2.0) mixed analysis of variance revealed a main effect of task, F (3,872) = 9.83, $p < .001$, with means of 4.79, 4.19, 4.41, and 4.19 respectively. Bonferoni multiple pairwise comparisons revealed significant differences between performance on the ba-ba span task and each of the other three tasks ($p < .05$). There were no significant differences between scores on the reading digits task, feature search task, and conjunction search task. There was also a main effect of ratio, F (3, 234) = 128.37, $p < .001$, with scores decreasing as the ratio increased (means of 5.35, 4.73, 4.48, 4.35, 4.10, 3.99, and 3.76 respectively). Seven out of the twenty one pairwise comparisons were significant

(those between the ratios of 0.5 and 0.67, 0.5 and 1.0, 0.67 and 1.0, 0.67 and

1.33, 1.0 and 1.33, 1.33 and 1.5, and 1.5 and 2). There was no interaction

between task and ratio, F (9, 224) = 1.71, p = .085.

A 2 (task: ba-ba task or reading digits task) x 7 (number of retrievals:

time ratio) mixed analysis of variance was then conducted on the ba-ba span and

reading digits span tasks, the two tasks used by Barrouillet et al. (2004). There

was a significant main effect of task, F (1, 38) = 75.53, p < .001, with means of

4.79 and 4.19 respectively. There was also a significant main effect of ratio, F (3,

104) = 73.66, p < .001, with scores decreasing as the ratio was increased (means

of 5.37, 4.84, 4.59, 4.43, 4.23, 4.11, and 3.88 respectively). Bonferoni pairwise

comparisons revealed differences between spans at each ratio, with p < .05 in

each case, with the exception of the ratios of 1.33 and 1.5, which did not differ

significantly (p > .05). There was also a significant interaction between task and

ratio, F (3, 104) = 4.59, p < .001, which appeared to be a result of a divergence in

scores from when immediate recall was required to when an intervening task was

present. The interaction graph is displayed below (Figure 5.2).

Figure 5.2 *Interaction between Ba-ba Task and Reading Digits Task*
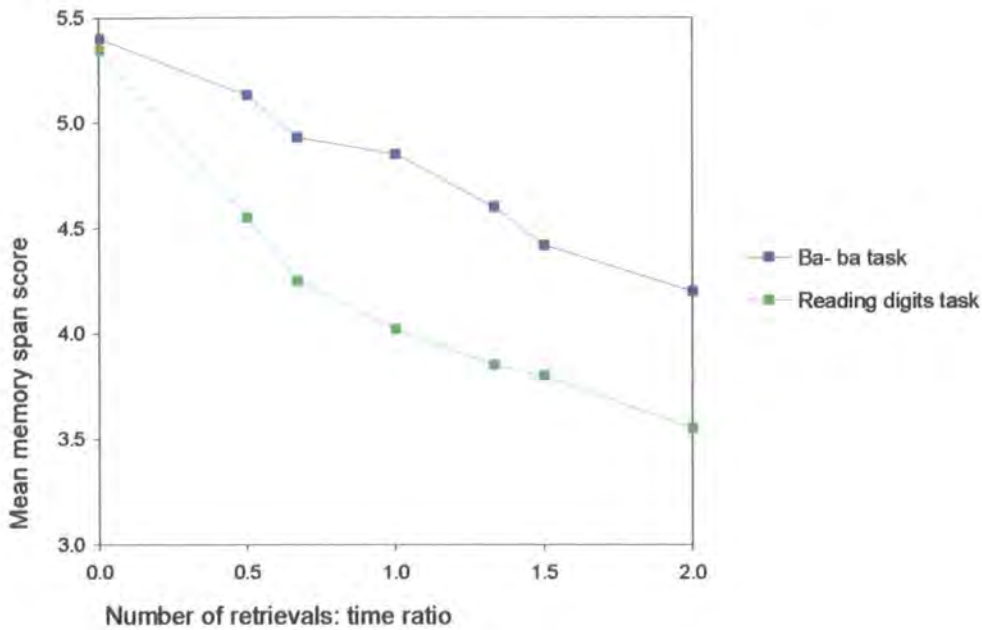
5.2.4: The number of retrievals: time ratio and memory span

Figure 5.3 shows the relationship between the number of retrievals: time ratio and scores on each of the four tasks, with the best fitting regression line for each task. Recall performance was highly correlated with the number of retrievals: time ratio for each of the four tasks. For the ba-ba task $r = -.78$, which accounted for more than 60% of the variance in spans. For the reading digits task $r = -.81$, which explained more than 65% of the variance in spans. For the feature search task $r = -.55$, which accounted for 30% of the variance in spans, and for the conjunction search task $r = -.56$, which explained in excess of 30% of the variance in spans.

Figure 5.3 *Number of Retrievals: Time Ratio and Span Scores for Each Task*

Number of retrievals: time ratio
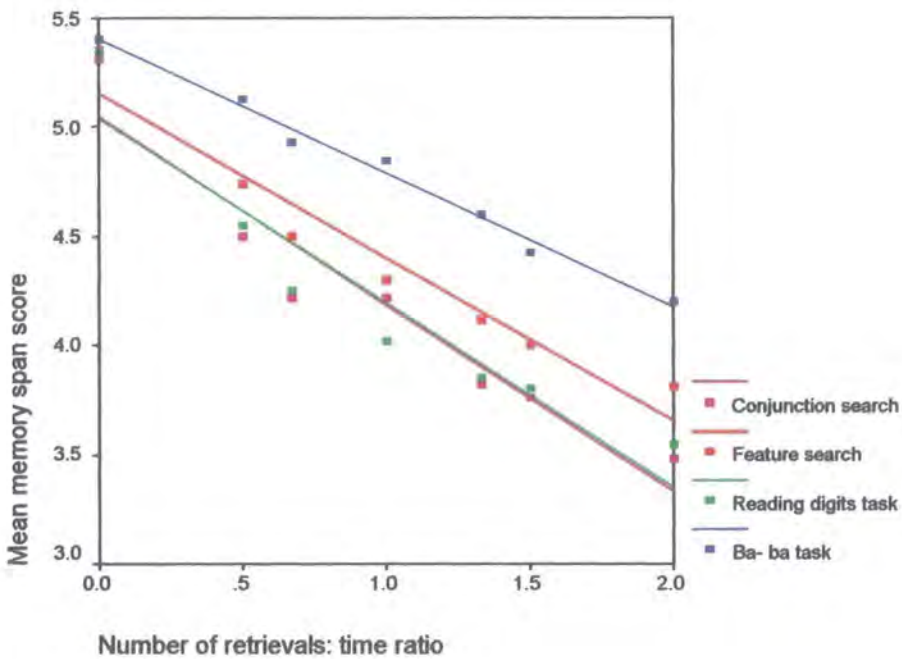
Regression equations revealed that the slope for the ba-ba task was -.61, the slope for the reading digits task was -.85, the slope for the feature task was -.75, and the slope for the conjunction search task was -.86. The intercept values were 5.40, 5.04, 5.15, and 5.05 respectively. Mean and intercept values were then derived for each participant, allowing for a direct comparison across the four tasks. A one- way between- subjects analysis of variance revealed a main effect of task on intercept, $F(3,75) = 2.88$, $p < .05$, with pairwise comparisons revealing that this was a result of differences between the ba-ba task and the reading digits task ($p = .059$). Due to a marked degree of heterogeneity of variance in the slope values, the slope values were analysed statistically using the Kruskal- Wallis test. Overall, there was a significant difference between the slopes, $\chi^2(3) = 8.97$, $p < .05$. Pairwise comparisons revealed significant differences in slopes between the ba-ba task and each of the other three tasks, $p <$

.05, but there were no significant differences between slopes for the reading digits task, feature search task and conjunction search task.

5.2.5: Performance on the intervening tasks

In the ba-ba span task and the reading span task there was no direct examination of participant's compliance to the intervening task i.e. repeating the syllable 'ba' or reading the digits. In the feature search and conjunction search tasks, however, participants were asked to respond as to whether a predetermined target was present in each visual search array. This generated accuracy data for these two tasks. This was expressed as the percentage of correct responses given during trials in which the consonants were recalled correctly, for each number of retrievals: time ratio. The results are presented in Table 5.2. A 2 (task: feature search or conjunction search) x 6 (number of retrievals: time ratio; 0.5, 0.67, 1.0, 1.33, 1.50, 2.0) mixed analysis of variance revealed a main effect of ratio, $F (3, 115) = 2260.30$, $p < .001$, with accuracy decreasing as the ratio increased (means 93.14, 89.92, 71.97, 33.42, 9.53, 5.03 respectively). Bonferoni multiple pairwise comparisons revealed significant differences between accuracy at each ratio, with $p < .05$ in each case. There was no significant main effect of task, $F (1, 34) = 1.52$, $p > .05$, and no significant interaction between task and ratio, $F (3, 115) = 1.14$, $p > .05$.

Table 5.2 *Mean Percentage of Correct Responses at Each Number of Retrievals:*

Time Ratio (Standard Deviations are Shown in Parentheses)

Task	Feature search	Conjunction search
Ratio		
0.50	93.50 (6.52)	92.78 (5.63)
0.67	87.22 (6.15)	88.61 (6.11)
1.00	73.56 (6.76)	70.39 (7.82)
1.33	34.78 (6.71)	32.06 (4.12)
1.50	10.44 (6.77)	8.61 (5.05)
2.00	6.56 (6.20)	3.50 (4.34)

5.3 Discussion

The results clearly indicate that performance on working memory tasks is constrained by both temporal duration and the nature of processing activities. The results also suggest that performance is a function of a task's cognitive demand, which corresponds to the difficulty of the retrievals it requires and the number of these retrievals divided by the time allowed to perform them. The results therefore provide support for the metric of cognitive load suggested by Barrouillet et al. (2004).

In each of the working memory tasks employed in the present study there was a significant effect of temporal duration. The longer the duration between presentation and recall of memory items, the higher the memory span score. As

pointed out by Barrouillet et al., this finding is inconsistent with the resource switching approach to working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) according to which retention periods have an effect on spans because longer durations allow more time over which memory items can be forgotten. By this view, longer durations should result in lower span scores. According to the time- based resource- sharing view (Barrouillet et al., 2004), however, cognitive load mediates the effect of time. Thus when the number of retrievals is held constant but the time allowed to perform them is increased, there is a reduced cognitive demand that results in higher span scores.

It is worthy of note, however, that the resource switching view could account for the findings if longer durations present more of an opportunity for participants to rehearse memory items. When durations were increased but the number of memory retrievals was kept constant there could have been time to rehearse memory items either before or after each processing activity (e.g. Engle et al., 1992). This would be inconsistent with the claim that externally paced tasks force participants to continuously focus and sustain their attention on processing in order to respond in due time before the next stimulus appears (e.g. Barrouillet et al., 2004; Gavens & Barrouillet, 2004).

In each of the tasks employed in the present study performance also varied as a result of the number of retrievals required during the processing interval. The greater the number of retrievals required, the lower the working memory span score. This finding is also contrary to the predictions of the resource- switching view of working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000), which would predict no difference among the tasks when their total durations were matched (see also; Barrouillet et al., 2004). However,

again resource switching could account for the findings if lower numbers of retrievals present an opportunity for participants to rehearse memory items either before or after a processing activity (e.g. Engle et al., 1992).

The resource sharing approach (e.g. Case et al., 1982; Daneman & Carpenter, 1980, Just & Carpenter, 1992) predicts a drop in span with an increase in the number of retrievals, because due to a processing/ storage trade- off fewer resources would be available for storage. The time- based resource- sharing view (Barrouillet et al., 2004) also predicts that when the duration of a task is held constant working memory span is dependent on the number of retrievals. The greater the number of retrievals the longer the period of time over which attention is captured and the less opportunity there is to retrieve memory traces. Thus the resource switching (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000), resource sharing (e.g. Case et al., 1982; Daneman & Carpenter, 1980, Just & Carpenter, 1992), and time- based resource- sharing (Barrouillet et al., 2004) approaches could all account for the present findings of lower memory spans being associated with higher numbers of retrievals.

Analysis also suggested that some of the tasks used in the present study were more demanding than others. Specifically, scores on the ba-ba task were significantly higher than scores on each of the other tasks (see also; Barrouillet et al., 2004). When comparing the results for the ba-ba task and the reading digits task, analysis also revealed an interaction between the number of retrievals: time ratio and task. This appeared to be a result of an initial divergence of the scores between when immediate recall was required and when an intervening task was present, this suggesting that the intervening activity of reading digits is more demanding than repeated articulation. It is important to note, however, that the

interaction between ratio and task was not significant when the data from all four tasks was analysed. There was also no difference in scores on the reading digits task, feature search task, and conjunction search task, suggesting that in terms of complexity, there was little difference between these activities.

Barrouillet et al. (2004) also claimed that the specific effect of task difficulty could be observed by comparing the slopes of regression lines between the number of retrievals: time ratio and memory span. In the present study there was a significant difference between the slope for the ba-ba span task and the slope for each of the other tasks, with the decrease in span as cognitive load increased being less pronounced for the ba-ba task. This supports the findings of Barrouillet et al. (2004), who suggested that a difference between the slopes for the ba-ba task and reading digits task reflected the difficulty of retrievals. Thus in the ba-ba span task participants simply had to keep track of a habituated stimulus and always produce the same response, which was not as difficult as the retrievals involved when reading digits or responding to visual search displays.

There was no significant difference, however, between scores or slopes for the feature search and conjunction search tasks. This suggests that when matched on time parameters and also on the number of retrievals required, counting items in arrays in which target items must be distinguished from distracter items using a conjunction of featural attributes is not necessarily more demanding than when items can be distinguished using a single featural cue. This is contrary to the findings of studies in to visual search (e.g. Duncan, 1987; Treisman, 1991; Treisman & Gelade, 1980; Treisman & Sato, 1990), which have suggested that conjunction searches are more attentionally demanding. The examination of the accuracy data from the visual search tasks also suggests that

participants were not neglecting the visual search in the conjunction search task in order to focus on the memory items.

For each task there was also a clear linear decrease in span as the number of retrievals: time ratio was increased. The findings therefore provide support for the metric of cognitive load imposed by the time- based resource- sharing theory (Barrouillet et al., 2004). It is worthy of note, however, that for the ba-ba task and the reading digits task the number of retrievals: time ratio predicted over 60% of the variance in span, compared to over 90% in Barrouillet et al. (2004). For the counting span tasks the number of retrievals: time ratio accounted for only 30% of the variance in span, leaving a large proportion of variance unaccounted for. This suggests that parameters other than the number of retrievals: time ratio, are also important in predicting counting spans, in line with suggestions that no single factor underlies complex memory span performance (Halford et al., 1994; Miyake & Shah, 1999; Ransdell & Hecht, 2003; Towse & Houston- Price, 2001).

The present study therefore provides evidence that performance on working memory measures is determined at least in part by cognitive demand. The cognitive demand of task corresponds to the difficulty of the retrievals it requires, and the number of these retrievals divided by the time allowed to perform them. This conception of cognitive load departs from more traditional conceptions that equate cognitive load with complexity. The processing activities involved in most complex span tasks require a high level of executive control e.g. reading comprehension or mental calculation. However, the time- based resource- sharing view (Barrouillet et al., 2004) predicts that even simple activities such as articulation can have a detrimental effect on span. This suggests

that the tasks cannot be completed using a single resource in which there is a trade- off between processing and storage (e.g. Case et al., 1982; Daneman & Carpenter, 1980, Just & Carpenter, 1992) because according to this view simple activities should have a minor effect on spans.

However, in terms of theories of working memory it is difficult to draw conclusions based on the current findings. When performing a self- paced task participants are free to strategically interrupt processing to update the list of memory items. They can also postpone their response to processing in order to rehearse the memory items that have already been presented. Barrouillet et al. (2004) claimed that these strategies are prevented when tasks are externally paced because tasks force participants to continuously focus and sustain their attention on processing in order to respond in due time before the next stimulus appears. However, as pointed out above, this is not necessarily the case. It is still possible, particularly at low ratios of the number of retrievals to time, that participants can use strategies such as the rehearsal of memory items before or after processing episodes. Therefore at this stage it is sufficient to conclude that complex span performance is constrained by both temporal duration and the nature of processing activities.

Chapter 6

General Discussion

This final chapter reviews the main findings presented in the thesis. The implications of the findings for current models of working memory and also for educational practice are discussed. Section 6.1 examines the role of role of working memory in the educational attainment of children aged 11 to 16 years of age. Section 6.2 discusses the role of executive processes in children's scholastic attainment. Section 6.3 examines the roles of speed of processing and response duration measures in children's scholastic skills. Section 6.4 discusses the effect of increasing complexity on working memory spans and the relationships between speeds of processing and working memory span performance. Section 6.5 examines the time-based resource- sharing view of working memory and the influence of cognitive load on memory span performance. Section 6.6 discusses the implications of the findings for educational practice. Finally, in section 6.7 the main theoretical implications are summarised and the final conclusions are formed.

6.1: The Role of Working Memory in Children's Educational Attainment

The general introduction presented evidence suggesting that working memory plays an important role in complex cognitive skills including vocabulary acquisition, language comprehension, reading, spelling and writing, speaking,

counting, mental arithmetic, and other mathematical skills. Both Chapter 1 and Chapter 2 also reviewed studies suggesting that children's working memory skills are closely associated with their performance on standardised tests of English and mathematics. Children with low levels of performance on national curriculum tests show impairments on measures of central executive functioning and visuo-spatial memory (Gathercole & Pickering, 2000; see also Gathercole et al., 2004). Working memory measures taken at school entry can also serve as predictors of later academic performance (Gathercole et al., 2003). However, each of these studies employed complex span tasks that were predominantly verbal in nature, involving for example the recall of the final words in sentences or sequences of digits in reverse order.

The evidence presented in section 1.2.1, however, suggested that verbal and visuo-spatial complex span tasks might tap separable resources (e.g. Friedman & Miyake, 2000; Handley et al., 2002; Jurden, 1995; Kane et al., 2004; Shah & Miyake, 1996). For example, Shah and Miyake (1996) found no significant correlation between verbal and spatial complex span measures. The spatial measure significantly correlated with spatial abilities but not with verbal abilities. Correspondingly, the verbal complex span measure was correlated with verbal ability, but not spatial abilities, suggesting separate pools of resources for the two domains. In the light of this evidence a major goal of study 1 was to examine whether nonverbal complex span tasks are uniquely related to school achievements. A further goal was to establish whether links between working memory and national curriculum test scores could be extended to Key Stage 2 (aged 11 years) as well as Key Stage 3 (aged 14 years) of the national

curriculum. Study 2 aimed to examine the utility of working memory as a predictor of later academic success.

6.1.1: Summary of findings

Study 1 provided direct evidence for links between working memory and performance on national curriculum tests at 11 and 14 years of age. Both verbal and nonverbal working memory were both closely related to children's performance on standardised tests of English, mathematics and science. Study 2 provided evidence for the utility of working memory as a predictor of later academic achievement. Both verbal and nonverbal working memory at 14 years of age were significantly associated with educational attainment at 16 years of age.

The findings build upon previous evidence of relationships between national curriculum test scores and working memory at 7 years of age and at 14 years of age (Gathercole & Pickering, 2000; Gathercole et al., 2004) and findings of the involvement of the phonological loop, visuo-spatial sketchpad, and central executive components of working memory in domains of skill related to education (e.g. Gathercole & Baddeley, 1993; Seitz & Schumann- Hengsteler, 2000; Reuhkala, 2001). The results further suggest that relationships between working memory and scholastic attainment can be extended to nonverbal working memory measures as well as verbal complex spans.

In study 1, detailed analysis of the relationships between working memory and school achievements revealed a degree of domain specificity (e.g.

see also; Bayliss et al., 2003; Daneman & Carpenter, 1980; Daneman & Tardiff, 1987; Shah & Miyake, 1996). Partial correlations revealed that at 11 and 14 years of age, verbal working memory tasks were uniquely associated with English and mathematics performance, whereas visuo-spatial tasks shared unique links with mathematics and science. In study 2, the associations between working memory scores at 14 years of age and scholastic attainment at 16 years of age, however, did not show the same pattern of domain- specificity. There was evidence for a domain specific link between verbal constructs and attainment in English and mathematics. However, spatial span predicted unique variance in attainment in each curricular area. It was suggested that this could be a result of general executive resources being more important for attainment later in childhood (see also; Miyake et al., 2001; Oberauer et al., 2000; Shah & Miyake, 1996).

In both studies 1 and 2, analysis of the interrelations between working memory tasks and attainment indicated that complex span tasks, associated with the central executive, were most closely related to attainment in all curricular areas. In study 1 at Key Stage 3, verbal complex span scores were uniquely correlated with attainment levels in English and mathematics. Spatial span scores were significantly correlated with mathematics and science levels. In study 2, verbal complex span scores at 14 years of age predicted unique variance in English at 16 years of age, and spatial span scores predicted unique variance in English and science. Tasks tapping the slave systems, however, were not uniquely related to levels in English, mathematics or science. This supports previous evidence that the central executive in particular plays a crucial role in the acquisition of complex cognitive abilities and skills such as literacy,

comprehension and arithmetic (e.g. Bull et al., 1999; Swanson, 1994; Yuill et al., 1989).

6.1.2: Implications for models of working memory

The results presented in studies 1 and 2 provide contrasting evidence in terms of the resources underlying working memory task performance. Factor analysis revealed a dissociation between verbal and nonverbal complex memory spans, consistent with suggestions of separate pools of resources for verbal and spatial working memory. This extends previous findings from adults to 11 and 14- year- old children (see also; Friedman & Miyake, 2000; Handley et al., 2002; Kane et al., 2004; Shah & Miyake, 1996). The finding is therefore inconsistent with the view that working memory is a limited capacity system where processing and storage operations compete for a limited pool of resources (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992).

Factor analysis also revealed that simple and complex span tasks within the same domain, either verbal or nonverbal, loaded on to a single factor. This finding is contrary to previous evidence of working memory span tasks being distinguishable from tasks that measure short- term memory capacity (e.g. Cantor et al., 1991; Conway et al., 2002; Engle & Tuholski et al., 1999; Kail & Hall, 2001), and does not provide strong support for the Baddeley and Hitch (1974) model of working memory.

However, the analyses of the relationships between short- term memory, working memory and educational attainment suggested that complex span tasks

tap cognitive resources that are not employed during short- term memory tasks. When statistically controlling for short- term memory, working memory showed unique relationships with educational attainment. When controlling for working memory, however, short- term memory was not associated with scholastic skills. This finding is consistent with the view that complex span tasks employ the storage components of working memory but also an executive processing component (e.g. Daneman & Carpenter, 1980; Daneman & Merickle, 1996; Engle & Tuholski et al., 1999).

It is worthy of note that the contrasting evidence from the factor analyses and the partial correlation coefficients may, in part, reflect differences between the statistical methods. Structural equation modelling identifies interrelationships among a set of variables. Thus because short- term memory and working memory tasks within each domain were highly correlated they loaded on to the same construct. Partial correlation coefficients, however, are used to identify unique relationships between variables. Thus this method could identify unique relationships between working memory and attainment, even though working memory and short- term were closely related.

6.2: The Role of Executive Processes in Children's Scholastic Attainment

Chapter 1 discussed a number of functions that are commonly attributed to the central executive within the multiple component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000). Individual differences

studies have provided some evidence for dissociations between these processes. For example, Miyake et al. (2000) found that the functions of updating working memory, inhibiting pre-potent responses, and shifting between tasks or mental sets, were separable, although moderately correlated. Similar findings have emerged from studies with children (see Lehto et al., 2003; Van der Sluis et al., in press).

Miyake et al. (2000) also demonstrated that the function of updating was closely linked with performance on a complex span task, suggesting that a common factor underlies updating and working memory. However, performance on complex memory measures has also been associated with the ability to shift between processing and storage (e.g. Conway & Engle, 1996; Towse et al., 1998) and the ability to inhibit information (e.g. Cataldo & Cornoldi, 1998). A major goal of study 3 was to investigate the organisation of executive functions including working memory in children. In the light of evidence presented in Chapter 2, that verbal and nonverbal working memory reflect distinct resources, a further aim was to investigate whether verbal and nonverbal complex memory tasks share common or distinct links with executive functions.

Section 1.3 also discussed evidence suggesting that inhibition, shifting, and updating play important roles in sub-domains of skills related to education (e.g. Bull & Scerif, 2001; De Beni et al., 1998; Passolunghi & Pazzaglia, 2004). Furthermore, shifting, inhibition and working memory have been found to make independent contributions to mathematics scores (Bull & Scerif, 2001). The final goal of study 3 was to explore the extent to which distinct executive functions contribute to children's performance on standardised tests of English, mathematics and science.

6.2.1: Summary of findings

Study 3 demonstrated that in 11 and 12- year- old children abilities to update the contents of working memory and to inhibit pre-potent responses were unrelated, consistent with the view that there are several diverse executive functions (see also; Espy, 1997; Klenberg et al., 2001; Miyake et al., 2000). The study did not, however, identify shifting as a third distinct executive factor. This was contrary to previous findings (e.g. Miyake et al., 2000), but may reflect a difference between the organisation of executive functions in children and in adults (e.g. Senn et al., 2004). It is also important to note, however, that the disparity could result from limitations associated with the paradigm used for the shifting tasks (see Emerson & Miyake, 2003; Rogers & Monsell, 1995). For example, the method used involved contrasting alternated and repeated tasks. This confounds switch costs and mixing costs i.e. costs associated with switching from one task to another and costs of mixing two tasks in a trial sequence rather than always performing the same task (Miyake et al., 2004).

Study 3 also demonstrated that both verbal and visuo-spatial working memory tasks share a common relationship with updating, but are not linked with inhibitory processes. This finding is consistent with claims that performance on complex span measures is constrained by the ability to monitor information and update the contents of working memory (Conway & Engle, 1996; Engle, Tuholski et al., 1999; Lehto, 1996; Miyake et al., 2000; Towse et al., 1998). Thus dissociations between verbal and nonverbal memory must arise from

domain- specific components, possibly reflecting the contributions of the storage systems within working memory (e.g. Baddeley & Logie, 1999).

The third main finding was that the executive functions provided independent contributions to children's scholastic attainment. When statistically controlling for inhibition, working memory was closely associated with performance in English and mathematics, consistent with the view that working memory plays an important role in both literacy (e.g. Gathercole & Pickering, 2000) and numeracy (see DeStefano & LeFevre, 2004 for review). When accounting for working memory, inhibitory skills were associated with performance in each curricular domain, although these correlations were substantially lower than those between working memory and attainment. The findings also demonstrated that verbal and nonverbal working memory, although closely related, accounted for unique variance in children's scholastic attainment. The links between visuo-spatial working memory and attainment, however, were more pervasive than those between verbal working memory and attainment scores.

6.2.2: Implications for models of working memory

The finding of some diversity among executive functions supports recent theoretical attempts to fractionate the central executive (e.g. Baddeley, 1996b; Baddeley & Logie, 1999; see also; Miyake et al., 2000) or the supervisory attentional system (e.g. Stuss, Shallice, Alexander, & Picton, 1995), both of which earlier took a more unitary approach (Miyake et al., 2000). One of the

questions that needs to be considered, however, is how best to classify separable

executive functions. Study 3 provided evidence for a distinction between

inhibition and updating working memory. Miyake et al. (2000) demonstrated a

distinction between inhibition, updating, and shifting. Other executive functions

have also been postulated, for example the coordination of multiple tasks

(Baddeley, 1996; Emerson, Miyake & Rettinger, 1999), productivity (Levin,

Fletcher, Kefera, & Harward et al., 1996), planning and fluency (Pennington &

Ozonoff, 1996). Therefore there are many more functions that need to be

explored with respect to the organisation of executive functions. At present it is

sufficient to note that the processes associated with the central executive cannot

be grouped together into a unitary account of executive functions.

6.3: The Contributions of Speeds of Processing and Response Durations to Children's Academic Skills

Section 1.4 discussed evidence suggesting that in addition to working

memory span scores serving as predictors of scholastic skills, the speed at which

the working memory tasks are performed also predicts unique variance. Hitch et

al. (2001) found that processing speeds during working memory tasks accounted

for unique variance in word reading scores when controlling for working

memory spans. Friedman and Miyake (2004b) demonstrated that controlling for

processing speeds only resulted in a small reduction in the relationship between

working memory and comprehension (see also; Bayliss et al., 2003). Cowan et

al. (2003) demonstrated that response durations in working memory tasks helped

to predict academic achievement, independently from the contributions of memory spans. One of the aims of study 4 was to examine the relative contributions of speeds and span scores to children's scholastic attainment.

6.3.1: Summary of relationships between speed, spans and scholastic attainment scores

The results showed that processing speeds and response durations loaded on to the same factor during factor analysis. This may have been because both measures reflected a general speed of processing (e.g. Cowan et al., 2003; Kail & Salthouse, 1994). A major goal, however, was to explore the relative contributions of memory spans and speed measures to educational attainment. Both speed and span accounted for shared and unique variance in English, mathematics and science scores (see also; Bayliss et al., 2003; Cowan et al., 2003; Friedman & Miyake, 2004b; Hitch et al., 2001).

Cowan et al. (2003) suggested that there were at least two ways to interpret the difference between accuracy and response duration measures. Response duration measures could be more detailed than span scores, revealing differences where spans do not. This interpretation accounts for why speeds explain unique variance. However, it does not account for the finding that span scores also predict unique variance. An alternative possibility is that spans and response durations may reflect different processes. For example, as discussed in Chapter 3, working memory spans may reflect the ability to update the contents of working memory (see also; Miyake et al., 2000). Response times, however,

may reflect retrieval speeds (e.g. Kail & Salthouse, 1994) and/ or the efficiency of memory organisation (Ericsson & Kintsch, 1995).

6.3.2: Implications for models of working memory

As discussed in study 4 (section 4.3), the findings that speeds and spans each predict unique variance in attainment has important theoretical implications. According to the resource sharing approach to working memory (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) memory span is determined by speed because more efficient and therefore faster processing allows more resources to be allocated to memory operations. The task switching approach (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) also assumes that span is determined by speed, because faster processing allows less time over which information can be forgotten. Both of these approaches therefore predict that span and speed should explain common variance in educational attainment. The observation that spans and speeds predict unique variance therefore suggests that accounts of working memory that are based upon both resource sharing (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) and time based forgetting (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) do not provide a complete account of working memory limitations. Thus, it is not just processing time *per se* that it is important in determining memory span.

6.4: Complexity, Speeds of Processing and Working Memory Spans

Two other themes that were explored in relation to the data in study 4 were concerned with the influence of the difficulty of processing on working memory task performance, and the relationship between speed of processing and working memory span scores.

The findings presented in Chapter 2 did not provide strong support for the multiple component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000) with a domain general central executive system and two domain specific storage systems. Both simple and complex memory span tasks within the same domain, either verbal or nonverbal, were found to load on to the same factor during factor analysis. A major goal of the study presented in Chapter 4 was to examine whether this could have been a result of the processing activities of the complex span tasks not placing a sufficient demand on the central executive (e.g. Baddeley et al., 1985) or not tapping cognitive resources sufficiently to disrupt maintenance of information (e.g. Barrouillet et al., 2004; Lepine et al., in press).

Children were administered with three versions of the counting span task (Case et al., 1982), which varied in terms of the complexity of processing. One required a feature search, one required a conjunction search, and one involved counting using an unfamiliar sequence. Speeds of processing and response durations were measured as indicators of complexity. Performance on the tasks was compared to performance on short- term memory tasks in order to examine whether tasks with more difficult processing activities were less closely associated with short- term memory measures.

The relationships between speed of processing and scores in the three counting span tasks were also explored in the interest of further understanding

what the tasks actually measure. Both the resource sharing (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992) and resource switching (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) approaches to working memory assume a linear relationship between speed and span. However, as pointed out in Chapter 4 the two approaches could make different predictions about the relationships between speed and span in different memory tasks. Resource sharing would seem to predict that different working memory tasks conform to the same span- speed relationships. Resource switching, however, could predict different span- speed relationships across different working memory tasks (see also; Hitch et al., 2001).

6.4.1: Summary of the effects of complexity of processing and the relationships between speed and memory span

Study 4 demonstrated that the three versions of counting span did differ significantly in terms of cognitive demand with the nonsense numbers task being most demanding, and the feature search task being least demanding. Thus participants found counting with unfamiliar numbers more demanding than counting with a familiar sequence (see also; Case et al., 1982), and found identifying targets using a conjunction of attributes more difficult than identifying them based on a single cue (see also; Duncan, 1987; Triesman, 1991; Triesman & Gelade, 1990; Triesman & Sato, 1990).

A major goal of the study, however, was to examine the relationships between short- term memory tasks and working memory measures varying in

cognitive demand. Analyses revealed that the counting span tasks and short- term memory tasks loaded on to distinct factors during factor analysis. The results therefore supported previous findings of dissociations between short- term memory measures and working memory measures (e.g. Cantor et al., 1991; Conway et al., 2002; Engle & Tuholski et al., 1999; Kail & Hall, 2001).

The findings of a distinction between short- term memory and working memory, however, were inconsistent with the findings presented in studies 1 and 2, which suggested that short- term memory tasks and working memory tasks within the verbal domain were not distinguishable. It was suggested in section 4.3 that this discrepancy could have been a result of differences between counting span and backwards digit recall and listening span. For example, the assumption that backwards recall requires executive intervention has been questioned by some authors (e.g. Engle & Tuholski et al., 1999; Farrand & Jones, 1996; Hutton & Towse, 2001; Isaacs & Vargha- Khadem, 1989).

The analysis of the relationships between speeds and spans for the three versions of the counting span task showed that scores on each version of the counting span task increased linearly with the time taken to perform the counting. As pointed out in section 4.3, however, for each task speed predicted only a moderate amount of variance in span scores. The relationship between speed and task scores, in terms of its regression equation, was also different for the nonsense numbers task when compared with the feature search and conjunction search tasks. This finding supports those of Hitch et al. (2001) who demonstrated different relationships between speed and span when comparing operation span and reading span. The finding also suggests that performance on complex span tasks is not determined by speed *per se,* but also by the nature of

processing activities. It would be premature, however, to conclude that the complexity of processing also influences working memory task performance. For example, as pointed out in study 4 cognitive demand cannot necessarily be equated with complexity. The time- based resource- sharing view of working memory (Barrouillet et al., 2004) proposes that even simple activities such as articulation can have a detrimental effect on memory span, provided that they are performed at a rate sufficient to disrupt the maintenance of memory items. The time- based resource-sharing approach assumes that cognitive cost is determined, at least in part, by the number of retrievals a processing activity requires. For example, in the nonsense numbers task retrievals were required to retrieve the unfamiliar numbers from long- term memory. It was this task that showed a span- speed relationship that was different to that in the feature search and conjunction search tasks. From the study presented in Chapter 4, however, it is difficult to draw conclusions based on the time- based resource- sharing approach (Barrouillet et al., 2004) because while cognitive demand was manipulated, durations were not controlled for.

6.4.2: Implications for models of working memory

The finding of a dissociation between short- term memory and working memory (see also; Cantor et al., 1991; Conway et al., 2002; Engle & Tuholski et al., 1999; Kail & Hall, 2001) provides support for the multiple component model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000), and suggests

that processing requirements of complex span measures are met by a system separate to that required for storage of information (e.g. Baddeley & Logie, 1999; Duff & Logie, 2001).

The findings of different relationships between speed and span in the three versions of the counting span task also appears to rule out a simple resource-sharing explanation in which processing and storage access a common pool of resources and processing time reflects the amount of resources available for storage (e.g. Case et al., 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992). Although as pointed out in section 4.3, Hitch et al. (2001) suggested that the resource- sharing model could come close to accounting for the findings if it was assumed that different tasks consume resources in working memory at different rates, for example because different amounts of time are taken up in processes outside of working memory.

The task switching model of working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; 2000) also predicts that span will vary with speed because faster processing allows less time over which items can be forgotten. However, as suggested by Hitch et al. (2001) the task- switching approach explains the effect of processing time in terms of forgetting, and span- speed relationships could depend upon the dynamics of activation loss in different task contexts, therefore accounting for findings of different span- speed relationships. Advocates of the task switching approach have, however, been careful to point out that task switching is unlikely to provide a complete explanation of working memory span and that other mechanisms may also be involved (Towse & Hitch, 1995; Towse et al., 1998), for example individual differences in memory decay

and the activation of memory traces (Byrne, 1998), or the ability to resist interference (e.g. Stolzfus, Hasher, & Zacks, 1996).

6.5: The Time- Based Resource- Sharing Approach

Study 4 involved varying the nature of the processing activities involved in the counting span task. For each task there was a significant relationship between speed of processing and working memory span, but this relationship differed across tasks with different processing requirements. Thus performance was constrained by both temporal duration and the nature of the processing activities. Section 1.2.1 and section 6.4.2, however, discussed an alternative approach to cognitive demand in which demand is not equated with the difficulty of processing, but is determined by the number of retrievals a processing task requires, and the time allowed to perform the retrievals.

Barrouillet et al. (2004) proposed a time- based resource- sharing account of working memory. The approach assumes that both processing and storage require attention and that memory traces decay as soon as attention is switched away from them. Thus participants are assumed to switch their attention from processing to storage *during* processing intervals. This approach to working memory allows for a calculation of cognitive cost. For a given period of time, the cognitive cost that a task involves is a function of the time during which it captures attention in such a way that the refreshing of memory traces is impeded. The longer this time, the fewer and shorter the periods of time that can be allocated to retrieving information to be recalled.

In one series of experiments Barrouillet et al. (2004) demonstrated that when retention intervals were held constant adults' working memory spans depended on the cognitive cost imposed by the processing. They then demonstrated that a span task completed over a shorter duration resulted in a higher cognitive load and thus a lower span score. In a final experiment they provided evidence that progressively increasing the ratio of the number of memory retrievals a processing component requires to the time allowed to perform them resulted in a smooth and linear decrease in span.

Study 5 aimed to replicate the findings of Barrouillet et al. (2004) of a linear relationship between the number of retrievals to time ratio and memory span, and to extend the findings to tasks involving different processing domains. Participants were tested on an articulation task and a reading digit task as used by Barrouillet et al., and also on a counting span task requiring a feature search and a counting span task requiring a conjunction search. Seven different ratios of the number of retrievals to time were used, one of which was 0, equating to the immediate recall of information.

6.5.1: Summary of findings relating to the time- based resource- sharing approach

Study 5 provided further evidence that performance on working memory tasks is constrained by both temporal duration and the nature of processing activities. For each of the working memory tasks there was a significant effect of temporal duration. The longer the duration between presentation and recall of

memory items, the higher the memory span score. For each task performance also varied as a result of the number of retrievals required during the processing interval. The greater the number of retrievals required, the lower the working memory span score.

The results also suggested that performance on working memory tasks is a direct function of a task's cognitive demand, which corresponds to the difficulty of the retrievals it requires and the number of these retrievals divided by the time allowed to perform them (see also; Barrouillet et al., 2004). In terms of the number of retrievals divided by the time allowed to perform them, the higher the ratio of the number of retrievals: time the lower the working memory score. With regards to the difficulty of retrievals, Barrouillet et al. (2004) claimed that the specific effect of task difficulty could be observed by comparing the slopes of regression lines between the number of retrievals: time ratio and memory span. Study 5 demonstrated a significant difference between the slope for the ba-ba span task and the slope for each of the other tasks. The decrease in span as cognitive load increased was less pronounced for the ba-ba task. This supported the findings of Barrouillet et al. (2004), who suggested that a difference between the slopes for the ba-ba task and reading digits task reflected the difficulty of retrievals. Thus in the ba-ba span task participants simply had to keep track of a habituated stimulus and always produce the same response, which was not as difficult as the retrievals involved when reading digits.

As discussed in study 5 (section 5.3), however, for the ba-ba task and the reading digits task the number of retrievals: time ratio predicted over 60 % of the variance in span. For the counting span tasks the number of retrievals: time ratio accounted for only 30 % of the variance in span, leaving a large proportion of

variance unaccounted for. This suggests that parameters other than the number of retrievals: time ratio, are also important in predicting counting span performance, in line with suggestions that no single factor underlies complex memory span (Halford et al., 1994; Miyake & Shah, 1999; Towse & Houston- Price, 2001; Ransdell & Hecht, 2003).

6.5.2: Implications for models of working memory

The findings presented in study 5 demonstrated that even simple activities such as articulation can have a detrimental effect on span (see also; Barrouillet et al., 2004). This suggests that the tasks cannot be completed using a single resource in which there is a trade- off between processing and storage (e.g. Case et al., 1982; Daneman & Carpenter, 1980, Just & Carpenter, 1992) because according to this view simple activities should have a minor effect on spans. Rather, it suggests that even simple retrievals tap some kind of limited resource that is also needed to maintain memory items. This finding provides support for models of working memory that view resources as a kind of mental energy available for activation (Anderson, 1993; Anderson & Lebiere, 1998; Just & Carpenter, 1992; Lovett, Reder, & Lebiere, 1999). The impact of simple retrievals on working memory spans also suggests that memory retrievals are subject to a bottleneck that only allows a single retrieval at a time (see Carrier & Pashler, 1995; Pashler, 1998).

The finding that longer durations resulted in higher spans is inconsistent with the resource switching approach to working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; Towse et al., 2000) according to which retention

periods have an effect on spans because longer durations allow more time over which memory items can be forgotten. By this view, longer durations should result in lower span scores. In the time- based resource- sharing view of working memory (Barrouillet et al., 2004) however, cognitive load mediates the effect of time. Thus when the number of retrievals is held constant but the time allowed to perform them is reduced, there is an increased cognitive demand that results in lower span scores.

The finding that greater numbers of retrievals resulted in lower working memory scores is also contrary to the predictions of the resource switching view of working memory (e.g. Towse & Hitch, 1995; Towse et al., 1998; Towse et al., 2000), which would predict no difference among the tasks when their total durations were matched. The time- based resource- sharing view (Barrouillet & Camos, 2004) however, predicts that when the duration of a task is held constant, working memory span varies as a function of the number of retrievals. The greater the number of retrievals the longer the period of time over which attention is captured, preventing the retrieval of memory traces. The resource sharing approach (e.g. Case et al., 1982; Daneman & Carpenter, 1980, Just & Carpenter, 1992) also predicts a drop in span with an increase in the number of retrievals because fewer resources would be available for storage.

However, the resource switching view could account for the findings if longer durations present more of an opportunity for participants to rehearse memory items. When durations were increased but the number of memory retrievals was kept constant, or when durations were held constant but the number of retrievals was reduced, there could have been time for participants to rehearse memory items either before or after each processing activity (e.g. Engle

et al., 1992). This would be inconsistent with the claim that externally paced tasks force participants to continuously focus and sustain their attention on processing in order to respond in due time before the next stimulus appears (e.g. Barrouillet et al., 2004; Gavens & Barrouillet, 2004).

Therefore the results provided evidence for the metric of cognitive cost proposed by Barrouillet et al. (2004). The approach may also be successful in predicting a number of phenomena related to working memory tasks, such as the different span- speed relationships observed in study 4. However, the resource sharing model could account for the findings of study 5 if it is assumed that participants can rehearse memory items before or after processing (e.g. Engle et al., 1992). More research is needed to gain a fuller understanding of the functions of working memory and its constraints. As mentioned in section 5.3 at this stage it is sufficient to conclude that complex span performance is constrained by both temporal duration and the nature of processing activities.

6.6: Implications for Educational Practice

In chapters 1, 2 and 3 the findings of strong links between children's working memory and scholastic attainments have important implications for educational practice. One possible reason for the relationships between working memory and scholastic skills is that processing components of working memory span tasks mimic the requirements of scholastic skills (e.g. Baddeley et al., 1985; MacDonald & Christianson, 2002; Waters & Caplan, 1996). However, many studies have demonstrated that the relationships between working memory and high- level cognitive skills are not explicable simply in terms of the processing

elements of tasks (e.g. Engle, Tuholski et al., 1999; Passolunghi & Siegel, 2001) and it appears that it is the general capacity of working memory that is important rather than skill in a particular processing domain (e.g. Conway & Engle, 1994; Gathercole et al., in press). For example, relationships between working memory and text comprehension are not specific to comprehension based working memory tasks, but reflect a modality free system (see Engle et al., 1992; Engle, Tuholski et al., 1999; Turner & Engle, 1989 for review). The working memory deficits observed in reading disabled children are not specific to verbal working memory tasks, suggesting that relationships are not an artefact of both tapping skills within a particular academic domain (Swanson, 2003). It is worthy of note, however, than in studies 1 and 2 there was some evidence for domain specific links between working memory and children's educational attainment (see also; Daneman & Carpenter, 1980; Daneman & Tardiff, 1987; Shah & Miyake, 1996).

A second possible explanation for the links between working memory and school attainment is that they both reflect fluid intelligence. Working memory (when statistically controlling for short- term memory) is a significant predictor of scores on tests of general fluid ability (e.g. Conway et al., 2002; Engle & Tuholski et al., 1999). Individuals with poor working memory capacities and individuals with low psychometric intelligence also show similar patterns of performance on tasks that require the selective focus of attention or attention amidst sources of distraction (See Engle, Kane, & Tuholski, 1999 for a review). However, although working memory and intelligence are highly related they are not the same construct; and the basis of their relationship is likely to be due to a demand for controlled attention (e.g. Conway et al., 2002). In addition, some children perform poorly on measures of working memory despite showing

normal performance on intelligence tests (e.g. Gathercole, Lamont, & Alloway, in press). Scores on working memory tasks also predict unique variance in educational skills when statistically controlling for intelligence (e.g. Gathercole et al., 1992; Geary et al., 1999). Therefore research into the role of working memory in children's scholastic skills is still likely to provide findings that have important implications for educational practice.

As suggested in section 2.4, the impact of working memory on academic achievement is likely to be a result of working memory being employed for storage, processing and integration of information during complex and demanding activities (e.g. Just & Carpenter, 1992). Such activities are common in the school classroom, for example writing while formulating the next part of a text, or engaging in mental arithmetic. It is important to note, however, that there are a number of aspects of working memory that could constrain children's learning, for example general storage capacity, processing efficiency, the ability to access information in long- term memory, or a combination of these processes (e.g. Swanson, 2003; 2004). Swanson (2004) considered three possible explanations for the role of working memory in children's mathematical problem solving, which required an interaction of text comprehension and mathematical processes. The first focussed on processing efficiency at a phonological level, and because age related changes in children's problem solving are often attributed to the phonological system (e.g. see Shankweiler & Crain, 1986 for a review), assumed that mathematical proficiency may follow from improvements in phonological processing. The second explanation was concerned with long-term memory and suggested that the influence of working memory on problem solving is related to one's ability to accurately access numerical, relational, and

question information in long- term memory, as well as accessing appropriate operations and algorithms for solutions (e.g. Hegarty, Mayer, & Monk, 1995; Mayer & Hegarty, 1996; Swanson, Cooney, & Brock, 1993). The third model focussed on executive processes operating independently of phonological processes and of long- term memory. The results demonstrated that partialing out processing efficiency did not eliminate the relationship between working memory and problem solving scores, suggesting that the relationship was not due to phonological processing. Phonological processing and working memory, however, contributed unique variance to problem solving, A factor drawing variance from both verbal and nonverbal working memory tasks correlated with problem solving even when controlling for phonological skills, suggesting a role for a domain- general working memory system. Measures of knowledge of operations and algorithms also predicted solution accuracy (see also; Swanson & Sachse- Lee, 2001). Therefore working memory is likely to be employed for the storage of information during mathematical operations (e.g. Hitch, 1978; Logie et al., 1994), the processing of information (e.g. DeStefano & LeFevre, 2004) and the retrieval of facts from long- term memory (e.g. Baddeley & Logie, 1999).

During the skills and processes important in English assessments, such as vocabulary, reading, comprehension, spelling and writing, working memory is likely to be employed for the storage (e.g. Baddeley, 1998; Bock, 1982; Caramazza et al., 1987) and processing (e.g. Gathercole & Baddeley, 1993; Swanson & Berninger, 1996b) of information, and the coordination of tasks (e.g. Towse & Houston- Price, 2001). Executive processes are likely to be required for

the inhibition of irrelevant information (e.g. De Beni et al., 1999; Gernsbacher, 1993), and shifting between tasks or mental sets (e.g. Wilcutt et al., 2001).

This suggests that one reason why children may fail to achieve expected levels in key curricular domains is that their performance on learning tasks in the classroom is constrained by their working memory capacities. There may therefore be significant benefits from creating structured learning activities that reduce opportunity for failure due to inadequate working memory resources. Gathercole and Alloway (2004) provided guidelines for reducing working memory loads during classroom activities. These included reducing the amount of material to be stored (e.g. shortening sentences to be written or the number of items to be remembered), increasing the meaningfulness and familiarity of material, simplifying the linguistic structures of verbal material, restructuring multi step tasks into separate independent steps, and encouraging the use of memory aids (e.g. providing useful spellings and number lines). They also suggested that good practice in the school classroom when working with children with working memory deficits would be to regularly repeat important information such as instructions or content for learning activities, and also to encourage children to develop strategies for overcoming memory problems, including using rehearsal, memory aids, and organisational strategies, and asking for help when information is forgotten.

Study 3 demonstrated that in addition to working memory, inhibitory skills predicted unique variance in English, mathematics and science scores, suggesting that inhibitory skills support general academic learning rather than the acquisition of skills in a particular domain. Several authors have discussed the importance of inhibitory processes in scholastic skills, and the implications of

this for curriculum development. However, these discussions have been mainly concerned with proactive and retroactive interference (see Dempster & Corkill, 1999 for review). Several theorists have proposed that inhibitory processes are a family of functions rather than a unitary construct (Dempster, 1993; Harnishfeger, 1995; Nigg, 2000). For example, Friedman & Miyake (2004a) found that resistance to proactive interference was separable from prepotent response inhibition and resistance to distractor interference. The inhibition of prepotent responses and resistance to distractor information, however, were highly related, and appeared to share the requirement to actively maintain task goals in the face of interference, usually from external stimuli.

Inhibition in the context of study 3 referred to the deliberate inhibition of prepotent responses. Although this type of inhibition has previously been related to performance on measures of reading (e.g. De Beni et al., 1998; Gernsbacher, 1993), comprehension (Dempster & Corkill, 1999), vocabulary learning (Dempster & Cooney, 1982) and mathematics (e.g. Bull & Scerif, 2001; Espy et al., 2004; van der Sluis et al., 2004), the role that inhibition plays in scholastic skills is relatively unspecified.

Reading and comprehension are likely to require inhibitory processes for a number of reasons. For example, narrative discourse in which there are multiple characters and each is engaged in a variety of activities can cause interference when questions ask for details of who did what (Thorndyke, 1977). Interference is also common when a text contains multiple arguments (Thorndyke & Hayes- Roth, 1979), when two individuals are introduced in one clause (Gernsbacher, 1989), and when two or more related topics are presented in succession (e.g. Dempster, 1985; 1988; Gunter, Berry, & Clifford, 1981; Gunter,

Clifford, & Berry, 1980). Interference is also likely when text contains ambiguous messages with more than one meaning (e.g. Gernsbacher & Faust, 1991; Hasher & Zacks, 1988) or contains irrelevant information that is similar to relevant details (e.g. Kouba, Brown, Carpenter, Lindquist, Silver, & Swafford, 1988; Muth, 1991).

During mathematics, inhibition could be important for inhibiting the retrieval of irrelevant associations when retrieving arithmetical facts from long-term memory (Barrouillet, Fayol, & Lathuliere, 1997; Conway & Engle, 1994; Geary, Hamson, & Hoard, 2000). It could also be necessary to inhibit irrelevant strategies. For example, Dempster and Corkill (1999) suggest that inefficient inhibition could lead children to make errors in missing addend tasks (e.g. 3 + ? = 9). Although the tasks seem simple they are difficult for young children. Most children add the two given numbers and arrive at an erroneous value (e.g. Case, 1975) because they apply previously correct strategies learned in the process of standard addition problems and they cannot inhibit this irrelevant strategy.

The finding presented in study 4, that spans and speeds predict unique variance in scholastic attainment measures, also has important practical implications. To the extent that the purpose of using working memory span tasks is to predict scholastic performance, the purpose appears to be much better served if timing measures are used along with span scores (see also; Cowan et al., 2003). The findings therefore support those of Waters and Caplan (1996) who proposed that in the reading span task processing times should be added to recall performance to create composite dual task scores. The addition of this information substantially increased the ability of the task to predict comprehension performance. Friedman and Miyake (2004b) also found that

using sentence- processing times in addition to recall scores increased correlations with comprehension, but only in self- paced and not externally-paced tasks. They therefore suggested that the benefit of including processing times might have arisen because adding processing times corrected for strategy use times.

Study 5 could also provide insights in to the role of working memory in scholastic skills because it employed externally- paced complex span tasks rather than traditional self- paced measures. As discussed earlier the first possible explanation of links between working memory and educational attainment is that the processing in complex span tasks mimics the requirements of scholastic skills (e.g. Baddeley et al., 1985; MacDonald & Christianson, 2002; Waters & Caplan, 1996). According to this view, high working memory span individuals are better able to store and process information, achieving better scores in working memory and other cognitive tasks. This view would predict that externally- paced working memory tasks such as those used in study 5 would have a low predictive value in terms of predicting scholastic skills because they involve only elementary processes.

The second explanation is that working memory is employed for the storage and processing of information during complex tasks (e.g. Just & Carpenter, 1992). According to this view, complexity is not a requirement of the processing element of tasks as long as they capture attention for sufficient periods of time to disrupt the maintenance of information. According to this view externally- paced tasks should serve as good predictors of scholastic skills. The temporal constraints of externally- paced tasks also prevent the use of strategies for coping with dual demand (e.g. Baddeley et al., 1985; Case et al., 1982;

Daneman & Carpenter, 1980; Turner & Engle, 1989). According to some authors these strategies may produce biased measures of working memory capacity (e.g. Lepine et al., in press). Therefore it could also be argued that externally- paced tasks would serve as better predictors of scholastic skills than self- paced tasks due to reducing the opportunity for strategy use. Although it was not addressed in the current studies, Lepine et al. (in press) demonstrated that compared to traditional self- paced working memory measures, externally paced tasks provided better estimates of academic achievement. This provides further evidence for the view that working memory is employed for the storage and processing of information during complex tasks (see also; Engle & Tuholski et al., 1999; Gathercole et al., in press; Passolunghi & Siegel, 2001) and is inconsistent with suggestions that working memory is related to scholastic skills due to overlapping requirements of tasks (e.g. Baddeley et al., 1985; MacDonald & Christianson, 2002; Waters & Caplan, 1996). It also suggests that to the extent that the purpose of using working memory span tasks is to predict performance on academic attainment measures, the purpose would appear to be better served if externally- paced working memory were employed rather than self- paced tasks.

6.7: Conclusions

The studies in this thesis demonstrated close links between both working memory and executive processes and children's learning achievements. This has important implications for educational practice. For example, there may be significant benefits from creating learning activities that reduce the opportunity

for failure due to inadequate working memory resources. Suggestions have been made as to how educational professionals could improve learning outcomes for children with working memory problems (e.g. Gathercole & Alloway, 2004), but more research is needed to examine whether the progress of children is improved when working memory loads are managed effectively in the classroom.

The studies also demonstrated that speed measures and memory span scores predicted unique variance in scholastic attainment. Relationships between speed and span also varied across different working memory tasks. These findings have important implications for current models of working memory because they suggest that performance on working memory tasks is not determined by speed *per se*, but also by the nature of processing activities. It was shown in study 5, however, that it is not necessarily the complexity of processing activities that is important, but rather the difficulty of the retrievals it requires and the number of retrievals divided by the time allowed to perform them.

More research is needed because several fundamental questions about working memory tasks have yet to be answered (e.g. Miyake, 2001; Saito & Miyake, 2000). The results do, however, suggest that working memory task performance is limited by both duration and the nature of processing activities, and highlight the need to simultaneously consider the processing and storage requirements of complex memory measures when investigating the relationship between working memory and high- level cognitive skills.

References

Ackerman, P.L., Beier, M.E., & Boyle, M.O. (2002). Individual differences in working memory within a nomological network of cognitive and perceptual speed abilities. *Journal of Experimental Psychology: General, 131,* 567- 589.

Ackerman, P.T., Dykman, R.A., & Gardner, M.Y. (1990). Counting rate, Naming rate, phonological sensitivity and memory span: major factors in dyslexia. *Journal of Learning Disabilities, 23,* 325- 327.

Adams, A.M., & Gathercole, S.E. (1995). Phonological working memory and speech production in preschool children. *Journal of Speech and Hearing Research, 38,* 403- 414.

Adams, A.M., & Gathercole, S.E. (1996). Phonological working memory and spoken language development in young children. *Quarterly Journal of Experimental Psychology, 49A,* 216- 233.

Alloway, T.P., Gathercole, S.E., & Pickering, S.J. (2004). Automated Working Memory Assessment. Available from the authors on request.

Alloway, T.P., Gathercole, S.E., Willis, C., & Adams, A.M. (2004). A structural analysis of working memory and related cognitive skills in young children. *Journal of Experimental Child Psychology, 87,* 85- 106.

Anderson, J.R. (1993). *Rules Of The Mind.* Hillsdale, NJ: Erlbaum.

Anderson, J.R., & Lebiere, C. (1998). *Atomic components of thought.* Hillsdale, NJ: Erlbaum.

Ashcraft, M.H. (1992). Cognitive arithmetic: A review of data and theory. *Cognition, 44,* 75- 106.

Ashcraft, M.H., & Battaglia, J. (1978). *Rules of the mind.* Hillsdale, NJ: Erlbaum.

Ashcraft, M.H., Donley, R.D., Halas, M.A., & Vakali, M. (1992). Working

memory, automaticity, and problem difficulty. In J. I. D. Campbell (Ed.).

The nature and origins of mathematical skills (pp. 301- 329). Amsterdam:

Elsevier Science Publishers.

Ashcraft, M.H., & Kirk, E.P. (2001). The relationships among working memory,

math anxiety, and performance. *Journal of Experimental Psychology,*

General, 130, 224- 237.

Ashcraft, M.H., & Stazyk, E.K.H. (1981). Mental addition: a test of three

verification models. *Memory and Cognition, 9,* 185- 196.

Atkinson, R.C., & Shiffrin, R.M. (1968). Human Memory: A proposed system

and its control processes. In Spence, K.W. *The psychology of learning*

and motivation: advances in research and theory. New York: Academic

press.

Avons, S.E., Wright, K.L., & Pammer, K. (1994). The word- length effect in

probed and serial recall. *Quarterly Journal of Experimental Psychology,*

47A, 207- 231.

Babcock, R.L., & Salthouse, T.A. (1990). Effects of increased processing

demands on age differences in working memory. *Psychology and Ageing,*

5, 421- 428.

Baddeley, A.D. (1966). Short- term memory for word sequences as a function of

acoustic, semantic and formal similarity. *Quarterly Journal of*

Experimental Psychology, 18, 362- 365.

Baddeley, A.D. (1986). *Working Memory.* Oxford: Oxford University Press.

Baddeley, A.D. (1990). *Human Memory: Theory and Practice*. Hove UK:

Lawrence Erlbaum.

Baddeley, A.D. (1993). Short- term phonological memory and long- term

learning: A single case study. *European Journal of Cognitive Psychology,*

5, 29- 148.

Baddeley, A.D. (1996a). Exploring the central executive. *Quarterly Journal of*

Experimental Psychology, 49A, 5- 28.

Baddeley, A.D. (1996b). The fractionation of working memory. *Proceedings of*

the national academy of sciences, 93, 13468-13472.

Baddeley, A. D. (1998). The central executive: A concept and some

misconceptions. *Journal of the International Neuropsychological Society,*

4, 523- 526.

Baddeley, A.D. (2000). The episodic buffer: a new component of working

memory? *Trends in cognitive sciences, 11(4),* 417- 423.

Baddeley, A.D., Chincota, D., & Adlam, A. (2001). Working memory and the

control of action: Evidence from task switching. *Journal of Experimental*

Psychology General, 130, 641-657.

Baddeley, A.D., Cocchini, G., Della Sala, S., Logie, R.H., & Spinnler, H. (1999).

Working memory and vigilance: Evidence from normal ageing and

Alzheimer's disease. *Brain and Cognition, 41,* 87- 108.

Baddeley, A.D., Della Sala, S., & Spinnler, H. (1991). The two- component

hypothesis of memory deficit in Alzheimers disease. *Journal of Clinical*

and Experimental Neuropsychology, 13, 372- 380.

Baddeley, A.D., Della Sala, S., Papagno, C., & Spinnler, H. (1997). Dual task

performance in dysexecutive and non- dysexecutive patients with a

frontal lobe lesion. *Neuropsychology, 11,* 187- 194.

Baddeley, A.D., Eldridge, M., & Lewis, V.J. (1981). The role of subvocalization

in reading. *Quarterly Journal of Experimental Psychology, 33,* 439- 454.

Baddeley, A.D., Emslie, H., Kolodny, J., & Duncan, J. (1998). Random

generation and the executive control of working memory. *Quarterly*

Journal of Experimental Psychology, 51A, 819-852.

Baddeley, A.D., Gathercole, S.E., & Papagno, C. (1998). The phonological loop

as a language learning device. *Psychological Review, 105,* 158- 173.

Baddeley, A.D., & Hitch, G. (1974). Working Memory. In Bower, G.H. (Ed.),

The Psychology of Learning and Motivation. New York: Academic Press.

Baddeley, A. D., & Lewis, V. (1981). Inner active processes in reading: The

inner voice, the inner ear, and the inner eye. In A.M. Lesgold & C. A.

Perfetti (Eds.), *Interactive processes in reading* (pp. 107- 129). Hillsdale,

NJ: Lawrence Erlbaum Associates Inc.

Baddeley, A.D., Lewis, V., & Vallar, G. (1984). Exploring the articulatory loop.

Quarterly Journal of Experimental Psychology, 36, 233- 252.

Baddeley, A.D., & Logie, R. (1999). Working memory: The multiple component

model. In Miyake, A., & Shah, P. (Eds.), *Models of Working Memory*

(pp. 28- 61). New York: Cambridge University Press.

Baddeley, A.D., Logie, R., Nimmo- Smith, L., & Brereton, N (1985).

Components of fluent reading. *Journal of Memory and Language, 24,*

119- 131.

Baddeley, A.D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short- term memory. *Journal of Verbal Learning and Verbal Behaviour, 14,* 575- 589.

Baddeley, A.D., Vallar, G., & Wilson, B. (1987). Sentence comprehension and phonological memory: some neurological evidence. *Attention and Performance, 12* 509- 529.

Baddeley, A.D., & Wilson, B. A. (2002). Prose recall and amnesia: Implications for the structure of working memory. *Neuropsychologia, 40,* 1737-1743.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology General, 133,* 83- 100.

Barrouillet, P., & Camos, V. (2001). Developmental increase in working memory span: Resource sharing or temporal decay? *Journal of Memory and Language, 45,* 1-20.

Barrouillet, P., Fayol, M., & Lathuliere, E. (1997). Selecting between competitors in multiplication tasks: An explanation of the errors produced by adolescents with learning difficulties. *International Journal of Behavioural Development, 21,* 253- 275.

Bauer, R.H. (1977). Memory processes in children with learning disabilities: Evidence for deficient rehearsal. *Journal of Experimental Child Psychology, 24,* 415- 430.

Bayliss, D.M., Jarrold, C., Gunn, D.M., & Baddeley, A.D. (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. *Journal of Experimental Psychology General. 132,* 71- 92.

Beckwith, M., & Restle, F. (1996). Process of enumeration. *Psychological Review, 73,* 437- 444.

Bentler, P.M. (1990). Comparative fit indexes in structural models. *Psychological Bulletin, 107,* 238- 246.

Bentler, P.M. (2001). EQS structural equation modelling software (version 6.0) [computer software]. USA: mvsoft.

Bentler, P.M., & Wu, E.J.C. (1995). *EQS for Macintosh user's guide.* Encino, CA: Multivariate Software Inc.

Benton, S.L., Kraft, R.G., Glover, J.A., & Plake, B.S. (1984). Cognitive capacity differences among writers. *Journal of Educational Psychology, 76,* 820- 834.

Bereiter, C., Burtis, C., & Scardamalia, M. (1988). Cognitive operations in constructing main points in written composition. *Journal of Memory and Language, 27,* 261- 278.

Berninger, V., & Swanson, H.L. (1994). Modification of the Hayes and Flower model to explain beginning and developing writing. In E. Butterfield (Ed.), *Children's writing: Toward a process theory of development of skilled writing* (pp. 57- 82). Greenwich, CT: JAI Press.

Besner, D., Davies, J., & Daniels, S. (1981). Reading for meaning: The effects of concurrent articulation. *Quarterly Journal of Experimental Psychology, 33,* 415- 437.

Bishop, D.V.M., North, T., & Donlan, C. (1996). Nonword repetition as a phenotypic marker for inherited language impairment: evidence from a twin study. *Journal of Child Psychology and Psychiatry, 33,* 1- 64.

Blake, J., Austin, W., Cannon, M, Lisus, A., & Vaughan, A. (1994). The relationship between memory span and measures of imitative and spontaneous language complexity in pre- school children. *International Journal of Behavioural Development, 17,* 91- 107.

Bock, J.K. (1982). Towards a cognitive psychology of syntax: Information processing contributions to sentence formulation. *Psychological Review, 89,* 1- 49.

Bourassa, D., & Besner, D. (1994). Beyond the articulatory loop: A semantic contribution to serial order recall of subspan lists. *Psychnomic Bulletin and Review, 1,* 122- 125.

Bourdin, B., & Fayol, M. (1994). Is written language production more difficult than oral language production? A working memory approach. *International Journal of Psychology, 29,* 591- 620.

Bradley, L., & Bryant, P.E. (1983). Categorising sounds and learning to read- a causal connection. *Nature, 301,* 419- 521.

Brady, S. (1991). The role of working memory in reading disability. In S. A. Brady & D. P. Shankweiler (Eds.), *Phonological Processes in Literacy.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Brady, S., Mann, V., & Schmidt, R. (1987). Errors in short- term memory for good and poor readers. *Memory and Cognition, 15,* 444- 453.

Brooks, L.R. (1967). The suppression of visualisation by reading. *Quarterly Journal of Experimental Psychology, 19,* 289-299.

Brown, G.D.A., & Hulme, C. (1995). Modelling item length effects in memory span: no rehearsal needed? *Journal of Memory and Language, 34,* 594- 621.

Brown, G.D.A., & Hulme, C. (1996). Non- word repetition, STM, and word age- of- acquisition: A computational model. In Gathercole, S.E. *Models of Short- Term Memory.* Hove, England: Psychology Press.

Bull, R., & Johnston, R.S. (1997). Children's arithmetical difficulties: contributions from processing speed, item identification, and short- term memory. *Journal of Experimental Child Psychology, 65,* 1-24.

Bull, R., Johnston, R.S., & Roy, J.A. (1999). Exploring the roles of the visuo- spatial sketchpad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology, 15,* 421- 442.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematical ability: Inhibition, Switching and Working memory. *Developmental Neuropsychology, 19,* 273- 293.

Butterworth, B., Campbell, R., & Howard, D. (1986). The uses of short- term memory: A case study. *Quarterly Journal of Experimental Psychology, 38,* 705- 737.

Butterworth, B., Cipolotti, L., & Warrington, E.K. (1996). Short- term memory impairment and arithmetical ability. *Quarterly Journal of Experimental Psychology, 49A,* 251- 262.

Byrne, M.D. (1998). Taking a computational approach to aging: The SPAN theory of working memory. *Psychology and Aging, 13,* 309- 322.

Camos, V., Barrouillet, P., & Fayol, M. (2001). Does the coordination of verbal and motor information explain the development of counting in children? *Journal of Experimental Child Psychology, 78,* 240- 262.

Camos, V., Fayol, M., & Barrouillet, P. (1999). Counting in children: Double task or procedure. *L'Annee Psychologique, 99,* 623- 645.

Cantor, J., Engle, R.W., & Hamilton, G. (1991). Short- term memory, working memory, and verbal abilities: How do they relate? *Intelligence, 15,* 229- 246.

Caplan, D., Rochon, E., & Waters, G. (1992). Articulatory and phonological determinants of word- length effects in span tasks. *Quarterly Journal of Experimental Psychology, 45A,* 177- 192.

Caramazza, A., & Hillis, A. (1990). Spatial presentation of words in the brain implied in the studies of a unilateral neglect patient. *Nature, 346,* 267- 269.

Caramazza, A., Miceli, G., Villa, G., & Romani, C. (1987). The role of the graphemic buffer in spelling: Evidence from a case of acquired dysgraphia. *Cognition, 26,* 59- 85.

Carella, J., & Hale, S. (1994). The rise and fall in information- processing rates over the life span. *Acta Psychologia, 86,* 109- 197.

Carrier, L.M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning, Memory and Cognition, 21,* 1339-1348.

Case, R. (1975). Gearing the demands of instruction to the developmental capacities of the learner. *Review of Educational Research, 45,* 59- 87.

Case, R., Kurland, D.M., & Goldberg, J. (1982). Operational efficiency and the growth of short- term memory span. *Journal of Experimental Child Psychology, 33,* 386- 404.

Cataldo, M.G., & Cornoldi, C. (1998). Self- monitoring in poor and good reading comprehenders and their strategy use. *British Journal of Developmental Psychology, 16,* 155-165.

Cermak, L.S., & Tarlow, S. (1978). Aphasic and Amnesic patients verbal vs non-verbal retention abilities. *Cortex, 14,* 32- 40.

Chen, C., & Stevenson, H.W. (1988). Cross- linguistic differences in digit span of preschool children. *Journal of Experimental Child psychology, 46,* 150- 158.

Clark, H.H., & Clark, E.V. (1987) *Psychology and Language.* New York: Harcourt Brace.

Coates, R., Sanderson, K., Hamilton, C.J., & Heffernan, T. (1999). Identifying differential processes in visuo-spatial working memory. *Proceedings of the British Psychological Society, 7,* 38.

Colle, H.A., & Welsh, A. (1976). Acoustic masking in primary memory. *Journal of Verbal learning and Verbal behaviour, 15,* 17- 32.

Conlin, J.A., Gathercole, S.E., & Adams, J.W. (in press). Children's working memory: Investigating performance limitations in complex span tasks. *Journal of Experimental Child Psychology.*

Conrad, R. (1964). Acoustic confusions in immediate memory. *British Journal of Psychology, 55,* 75.

Conrad, R., & Hull, A.J. (1964). Information, Acoustic Confusion and memory span. *British Journal of Psychology, 55,* 429- 432.

Conway, A.R.A., Cowan, N., Bunting, M.F., Therriault, D., & Minkoff, S. (2002). A latent variable analysis of working memory capacity, short

term memory capacity, processing speed, and general fluid intelligence. *Intelligence, 30,* 163- 183.

Conway, A.R.A., & Engle, R.W. (1994). Working memory and retrieval: A resource- dependent inhibition model. *Journal of Experimental Psychology General, 123,* 354- 373.

Conway, A.R.A., & Engle, R.W. (1996). Individual differences in working memory capacity: More evidence for a general capacity theory. *Memory, 4,* 577- 590.

Cowan, N. (1992). Verbal memory span and the timing of spoken recall. *Journal of Memory and Language, 31,* 668- 684.

Cowan, N., Day, L., Saults, J.S., Keller, T.A., Johnson, T., & Flores, L. (1992). The role of verbal output time in the effects of word length on immediate memory. *Journal of Memory and Language, 31,* 1-17.

Cowan, N., & Kail, R. (1996). Covert processes and their development in short-term memory. In Gathercole, S.E. *Models of Short- Term Memory.* Hove, England: Psychology Press.

Cowan, N., Keller, T., Hulme, C., Roodenrys, S., McDougall, S., & Rack, J. (1994). Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects. *Journal of Memory and Language, 33,* 234- 250.

Cowan, N., Towse, J.N., Saults, J.S., Elliot, E.M., Lacey, J.F., Moreno, M.V., & Hitch, G.J. (2003). Children's working- memory processes: A response-timing analysis. *Journal of Experimental Psychology General, 132,* 113-132.

Cowan, N., Wood, N.L., Wood, P.K., Keller, T.A., Nugent, L.D., & Keller, C.V. (1998). Two separate verbal processing rates contributing to short- term memory span. *Journal of Experimental Psychology General, 127,* 141- 160.

Daneman, M., & Carpenter, P.A. (1980). Individual differences in working memory and reading. *Journal of Verbal learning and Verbal Behaviour, 19,* 450- 466.

Daneman, M., & Carpenter, P.A. (1983). Individual differences in integrating information between and within sentences. *Journal of Experimental Psychology: Learning, Memory and Cognition, 9,* 561- 583.

Daneman, M., & Case, R. (1981). Syntactic form, semantic complexity, and short- term memory: influences on children's acquisition of new linguistic structures. *Developmental Psychology, 17,* 367- 378.

Daneman, M., & Green, I. (1986). Individual differences in comprehending and producing words in context. *Journal of Memory and Language, 25,* 1- 18.

Daneman, M., & Merickle, P.M. (1996). Working memory and language comprehension: A meta- Analysis. *Psychonomic Bulletin and Review, 3,* 422- 433.

Daneman, M., & Stainton, M. (1991). Phonological recoding in silent reading. *Journal of Experimental Psychology: Learning, Memory and Cognition, 17,* 618- 632.

Daneman, M., & Tardiff, T. (1987). Working memory and reading skill re- examined. In Colthart, M. (Ed.), *Attention and performance X11: The Psychology of Reading.* Hillsdale, NJ: Erlbaum.

Dark, V.J., & Benbow, C.P. (1990). Enhanced problem translation and short-term memory: Components of mathematical talent. *Journal of Educational Psychology, 82,* 420- 429.

Dansereau, D.F., & Gregg, L.W. (1966). An information processing analysis of mental multiplication. *Psychonomic Science, 6,* 71-72.

De Beni, R., Palladino, P., Pazzaglia, F., & Cornoldi, C. (1998). Increases in intrusion errors and working memory deficits of poor comprehenders. *Quarterly Journal of Experimental Psychology, 51,* 305- 320.

Dehaene, S. (1992). Varieties of numberical abilities. *Cognition, 44,* 1- 42.

Dehaene, S., & Mehler, J. (1992). Cross- linguistic regularities in the frequency of number words. *Cognition, 43,* 1- 29.

De Jong, P.P. (1998). Working memory deficits of reading disabled children. *Journal of Experimental Child Psychology, 70(2),* 75- 96.

Della Sala, S., Gray, C., Baddeley, A.D., Allamano, M., & Wilson, L. (1999). Pattern span: A tool for unwelding visuo-spatial memory. *Neuropsychologia, 37,* 1189- 1199.

Della Sala, S., Gray, C., Baddeley, A.D., & Wilson, L. (1997). *The visual patterns test: A test of short- term visual recall.* Thames Valley Test company.

Dempster, F.N. (1985). Short- term memory development in childhood and adolescence. In C. J. Brainerd & M. Pressley (Eds.), *Basic Processes in Memory Development* (pp. 208- 248). New York: Springer Verlag.

Dempster, F.N. (1988). Retroactive interference in the retention of prose: A reconsideration and new evidence. *Applied Cognitive Psychology, 2,* 97- 113.

Dempster, F.N. (1993). Resistance to interference: Developmental changes in a basic processing dimension. In M.L. Howe, & R. Pasnak (Eds.), *Emerging themes in cognitive development, Vol 1: Foundations* (pp. 3-27). Springer- Verlag: New York.

Dempster, F.N., & Cooney, J.B. (1982). Individual differences in digit span, susceptibility to proactive interferences, and aptitude/ achievement test scores. *Intelligence, 6,* 399- 416.

Dempster, F.N., & Corkill, A. J. (1999). Interference and inhibition in cognition and behaviour: Unifying themes for educational psychology. *Educational Psychology Review, 11,* 1-88.

De Rammelaere, S., Stuyven, E., & Vandieredonck, A. (1999). The contribution of working memory resources in the verification of simple mental arithmetic sums. *Psychological Research, 62,* 72- 77.

De Rammelaere, S., Stuyven, E., & Vandieredonck, A. (2001). Verifying simple arithmetic sums and products: Are the phonological loop and central executive involved? *Memory and Cognition, 29,* 267- 273.

De Renzi, E & Nichelli, P. (1975). Verbal and nonverbal short- term memory impairment following hemispheric damage. *Cortex, 11,* 341-353.

DeStefano, D., & LeFevre, J. (2004). The role of working memory in mental arithmetic. *European Journal of cognitive Psychology, 16,* 353- 386.

Dollaghan, C., & Campbell, T. (1998). Nonword repetition and child language impairment. *Journal of Speech, Language and Hearing Research, 41,* 1136- 1146.

Done, D.J., & Mills, T.R. (1978). Learning, memory and reading disabilities. In M.M. Gruneberg, P.E. Morris, & R.N. Sykes (Eds.), *Practical Aspects of Memory*. London: Academic Press.

Dosher, B.A., & Ma., J. J. (1998). Output loss or rehearsal loop? Ouput- time versus pronunciation- time limits in immediate recall for forgetting- matched materials. *Journal of Experimental Psychology: Learning, Memory and Cognition, 24,* 316- 335.

Duff, S.C., & Logie, R.H. (2001). Processing and storage in working memory span. *The Quarterly Journal of Experimental Psychology, 54,* 31-48.

Duncan, J. (1987). Attention and Reading: Wholes and parts in shape recognition- A tutorial review. In M. Coltheart (Ed). *Attention and Performance X11: The psychology of reading* (pp 39- 62). Hillsdale NJ: Lawrence Erlbaum.

Duncan, J., Johnson, R., Swales, M., & Freer, C. (1997) Frontal lobe deficits after head injury: Unity and diversity of function. *Cognitive Neuropsychology, 14,* 713- 741.

Eddy, J.K., & Glass, A.L. (1981). Reading and listening to high and low imagery sentences. *Journal of Verbal Learning and Verbal Behaviour, 20,* 333- 345.

Edwards, J. & Lahey, M. (1998). Nonword repetitions of children with specific language impairment: Exploration of some explanations for their inaccuracies. *Applied Psycholinguistics, 19,* 279- 309.

Elbro, C. (1996). Early linguistic abilities and reading development: A review and a hypothesis. *Reading and Writing, 8,* 453- 485.

Elliot, C. D. (1983). *British Abilities Scales.* Windsor, England: NFER- Nelson.

Elliot, C.D., Smith, P., & McCulloch, K. (1997). *British Abilities Scale 11. Technical manual.* Windsor, UK: NFER- Nelson.

Ellis, A. (1979). Speech production and short- term memory. In J. Morton & J.C. Marshall (Eds.), *Psycholinguistic Series Vol. 2: Structures and Processes,* (pp. 157- 187). London: Paul Elek/Cambridge, MA: MIT Press.

Ellis, N.C., & Hennelley, R.A. (1980). A bilingual word length effect: Implications for intelligence testing and the relative ease of mental calculation in Welsh and English. *British Journal of Psychology, 71,* 43-52.

Ellis, N.C., & Large, B. (1988). The early stages of reading: A longitudinal study. *Applied Cognitive Psychology, 2,* 47- 76.

Ellis Weismer, S., Tomblin, B., Zhang, X., Buckwalter, P., Chynoweth, J., & Jones, M. (2000). Nonword repetition performance in school- age children with and without specific language impairment. *Journal of Speech, Language and Hearing Research, 43,* 865- 878.

Emerson, M.J., & Miyake, A. (2003). The role of inner speech in task switching: A dual task investigation. *Journal of Memory and Language, 48,* 148-168.

Emerson, M.J., Miyake, A., & Rettinger, D.A. (1999). Individual differences in integrating and coordinating multiple sources of information. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25,* 1300-1321.

Engle, R.W., Cantor, J., & Collins, K.W. (1991). Individual differences in working memory capacity for comprehension and following directions. *Journal of Educational Research, 84,* 253- 262.

Engle, R.W., Cantor, J., & Curullo, J.J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory and Cognition, 18,* 972-992.

Engle, R.W., Kane, M.J., & Tuholski, S.W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In Miyake, A., and Shah, P. (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control.* New York: Cambridge Univ. Press.

Engle, R. W., Nations, J. K., & Cantor, J. (1990). Is 'working memory capacity' just another name for word knowledge? *Journal of Educational Psychology, 82,* 799- 804.

Engle, R.W., Tuholski, S.W., Laughlin, J.E., & Conway, A.R.A. (1999). Working memory, short- term memory, and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology General, 128,* 309- 331.

Ericsson, K.A., & Kintsch, W. (1995). Long- term working memory. *Psychological Review, 102,* 211- 245.

Espy, K. A. (1997). The shape school: Assessing executive function in preschool children. *Developmental Neuropsychology, 13,* 495- 499.

Espy, K. A., McDiarmid, M.M., Cwik, M.F., Stalets, M., Hamby, A., & Senn, T.E. (2004). The contribution of executive functions to emergent mathematical skills in preschool children. *Developmental Neuropsychology, 26,* 465-486.

Everatt, J., Warner, J., Miles, T.R., & Thomson, M.E. (1997). The incidence of Stroop interference in dyslexia. *Dyslexia, 3,* 222- 228.

Farah, M.J., Hammond, K.M., Levine, D.N., & Calvanio, R. (1988). Visual and Spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology, 20,* 439- 462.

Farrand, P., & Jones, D. (1996). Direction of report in spatial and verbal serial short- term memory. *Quarterly Journal of Experimental Psychology, 20,* 80- 115.

Fayol, M. (1999). From online management problems to strategies in written composition. In M. Torrence & G. Jeffery (Eds.), *The Cognitive Demands of Writing,* (pp. 13-23). Amsterdam: Amsterdam University Press.

Fayol, M., Largy, P., & Lemaire, P. (1994). Cognitive overload and orthographic errors : when cognitive overload enhances subject- verb agreement, a study in French written language. *Quarterly Journal of Experimental Psychology, 47,* 437- 464.

Fournet, N., Moreaud, O., Roulin, J.L., Naegele, B., & Pellat, J. (2000). Working memory function in medicated Parkinson's disease and the effects of withdrawal of dopaminergic medication. *Neuropsychology, 14(2),* 247- 253.

Friedman, N.P., & Miyake, A. (2000). Differential roles for visuospatial and verbal working memory in situation model construction. *Journal of Experimental Psychology General, 129,* 61-83.

Friedman, N.P., & Miyake, A. (2004a). The relations among inhibition and interference control functions: A latent variable analysis. *Journal of Experimental Psychology General, 133,* 101- 135.

Friedman, N.P., & Miyake, A. (2004b). The reading span test and its predictive power for reading comprehension. *Journal of Memory and Language, 31,* 136- 158.

Friedrich, F. J., Martin, R., & Kemper, S. J. (1985). Consequences of a phonological coding deficit on sentence processing. *Cognitive Neuropsychology, 2,* 385- 412.

Furst, A.J., & Hitch, G.J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Memory and Cognition, 28,* 774- 782.

Fuson, K.C. (1988). *Children's Counting and Concepts of Number.* New York: Springer- Verlag.

Fuson, K.C., & Hall, J.W. (1983). The acquisition of early number word meanings. In H. Ginsburg (Ed.), *The Development of Children's Mathematical Thinking* (pp. 49- 107). New York: Academic Press.

Fuson, K.C., Richards, J., & Briars, D.J. (1982). The acquisition and elaboration of number word sequence. In C. Brainerd (Ed.), *Progress in Cognitive Development: Children's Logical and Mathematical Cognition* (Vol. 1.) New York: Springer- Verlag.

Gallistel, C.R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition, 44,* 43- 74.

Garnett, K., & Fleischner, J.E. (1983). Automatization and basic fact performance of normal and learning disabled children. *Learning Disabilities Quarterly, 6,* 223- 230.

Gathercole, S.E. (1999). Cognitive approaches to the development of short- term memory. *Trends in Cognitive Sciences, 3,* 410- 419.

Gathercole, S.E., & Adams, A. (1993). Phonological working memory in very young children. *Developmental Psychology, 29,* 770- 778.

Gathercole, S.E., & Adams, A. (1994). Children's phonological working memory: Contributions of long- term memory and rehearsal. *Journal of Memory and Language, 33,* 672- 688.

Gathercole, S.E., & Alloway, T.P. (2004). Understanding working memory: A classroom guide.

www.psychology.dur.ac.uk/research/wm/myweb15/index.htm.

Gathercole, S.E., & Baddeley, A.D. (1989). Evaluation of the role of phonological STM in the development of vocabulary in children: A longitudinal study. *Journal of Memory and Language, 28,* 200- 213.

Gathercole, S.E., & Baddeley, A.D. (1990). The role of phonological memory in vocabulary acquisition: A study of young children learning new names. *British Journal of Psychology, 81,* 439- 454.

Gathercole, S.E., & Baddeley, A.D. (1993). *Working Memory and Language.* Hillsdale, NJ: Erlbaum.

Gathercole, S.E., Brown, L., & Pickering, S.J. (2003). Working memory assessments at school entry as longitudinal predictors of National Curriculum attainment levels. *Educational and Child Psychology, 20,* 109- 122.

Gathercole, S.E., Frankish, C.R., Pickering, S.J., & Peaker, S.H. (1999). Phonotactic influences on serial recall. *Journal of Experimental Psychology: Learning, Memory and cognition, 25,* 84- 95.

Gathercole, S.E., & Hitch, G.J. (1993). Developmental changes in short- term memory: A revised working memory perspective. In Collins, A.,

Gathercole, S.E., Conway, M.A., & Morris, P.E. *Theories of Memory*. Hillsdale, NJ: Erlbaum.

Gathercole, S.E., Hitch, G.J., Service, E., & Martin, A.J. (1997). Phonological short- term memory and new word learning in children. *Developmental Psychology, 33,* 966- 979.

Gathercole, S. E., Lamont, E., & Alloway, T. (in press). Working memory in the classroom. In S. J. Pickering (Ed) *Working Memory and Education*. Elsevier Press.

Gathercole, S.E., & Pickering, S.J. (2000). Working memory deficits in children with low achievement in the national curriculum at 7 year of age. *British Journal of Educational Psychology, 70,* 177-194.

Gathercole, S.E., Pickering, S.J., Knight, C., & Stegmann, Z. (2004). Working memory skills and educational attainment: Evidence from national curriculum assessments at 7 and 14 years of age. *Applied Cognitive Psychology, 18,* 1- 16.

Gathercole, S.E., Service, E., Hitch, G.J., Adams, A.M., & Martin, A.J. (1999). Phonological short- term memory and vocabulary development: Further evidence of the nature of the relationship. *Applied Cognitive Psychology, 13,* 65-77.

Gathercole, S.E., Willis, C., & Baddeley, A.D. (1991). Differentiating phonological memory and awareness of rhyme: Reading and vocabulary development in children. *British Journal of Psychology, 82,* 387- 406.

Gathercole, S.E., Willis, C., Emslie, H., & Baddeley, A.D. (1991). The influences of syllables and wordlikeness on children's repetition of non- words. *Applied Psycholinguistics, 12,* 349- 367.

Gathercole, S.E., Willis, C., Emslie, H., & Baddeley, A.D. (1992). Phonological memory and vocabulary development during the early school years: A longitudinal study. *Developmental Psychology, 28,* 887- 898.

Gavens, N., & Barrouillet, P. (2004). Delays of retention, processing efficiency, and attentional resource in working memory span development. *Journal of Memory and Language, 51,* 644- 657.

Geary, D.C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin, 114,* 345- 362.

Geary, D.C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities, 37,* 4- 15.

Geary, D.C., Hamson, C.O., & Hoard, M.K. (2000). Numerical and arithmetical cognition: A longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology, 77,* 236- 263.

Geary, D.C., Hoard, M.K., & Hamson, C.O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for mathematical disability. *Journal of Experimental Child Psychology, 74,* 213- 239.

Geary, D.C., & Widaman, K.F. (1987). Individual differences in cognitive arithmetic. *Journal of Experimental Psychology General, 116,* 154- 171.

Gelman, R., & Meck, E. (1983). Preschooler's counting: Principles before skills. *Cognition, 13,* 343- 359.

Gernsbacher, M.A. (1989). Mechanisms that improve referential access. *Cognition, 32,* 99-156.

Gernsbacher, M.A. (1993). Less skilled readers have less efficient suppression mechanisms. *Psychological Science, 4,* 294- 298.

Gernsbacher, M.A., & Faust, M.E. (1991). The mechanism of suppression: A component of general comprehension skill. *Journal of Experimental Psychology: Learning, Memory and Cognition, 17,* 245- 262.

Glass, A.L., Eddy, J.K., & Schwanenflugel, J. (1980). The verification of high and low imagery sentences. *Journal of Experimental Psychology: Human Learning and Memory, 6,* 692- 704.

Goswami, U., & Bryant, P. (1990). *Phonological Skills and Learning to Read.* London: Erlbaum.

Gregg, V.H., Freedman, C.M., & Smith, D.K. (1989). Word Frequency, articulatory suppression and memory span. *British Journal of Psychology, 80,* 363- 374.

Groeger, J.A., Field, D., & Hammond, S.M. (1999). Measuring memory span. *International Journal of Psychology, 34,* 359- 363.

Gunter, B., Berry, C., & Clifford, B.R. (1981). Proactive interference effects with television news items: Further evidence. *Journal of Experimental Psychology, Human Learning and Memory, 7,* 480- 487.

Gunter, B., Clifford, B.R., & Berry, C. (1980). Release from proactive interference with television news items: Evidence for encoding dimensions within televised news. *Journal of Experimental Psychology, Human Learning and Memory, 6,* 216- 223.

Gupta, P. (2003). Examining the relationship between word learning, nonword repetition, and immediate serial recall in adults. *Quarterly Journal of Experimental Psychology, 56A,* 1213- 1236.

Haenggi, D., Kintsch, W., & Gernsbacher, M.A. (1995). Spatial situation models and text comprehension. *Discourse Processes, 19,* 173- 199.

Halford, G.S., Maybery, M.T., O'Hare, A.W., & Grant, P. (1994). The development of working memory capacity. *Child Development, 65,* 1338- 1356.

Hamilton, C.J., Coates, R.O., & Heffernan, T. (2003). What develops in visuo-spatial working memory development? *European Journal of Cognitive Psychology, 15,* 43- 69.

Handley, S.J., Capon, A, Copp, C. & Harper, C. (2002). Conditional reasoning and the Tower of Hanoi: The role of spatial and verbal working memory. *British Journal of Psychology, 93,* 501-518.

Hanley, J.R., Pearson, N.A., & Young, A.W. (1990). Impaired memory for new visual forms. *Brain, 113,* 1131- 1148.

Hanley, J.R., Young, A.W., & Pearson, N.A. (1991). Impairment of the visuo-spatial sketch pad. *Quarterly Journal of Experimental Psychology, 43A,* 101- 125.

Hanten, G., & Martin, R.C. (2000). Contributions of phonological and semantic short- term memory to sentence processing: Evidence from two cases of closed head injury in children. *Journal of Memory and Language, 43,* 335- 361.

Harnishfeger, K.K. (1995). The development of cognitive inhibition: Theories, definitions and research evidence. In F.N. Dempster & C.J. Brainerd (Eds.), *Interference and Inhibition in Cognition* (pp. 175-204). San Diego, CA: Academic Press.

Hasher, L., & Zacks, R.T. (1988). Working memory, comprehension and aging: A review and a new view. In G.H. Bower (Ed.). *The Psychology of Learning and Motivation: Advances in Research and Theory Vol 22* (pp. 193- 224). New York: Academic Press.

Hayes, J.R. (1973). On the function of visual imagery in elementary mathematics. In Chase, W.G.. *Visual Information Processing* (pp. 177- 214). New York: Academic press.

Hayes, D.P. (1988). Speaking and Writing: Distinct patterns of word choice. *Journal of Memory and Language, 27,* 572- 585.

Healy, A.F., & Nairne, J.S. (1985). Short- term memory processes in counting. *Cognitive Psychology, 17,* 417- 444.

Heathcote, D. (1994). The role of visual- spatial working memory in the mental addition of multi- digit addends. *Cahiers de Psychologie Cognitive, 13,* 207- 245.

Hecht, S.A. (2002). Counting on working memory in simple arithmetic when counting is used for problem solving. *Memory and Cognition, 30,* 447- 455.

Hecker, R., & Mapperson, B. (1997). Dissociation of visual and spatial processing in working memory. *Neuropsycholgia, 35,* 599- 603.

Hegarty, M., Mayer, R., & Monk, C. (1995). Comprehension of arithmetic word problems: A comparison of successful and unsuccessful problem solvers. *Journal of Educational Psychology, 87,* 18- 32.

Helland, T., & Asbjornsen, A. (2000). Executive functions in dyslexia. *Child Neuropsychology, 6,* 37- 48.

Henry, L.A. (1991). The effects of word- length and phonemic similarity in young children's short- term memory. *Quarterly Journal of Experimental Psychology, 43A,* 35- 52.

Henry, L.A. (2001). How does the severity of a learning disability affect working memory performance? *Memory, 9,* 233- 247.

Henson, R.N.A., Noris, D., Page, M.P.A., & Baddeley, A.D. (1996). Unchained memory: Error patterns rule out chaining models of immediate serial recall. *Quarterly Journal of Experimental Psychology, 49A* 80-115.

Hitch, G.J. (1978). The role of short- term working memory in mental arithmetic. *Cognitive Psychology, 10,* 303- 323.

Hitch, G.J., Halliday, M.S., & Littler, J.E. (1989). Item identification time and rehearsal as predictors of memory span in children. *Quarterly Journal of Experimental Psychology, 41A,* 321- 338

Hitch, G.J., Halliday, M.S., Schaafstal, A, M., & Schraagen, J.M.C. (1988). Visual working memory in young children. *Memory and Cognition, 16,* 120-132.

Hitch, G.J., & McAuley, E. (1991). Working memory in children with specific arithmetical learning difficulties. *British Journal of Psychology, 82,* 375-386.

Hitch, G.J., Towse, J.N., & Hutton, U. (2001). What limits children's working memory span: Theoretical accounts and applications for scholastic development. *Journal of Experimental Psychology General, 130,* 184-198.

Holligan, C., & Johnston, R.S. (1988). The use of phonological information by good and poor readers in memory and reading tasks. *Memory and Cognition, 16,* 522- 532.

Hooper, S.R., Swartz, C.W., Wakely, M. B., de Kruif, R.E.L., & Montgomery, J.W. (2002). Executive functions in elementary school children with and without problems in written expression. *Journal of Learning Disabilities, 35,* 57- 68.

Howard, L.A., Binks, M.G., Moore, A.P., & Playfer, J.R. (2000). The contribution of apraxic speech to working memory deficits in Parkinson's disease. *Brain and Language, 74,* 269- 288.

Howard, D., & Franklin, S. (1990). Memory without rehearsal. In G. Vallar and T. Shallice (Eds), *Neuropsychological Impairments of Short- Term Memory* (pp. 287- 319). Cambridge: Cambridge University Press.

Hu, L., & Bentler, P.M. (1999). Cut off criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modelling, 6,* 1-55.

Hue, C., & Ericsson, J. R. (1988). Short- term memory for Chinese characters and radicals. *Memory and Cognition, 16,* 196- 205.

Hulme, C., & Mackenzie, S (1992). *Working Memory and Severe Learning Difficulties.* Hove, UK: Lawrence Erlbaum Associates Ltd.

Hulme, C., Maughan, S., & Brown, G.D.A (1991). Memory for familiar and unfamiliar words: Evidence for a long- term memory contribution to short- term memory span. *Journal of Memory and Language, 30,* 685- 701.

Hulme, C., Newton, P., Cowan, N., Stuart, G., & Brown, G. (1999). Think before you speak: Pause, memory search and redintegration processes in verbal memory span. *Journal of Experimental Psychology: Learning, Memory and Cognition, 25,* 447- 463.

Hulme, C., & Roodenrys, S. (1995). Verbal working memory development and it's disorders. *Journal of Child Psychology and Psychiatry, 36,* 373- 398.

Hulme, C., Roodenrys, S., Schweickert, R., Brown, G.D.A., Martin, S., & Stuart, G. (1997). Word frequency effects on short-term memory tasks: Evidence for a redintegration process in immediate serial recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 1217-1231.

Hulme, C., Thomson, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short- term memory. *Journal of Experimental Child Psychology, 38,* 241- 253.

Hunt, E., Frost, N., & Lunneborg, C. (1973). Individual differences in cognition: A new approach to intelligence. In Bower, G., *The Psychology of Learning and Motivation.* New York: Academic Press.

Hutton, U.M.Z., & Towse, J.N. (2001). Short- term memory and working memory as indices of children's cognitive skills. *Memory, 9,* 383- 394.

Isaacs, E.B., & Vargha- Khadem, F (1989). Differential course of development of spatial and verbal memory span. *British Journal of Developmental Psychology, 7,* 377- 380.

Jarrold, C., & Baddeley, A.D. (1997). Short- term memory for verbal and visuospatial information in Down's syndrome. *Cognitive Neuropsychiatry, 2,*102- 122.

Jarrold, C., Baddeley, A.D., & Hewes, A.K. (1998). Verbal and non- verbal

abilities in the Williams Syndrome phenotype: Evidence for diverging

developmental trajectories. *Journal of Child Psychology and Psychiatry,*

39, 511- 523.

Jarrold, C., Baddeley, A.D., & Hewes, A.K. (1999). Genetically dissociated

components of working memory: Evidence from Down's and Williams

Syndrome. *Neuropsychologia, 37,* 637- 651.

Jarrold, C., Baddeley, A.D., & Hewes, A.K. (2000). Verbal short- term memory

deficits in Down Syndrome: A consequence of problems in rehearsal?

Journal of Child Psychology and Psychiatry, 40, 233- 244.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology,* Whole no. 89.

Johnston, R.S. (1982). Phonological coding in dyslexic readers. *British Journal*

of Psychology, 73, 455- 460.

Johnston, R.S., & Anderson, M. (1998). Memory span, naming speed, and

memory strategies in poor and normal readers. *Memory, 6,* 143- 163.

Johnston, R.S., Rugg, M.D., & Scott, T. (1987). Phonological similarity effects,

memory span and developmental reading disorders: The nature of the

relationship. *British Journal of Psychology, 78,* 205- 211.

Johnston, R.S., & McDermott, E.A. (1986). Suppression effects in rhyme

judgement tasks. *Quarterly Journal of Experimental Psychology, 38,* 111-

124.

Jonides, J., & Smith, E.E. (1997). The architecture of working memory. In M.D.

Rugg (Ed), *Cognitive Neuroscience* (pp. 243- 276). Cambridge MA: MIT

Press.

Jorm, A.F. (1983). Specific reading retardation and working memory: A review. *British Journal of Psychology, 74,* 311- 342.

Jurden, F.H. (1995). Individual differences in working memory and complex cognition. *Journal of Educational Psychology, 87,* 93- 102.

Just, M.A., & Carpenter, P.A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99,* 122- 149.

Kail, R. (2002). Developmental change in proactive interference. *Child Development, 73,* 1703- 1714.

Kail, R., & Hall, L.K. (2001). Distinguishing short- term memory from working memory. *Memory and Cognition, 29,* 1-9.

Kail, R., & Park, Y.A. (1994). Processing time, articulation time and memory span. *Journal of Experimental Child Psychology, 57,* 281- 291.

Kail, R., & Salthouse, T.A. (1994). Processing speed as a mental capacity. *Acta Psychologica, 96,* 199- 255.

Kamhi, A.G., & Catts, H.W. (1986). Toward an understanding of developmental language and reading disorders. *Journal of Speech and Hearing Research, 51,* 337- 347.

Kane, M. J., Hambrick, D. Z., Tuholski, S.W., Wilhelm, O., Payne, T.W., & Engle, R. W. (2004). The generality of working memory capacity: A latent- variable approach to verbal and visuo-spatial memory span and reasoning. *Journal of Experimental Psychology General, 133,* 189- 217.

Katz, R.B, & Shankweiler, D. (1985). Repetitive naming and the detection of word retrieval deficits in the beginning reader. *Cortex, 21,* 617- 625.

Kaye, D. B., deWinstanley, P., Chen, Q., & Bonnefil, V. (1989). Development of efficient arithmetic computation. *Journal of Educational Psychology, 81,* 467- 480.

Kellogg, R. T. (1996). A model of working memory in writing. In C. M. Levy, & S. Randall (Eds.), *The Science of Writing, Theories, Methods, Individual Differences, and Applications.* (pp. 47- 71). Mahwah, NJ: Erlbaum.

Kelter, S., Cohen, R., Engel, D., List, G., & Strohner, H. (1977). Verbal coding and visual memory in aphasics. *Neuropsychologia, 15,* 51- 60.

Kemps, E., De Rammelaere, S., & Desmet, T. (2000). The development of working memory: Exploring the complementarity of two models. *Journal of Experimental Child Psychology, 77,* 89- 109.

Kennedy, A. (1983). On looking in to space. In Rayner, K. *Eye movements in reading: perceptual and language processes.* Academic press.

Kibby, M.Y., Marks, W., Morgan, S., & Long, C.J. (2004). Specific impairment in developmental reading disabilities: A working memory approach. *Journal of Learning Disabilities, 37,* 349- 363.

Kintsch, W., & Van Dijk, T.A. (1978). Toward a model of text comprehension and production. *Psychological Review, 85,* 363- 394.

Kirchner, D., & Klatzky, R.L. (1985). Verbal memory and rehearsal in language- disordered children. *Journal of Speech and Hearing Disorders, 28,* 556- 565.

Klapp, S.T. (1976). Short- term memory as a response separation state. *Memory and Cognition 4,* 721- 729.

Klapp, S.T., Greim, D.M., & Marshburn, E.A. (1981). Articulation and the articulatory loop: Two names for the same mechanism or two distinct

components of short- term memory? In Log, J., & Baddeley, A. *Attention and Performance, IX* (pp. 459- 472). Hillsdale NJ: Lawrence Erlbaum.

Klenberg, L., Korkman, M., & Lahti- Nuuttila, P. (2001). Differential development of attention and executive functions in 3- to 12- year old Finnish children. *Developmental Neuropsychology, 20*, 407- 428.

Kline, R.B. (1998). *Principles and Practice of Structural Equation Modelling.* New York: Guilford.

Kouba, V.L., Brown, C.A., Carpenter, T.P., Lindquist, M.M., Silver, E.A., & Swafford, J.O. (1988). Results of the fourth NAEP assessment of mathematics: Number, operations and word problems. *Arithmetic Teaching, 35,* 14- 19.

Kreiner, D.S. (1992) Reaction time measures of spelling: Testing a two- strategy model of skilled spelling. *Journal of Experimental Psychology: Learning, Memory and Cognition, 18,* 765- 776.

Kyllonen, P.C. (1993). Aptitude testing inspired by information processing: A test of the four- sources model. *Journal of General Psychology, 120,* 375- 405.

Kyllonen, P.C., & Christal, R.E. (1990). Reasoning ability is (little more than) working memory capacity! *Intelligence, 14,* 389- 433.

Kyllonen, P.C., & Stephens, D.L. (1990). Cognitive abilities as determinants of success in acquiring logic skills. *Learning and Individual Differences, 2,* 129- 150.

Landauer, T.K. (1962). Rate of implicit speech. *Perceptual and Motor Skills, 15,* 646.

LaPointe, L.B., & Engle, R.W. (1990). Simple and complex word spans as

measures of working memory capacity. *Journal of Experimental*

Psychology: Learning, Memory, and cognition, 16, 1118-1133.

Law, D.J., Morrin, K.A., & Pelligrino, J.W. (1995). Training effects and working

memory contributions to skill acquisition in a complex coordination task.

Learning and Individual Differences, 7, 207- 234.

Lea, J., & Levy, C.M. (1999). Working memory as a resource in the writing

process. In M. Torrence and G. Jeffery (Eds.), *The Cognitive Demands of*

Writing, (pp. 63-82). Amsterdam: Amsterdam University Press.

Lebiere, C., & Anderson, J.R. (1998). Cognitive arithmetic. In J.R. Anderson &

C. Lebiere (Eds.), *Atomic Components of Thought* (pp. 297- 342).

Hillsdale, NJ: Erlbaum.

Lee, K., & Kang, S. (2002). Arithmetic operation and working memory:

Differential suppression in dual tasks. *Cognition, 83,* B63- B68.

LeFevre, J. (1998). Interactions among encoding, calculation, and production

strategies in the multiplication performance of Chinese- speaking adults.

Mathematical Cognition, 4, 47- 65.

LeFevre, J., Lei, Q., Smith- Chant, B., & Mullins, D. (2001). Multiplication by

eye and by ear for Chinese- speaking and English- speaking adults.

Canadian Journal of Experimental Psychology, 55, 277- 284.

Lehto, J. (1995). Working memory and school achievements in the ninth form.

Educational Psychology, 15, 271-281.

Lehto, J. (1996). Are executive Function Tests Dependent on Working Memory

Capacity? *The Quarterly Journal of Experimental Psychology, 49A ,* 29-

50.

Lehto, J.E., Juujarvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of

executive functioning: Evidence from children. *British Journal of*

Developmental Psychology, 21, 59- 80. .

Lemaire, P., Abdi, H., & Fayol, M. (1996). The role of working memory

resources in simple cognitive arithmetic. *European Journal of Cognitive*

Psychology, 8, 73- 103.

Lepine, R., Barrouillet, P., & Camos, V. (in press). What makes working

memory spans so predictive of high level cognition? *Psychonomic*

Bulletin and Review.

Levin, H.S., Fletcher, J.M., Kufera, J.A., Harward, H., Lily, M.A., Mendelsohn,

D., Bruce, D., & Eisenberg, H.M. (1996). Dimensions of cognition

measured by the Tower of London and other cognitive tasks in head-

injured children and adolescents. *Developmental Neuropsychology, 12,*

17- 34.

Levy, B.A. (1971). The role of articulation in auditory and visual short- term

memory. *Journal of Verbal Learning and Verbal Behaviour, 10,* 123-

132.

Levy, C.M., & Marek, P. (1999). Testing components of kellogg's

multicomponent model of working memory in writing: The role of he

phonological loop. In M. Torrence & G. Jeffery (Eds.), *The Cognitive*

Demands of Writing (pp. 25-41). Amsterdam: Amsterdam University

Press.

Lian, A., Karlsen, P.J., & Winsvold, B. (2001). A re-evaluation of the

phonological similarity effect in adults' short- term memory of words and

nonwords. *Memory, 9,* 281- 299.

Liberman, I.Y., Mann, V.A., Shankweiler, D., & Werfelman, M. (1982). Children's memory for recurring linguistic and non-linguistic material in relation to reading ability. *Cortex, 18,* 367- 375.

Liefooghe, B., Vandierendonck, A., Muyllaert, I., Verbruggen, F., & Vanneste, W. (in press). The phonological loop in task alternation and task repetition. *Memory.*

Lobley, K.J., Gathercole, S.E., & Baddeley, A.D. (2003). The phonological loop and complex memory span: A developmental analysis. Unpublished Manuscript.

Locke, J.L., & Scott, K.K. (1979). Phonetically mediated recall in the phonetically disordered child. *Journal of Communication Disorders, 12,* 125- 131.

Logan, G.D. (1976). Converging evidence for automatic perceptual processing in visual search. *Canadian Journal of Psychology, 30,* 193- 200.

Logan, G. D. (1994). On the ability to inhibit thought and action: A users guide to the stop- signal paradigm. In D. Dagenbach & T. H. Carr (Eds), *Inhibitory Processes in Attention, Memory, and Language* (pp. 189-239). San Diego; CA: Academic Press.

Logie, R.H. (1986). Visuo-spatial processing in working memory. *Quarterly Journal of Experimental Psychology, 38,* 229- 247.

Logie, R.H. (1989).Characteristics of visual short- term memory. *European Journal of Cognitive Psychology, 1,* 275- 284.

Logie, R.H. (1991). Visuo- spatial short- term memory: Visual working memory or visual buffer? In C. Cornoldi & M. McDaniel (Eds.), *Imagery and Cognition* (pp. 77- 102). Berlin: Springer- Verlag.

Logie, R.H (1995). *Visuo- spatial working memory.* Hove, UK: Lawrence Erlbaum.

Logie, R.H., & Baddeley, A.D. (1987). Cognitive processes in counting. *Journal of Experimental Psychology, 13,* 310- 326.

Logie, R.H., Della, Sala, S., Wynn, V., & Baddeley, A. (2000). Visual similarity effects in immediate serial recall. *Quarterly Journal of Experimental Psychology, 53A,* 626- 646.

Logie, R.H., Gilhooly, K.J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory and Cognition, 22,* 395- 410.

Logie, R.H., & Marchetti, C. (1991). Visuo- spatial working memory: Visual, Spatial, or central executive? In Logie, D.H., & Dennis, M. *Mental Images in Human Cognition.* Amsterdam: Elsevier.

Logie, R.H., & Pearson, D.G. (1997). The inner eye and the inner scribe of visuo- spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology.*

Lorsbach, T.C., Wilson, S., & Reimer, J. F. (1996). Memory for relevant and irrelevant information: Evidence for deficient inhibitory processes in language/ learning disabled children. *Contemporary Educational Psychology, 21,* 447- 466.

Lovatt, P.J., Avons, S.E., & Masterson, J. (2000). The word length effect and disyllabic words. *Quarterly Journal of Experimental Psychology, 53A,* 1- 22.

Lovett, M.C., Reder, L.M., & Lebiere, C. (1999). Modelling working memory in a unified architecture: An ACT-R perspective. In A. Miyake & P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance*

and Executive Control (pp. 135- 182). Cambridge: Cambridge University Press.

Luzatti, C., Vecchi, C., Agazzi, D., Cesa- Bianchi, M., & Vergani, C. (1998). A neurological dissociation between visual and spatial processing in mental imagery. *Cortex, 34,* 461- 469.

MacDonald, M.C., & Christiansen, M.H. (2002). Reassessing working memory. Comment on Just & Carpenter (1992) and Waters & Caplan (1996). *Psychological Review, 109,* 35- 54.

Mackay, D. J. (1970). Spoonerisms and the structure of errors in the serial order of speech. *Neuropsychologia, 8,* 323- 350.

Mann, V.A., Cowin, E., & Schoenheimer, J. (1989). Phonological processing, language comprehension, and reading ability. *Journal of Learning Disabilities, 22,* 76- 89.

Mann, V.A., Liberman, I.Y., & Shankweiler, D. (1980). Children's memory for sentences and word strings in relation to reading ability. *Memory and Cognition, 8,* 329- 335.

Margolin, D.I. (1984). The neuropsychology of writing and spelling: Semantic, phonological, motor and perceptual processes. *Quarterly Journal of Experimental Psychology, 36A,* 49- 489.

Martin, R.C. (1993). Short- term memory and sentence processing: Evidence from neuropsychology. *Memory and Cognition, 21,* 76- 183.

Martin, R.S., Lesch, M.F., & Bartha, M.C. (1999). Independence of input and output phonology in word processing and short- term memory. *Journal of Memory and Language, 41,* 3- 29.

Martin, R.C., & Romani, C. (1994). Verbal working memory and sentence comprehension: A multiple components view. *Neuropsychology, 8,* 506-523.

Martin, R.C., Shelton, J.R., & Yaffee, L.S. (1994). Language processing and working memory- neuropsychological evidence for separate phonological and semantic capacities. *Journal of Memory and Language, 33,* 83- 111.

Masson, M., & Miller, J. (1983). Working memory and individual differences in comprehension and memory of text, *Journal of Educational Psychology, 75,* 314- 318.

Mayberry, M.T., & Do, N. (2003). Relationships between facets of working memory and performance on a curriculum- based mathematics test in children. *Educational and Child Psychology, 20,* 77- 92.

Mayer, R.E., & Hegarty, M. (1996). The process of understanding mathematical problem solving. In R. J Sternberg & T. Ben- Zeev (Eds.), *The Nature of Mathematical Thinking* (pp. 29- 54). Mahwah, NJ: Erlbaum.

McCarthy, R.A., & Warrington, E.K. (1987a). The double dissociation of short-term memory for lists and sentences. *Brain, 110.* 1545- 1563.

McCarthy, R.A., & Warrington, E.K. (1987b). Understanding: A function of short- term memory? *Brain, 110,* 1565- 1578.

McCloskey, M. (1992). Cognitive mechanisms in numerical processing: Evidence from acquired dyscalculia. *Cognition, 44,* 107- 157.

McCloskey, M., Caramaza, A., & Basili, A. (1985). Cognitive mechanisms in number processing and calculation: Evidence from dyscalculia. *Brain and Cognition, 4,* 171- 196.

McCloskey, M. & Macaruso, P. (1995). Representing and using numerical information. *American Psychologist, 50,* 351- 363.

McCloskey, M., Sokol, S., & Goodman, R.A. (1986). Cognitive processes in verbal number production: Inferences from the performances of brain damaged subjects. *Journal of Experimental Psychology General, 115,* 307- 330.

McCutchen, D. (1996). A capacity theory of writing: Working memory in text composition. *Educational Psychology Review, 8,* 299-325.

McDougall, S., & Hulme, C. (1994). Short- term memory, speech rate and phonological awareness as predictors of learning to read. In C. Hulme and M. Snowling (Eds.), *Reading Development and Reading disabilities* (pp. 31- 44). London: Whurr.

McDougall, S., Hulme, C., Ellis, A., & Monk, A. (1994). Learning to read: The role of short- term memory and phonological skills. *Journal of Experimental Child Psychology, 58,* 112- 133.

McLean, J.F., & Hitch, .J. (1999). Working memory impairments in children with specific arithmetical learning difficulties. *Journal of Experimental Child Psychology, 74,* 240- 260.

McNeil, A.M., & Johnston, R.S. (2004). Word Length, phonemic, and visual similarity effects in poor and normal readers. *Memory and Cognition, 32,* 687- 695.

Menyuk, P., & Looney, P.L. (1976). A problem of language disorder. Length versus structure. In Morehead, D.M., & Morehead, E.A. *Normal and Deficient Child Language* (pp. 259- 279). Baltimore: MD University Park Press.

Miceli, G., Romani, C., Silveri, M.C., Villa, G., & Caramazza, A. (1985). The role of the graphemic output buffer in writing- evidence from a case of acquired dysgraphia. *Journal of Clinical and Experimental Neuropsychology, 7,* 152- 153.

Michas, I.C., & Henry, L.A. (1994). The link between phonological memory and vocabulary acquisition. *British Journal of Developmental Psychology, 12,* 147- 163.

Miller, H., & Bichsel, J. (2004). Anxiety, working memory, gender, and math performance. *Personality and Individual differences, 37,* 591-606.

Miyake, A. (2001). Individual differences in working memory: Introduction to the special section. *Journal of Experimental Psychology General, 130,* 163- 168.

Miyake, A., Emerson, M.J., Padeilla, F., & Ahn, J-C. (2004). Inner speech as a retrieval aid for task goals: The effects of cue type and articulatory suppression in the random task cuing paradigm. *Acta Psychologica, 115,* 123- 142.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). The Unity and Diversity of Executive Functions and Their contributions to Complex 'Frontal Lobe' Tasks: A Latent Variable Analysis. *Cognitive Psychology, 41,* 49-100.

Miyake, A., Friedman, N. P., Rettinger, D.A., Shah, P., & Hegarty, M. (2001). How are visuo-spatial working memory, executive functioning and spatial abilities related? A latent- variable analysis. *Journal of Experimental Psychology General, 130,* 621- 640.

Miyake, A., and Shah, P. (1999). Toward unified theories of working memory: Emerging general consensus, unresolved theoretical issues, and future research directions. In Miyake, A., and Shah, P. *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control.* New York, Cambridge Univ. Press.

Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved Mysteries of the Mind: Tutorial Essays in Cognition* (pp 94- 148). Hove UK: Erlbaum.

Montgomery, J. (1995). Examination of phonological working memory in specifically language impaired children. *Applied Psycholinguistics, 16,* 355- 378.

Montgomery, J. (2000a). Relation of working memory to off-line and real- time sentence processing in children with specific language impairment. *Applied Psycholinguistics, 21,* 117- 148.

Montgomery, J. (2000b). Verbal working memory and sentence comprehension in children with specific language impairment. *Journal of Speech, Language and Hearing Research, 43, 293- 308.*

Montgomery, J. (2002). Understanding the language difficulties of children with specific language impairments: Does working memory matter? *American Journal of Speech- Language Pathology, 11,* 77- 91.

Morais, J., Allegria, J., & Content, A. (1987). The relationships between segmental analysis and alphabetic literacy: An interactive view. *Cahiers de Psychologie Cognitive, 7,* 415- 438.

Morra, S. (1994). Issues in working memory assessment: Testing for M capacity. *International Journal of Behavioural Development, 17,* 143- 159.

Morrell, R.W., & Park, D.C. (1993). The effects of age, illustrations, and task variables on the performance of procedural assembly tasks. *Psychology and Ageing, 8,* 389-399.

Morris, N. (1987). Exploring the visuo-spatial sketchpad. *Quarterly Journal of Experimental Psychology, 39,* 409- 430.

Morris, N., & Jones, D.M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology, 81,* 111-121.

Morton, J. (1970). A functional model for memory. In Norman, D.A. *Models of Human Memory.* New York: Academic press.

Moyer, R.S., & Landauer, T.K. (1967). Time required for judgement of numerical inequality. *Nature, 215.* 1519- 1520.

Murdock, B.B. (1961). The retention of individual items. *Journal of Experimental Psychology, 62,* 618- 625.

Murray, D. (1965). Vocalization- at- presentation, with varying presentation rates. *Quarterly Journal of Experimental Psychology, 17,* 47- 56.

Murray, D. (1967). The role of speech responses in short- term memory. *Canadian Journal of Psychology, 21,* 263- 276.

Murray, D. (1968). Articulation and acoustic confusability in short- term memory. *Journal of Experimental Psychology, 78,* 679- 84.

Muth, K.D. (1991). Effects of cuing on middle- school students' performance on arithmetic word problems containing extraneous information. *Journal of Educational Psychology, 83,* 173- 174.

Nagy, W.E., & Anderson, R.C. (1984). How many words are there in printed school English? *Reading Research Quarterly, 19,* 304- 330.

Nation, K., Adams, J.W., Bowyer- Crane, C.A., Snowling, M.J. (1999). Working memory deficits in poor comprehenders reflect underlying language impairments. *Journal of Experimental Child Psychology, 73*, 139- 158.

Naveh- Benjamin, M., & Ayres, T.J. (1986). Digit span, reading rate, and linguistic relativity. *Quarterly Journal of Experimental Psychology, 38A*, 739- 751.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9*, 353- 383.

Neath, I., & Nairne, J.S. (1995). Word- length effects in immediate memory: Overwriting trace decay theory. *Psychonomic Bulletin and Review, 2*, 429- 441.

Nigg, J.T. (2000). On inhibition/ disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin, 126*, 220- 246.

Noel, M-P., Desert, M., Aybrun, A., & Seron, X. (2001). Involvement of short- term memory in complex mental calculation. *Memory and Cognition, 29*, 34- 42.

Nolan, K., & Caramazza, A. (1983). An analysis of writing in a case of deep dyslexia. *Brain and Language, 20*, 305- 328.

Norman, D.A., & Shallice, T. (1980). *Attention to Action: Willed and automatic control of behaviour.* CHIP document no. 99, Centre for human information processing, University of California, San Diego, La Jolla.

Oakhill, J., & Yuill, N. (1986). Pronoun resolution in skilled and less skilled comprehenders: effects of memory load and inferential complexity. *Language and Speech, 29*, 25- 37.

Oberauer, K., SüB, H. –M., Schulze, R., Wilhelm, O., & Wittmann, W.W. (2000). Working memory capacity- Facets of a cognitive ability construct. *Personality and Individual Differences, 29,* 1017- 1045.

Oberauer, K., SüB, H. –M., Wilhelm, O., & Wittmann, W.W. (2003). The multiple faces of working memory: Storage, processing, supervision, and coordination. *Intelligence, 31,* 167- 193.

Ormrod, J.E., & Cochran, K.F. (1988). Relationship of verbal ability and working memory to spelling achievement and learning to spell. *Reading Research and Instruction, 28,* 33- 43.

O'Shaughnessy, T., & Swanson, H.L. (1998). Do immediate memory deficits in students with learning disabilities in reading reflect a developmental lag or deficit? A selective meta- analysis of the literature. *Learning Disability Quarterly, 21,* 123- 148.

Ozonoff, S., & Jensen, J. (1999). Brief Report: Specific executive function profiles in three neurodevelopmental disorders. *Journal of Autism and Developmental Disorders, 29,* 171- 177.

Page, M.P.A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review, 105,* 761- 781.

Papagno, C., Valentine, T., & Baddeley, A.D. (1991). Phonological short- term memory and foreign- language vocabulary learning. *Journal of Memory and Language, 30,* 331- 374.

Papagno, C., & Vallar, G. (1992). Phonological short- term memory and the learning of novel words: The effect of phonological similarity and item length. *Quarterly Journal of Experimental Psychology, 44A,* 47- 67.

Papagno, C., & Vallar, G. (1995). Short- term memory and vocabulary in

polyglots. *Quarterly Journal of Experimental Psychology, 48A,* 98- 107.

Park, D.C., Lautenschlager, G., Hedden, T., Davidson, N., Smith, A.D., & Smith,

P. K. (2002). Models of visuospatial and verbal memory across the adult

lifespan. *Psychology and Ageing, 17,* 299- 320.

Pashler, H. (1998). *The Psychology of Attention.* Cambridge, MA: MIT Press.

Passolunghi, M.C., & Pazzaglia, F. (2004). Individual differences in memory

updating in relation to arithmetic problem solving. *Learning and*

Individual Differences, 14, 219- 230.

Passolunghi, M.C., & Siegel, L.S. (2001). Short- term memory, working

memory, and inhibitory control in children with difficulties in arithmetic

problem solving, *Journal of Experimental Child Psychology, 80,* 44-57.

Passolunghi, M.C., & Siegel, L.S. (2004). Working memory and access to

numerical information in children with disability in mathematics. *Journal*

of Experimental Child Psychology, 88, 348- 367.

Pearson, D.G., & Sahraie, A. (2003). Oculomotor control and the maintenance of

spatially and temporally distributed events in visuo-spatial working

memory. *Quarterly Journal of Experimental Psychology A, 56,* 1089-

1111.

Pennington, B.F., & Ozonoff, S. (1996). Executive functions and developmental

psychopathology. *Journal of Child Psychology and Psychiatry, 37,* 51-

87.

Perfetti, C.A., & Lesgold, A.N. (1977). Discourse comprehension and sources of

individual differences. In Just, M., and Carpenter, P. *Cognitive Processes*

in Comprehension. Hillsdale: Erlbaum.

Pesenti, M., Tzourio, N., Doroux, B., Samson, D., Beaudouin, V., Seron, X., & Mazoyer, B. (1998). Functional anatomy of mental calculation in a calculating prodigy. *Neuroimage, 7*, 822.

Phillips, W.A., & Christie, D.F.M. (1977). Interferences with visualization. *Quarterly Journal of Experimental Psychology, 29*, 637- 650.

Phillips, L.H., & Hamilton, C. (2001). The working memory model in adult aging research. In J. Andrade (Ed.), *Working Memory in Perspective*. UK: Psychology Press.

Pickering, S., & Gathercole, S. (2001). Working Memory Test Battery for Children (WMTB- C). London: The Psychological Corporation.

Pickering, S.J., Gathercole, S.E., Hall, M., & Lloyd, S. (2001). Development of memory for pattern and path: Further Evidence for the fractionation of visuo-spatial short- term memory. *Quarterly Journal of Experimental Psychology, 54A*, 397- 420.

Potter, M.C., & Levy, E.I. (1986). Spatial enumeration without counting. *Child Development, 39*, 265- 272.

Power, M.J. (1985). Sentence production and working memory. *Quarterly Journal of Experimental Psychology, 37*, 367- 386.

Qualifications and Curriculum Authority (2001). *Statutory tests standards and evaluations reports 1999-2001*. Retrieved from http:// www.qca.org.uk/ca/tests/standardsmain.asp #evaluation

Quinn, J.G. (1998). Interference effects in the visuo-spatial sketchpad. (In M. Denis, J Englekamp, & J.T.E. Richardson (Eds.), *Cognitive and Neuropsychological Approaches to Mental Imagery* (pp181- 189). Amsterdam: Martinus Nijhoff.

Quinn, J.G., & McConnell, J. (1996). Irrelevant pictures in visual working memory. *Quarterly Journal of Experimental Psychology, 49A,* 200-215.

Quinn, J.G., & McConnell, J. (1999). Manipulation of interference in the passive visual store. *European Journal of Cognitive Psychology, 11,* 373- 389.

Raine, A., Hulme, C., Chadderton, H., & Bailey, P. (1991). Verbal short- term memory span in speech disordered children. *Child Development, 62,* 415- 423.

Ransdell, S., & Hecht, S. (2003). Time and resource limits on working memory: Cross- age consistency in counting span performance. *Journal of Experimental Child Psychology, 86,* 303- 313.

Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology, 83,* 274- 278.

Reuhkala, M. (2001). Mathematical skills in ninth- graders: Relationship with visuo-spatial abilities and working memory. *Educational Psychology, 21,* 387- 399.

Richardson, J.T.E. (1996). Evolving concepts of working memory. In J.T.E. Richardson, R.W. Engle, L. Hasher, R.H. Logie, E.R. Stoltzfus, & R.T. Zacks. (Ed.). *Working Memory and Human Cognition* (pp. 3-30). New York: Oxford University Press.

Rogers, R.D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology General, 124,* 207- 231.

Roodenrys, S., Hulme, C., & Brown, G. (1993). The development of short- term memory: Separable effects of speech rate and long- term memory. *Journal of Experimental Child Psychology, 56,* 431- 442.

Rosen, V.M., & Engle, R.W. (1997). The role of working memory capacity in retrieval. *Journal of Experimental Psychology General, 126,* 211- 227.

Rubenstein, H., Lewis, S.S., & Rubenstein, M.A. (1971). Homographic entries in the internal lexicon: effects of systemacity and relative frequency of meanings. *Journal of Verbal Learning and Verbal Behaviour, 10,* 57- 62.

Russell, J., Jarrold, C., & Henry, L. (1996). Working memory in children with autism and with moderate learning difficulties. *Journal of Child Psychology and Psychiatry, 37,* 673- 686.

Saeki, E., & Saito, S. (2004). Effect of articulatory suppression on task- switching performance: Implications for models of working memory. *Memory, 12,* 257-271.

Saffran, E.M., & Marin, O.S.M. (1975). Immediate memory for word lists and sentences in a patient with deficient auditory short- term memory. *Brain and Language, 2,* 420- 433.

Saito, S., & Miyake, A. (2000). A systematic evaluation of six hypotheses regarding the reading span test. *Japanese Psychological Review, 43,* 387- 410.

Saito, S., & Miyake, A. (2004). On the nature of forgetting and the processing- storage relationship in reading span performance. *Journal of Memory and Language, 50,* 425- 443.

Salame, P., & Baddeley, A.D. (1982). Disruption of short- term memory by unattended speech – implications for the structure of working memory. *Journal of Verbal Learning and Verbal Behaviour, 12,* 150- 164.

Salame, P., & Baddeley, A.D. (1987). Noise, unattended speech and short- term memory. *Ergonomics, 30,* 1185- 1193.

Salthouse, T.A. (1995). Differential age- related influences on memory for verbal- symbolic and visual- spatial information. *Journal of Gerontology: Psychological Sciences, 50B,* 193- 201.

Salthouse, T.A., Babcock, R.L., & Shaw, R.J. (1991). Effects of adult age on structural and operational capacities in working memory. *Psychology and Ageing, 6,* 118- 127.

Salthouse, T.A., & Mitchell, D.R.D. (1989). Structural and operational capacities of integrative spatial ability. *Psychology and Aging, 4,* 18- 25.

Sallthouse, T.A., Mitchell, D.R.D., Skovonek, E., & Babcock, R.L. (1989). Effects of adult age and working memory on reasoning and spatial abilities. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 507- 516.

Salway, A.F., & Logie, R.H. (1995). Visuospatial working memory, movement control and executive demands. *British Journal of Psychology, 86,* 253- 269.

Scardamalia, M. (1981). How children code with the cognitive demands of writing. In C. H. Frederikson, and J. F. Dominic (Eds.). *Writing: The Nature, Development and Teaching of Written Communication, Vol 2.* (pp81- 104). Hillsdale, NJ: Erlbaum.

Scardamalia, M., & Bereiter, C. (1986). Research on written composition. In M. C. Wittrock (Ed.), *Handbook of research on teaching* (3rd Ed., pp. 778- 803). New York: Macmillan.

Schweickert, R., & Boruff, B. (1986). Short- term memory capacity: Magic number or magic spell? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12,* 419- 425.

Seitz, K., & Schumann- Hengsteler, R. (2000). Mental multiplication and working memory. *European Journal of Cognitive Psychology, 12,* 552- 570.

Seitz, K., & Schumann- Hengsteler, R. (2002). Phonological loop and central executive processes in mental addition and multiplication. *Psychologische Beitrage, 44,* 275- 302.

Senn, T.E., Espy, K.A., & Kaufmann, P.M. (2004). Using path analysis to understand executive function in preschool children. *Developmental Neuropsychology, 26,* 445- 464.

Seron, X., Pesenti, M., Noel, M-P., Deloche, G., & Cornet, J-A. (1992). Images of numbers or 'when 98 is upper left and 6 sky blue'. *Cognition, 44,* 159- 196.

Service, E. (1998). The effects of word length on immediate serial recall depends on phonological complexity, not articulatory duration. *Quarterly Journal of Experimental Psychology, 51A,* 283- 304.

Service, E., & Turpeinen, R. (2001). Working memory in spelling: Evidence from backwards typing. *Memory, 9,* 395- 421.

Seyler, D.J., Kirk, E.P., & Ashkraft, M.H. (2003). Elementary subtraction. *Journal of Experimental Psychology: Learning, Memory and Cognition, 29,* 1339- 1352.

Shah, P., & Miyake, A. (1996). The Separability of Working Memory Resources for Spatial Thinking and Language Processing: An Individual Differences Approach. *Journal of Experimental Psychology General, 125,* 4- 27.

Shallice, T., & Butterworth, B. (1977). Short- term memory impairment and spontaneous speech. *Neuropsychologia, 15, 729- 735.*

Shallice, T., & Warrington, E.K. (1970). Independent functioning of the verbal memory stores: A neuropsychological study. *Quarterly Journal of Experimental Psychology, 22,* 261- 273.

Shankweiler, D., & Crain, S. (1986). Language mechanisms and reading disorder- a modular approach. *Cognition, 24,* 139- 168.

Shankweiler, D., Liberman, I.Y., Mark, L.S., Fowler, C.A., & Fischer, F. (1979). The speech code and learning to read. *Journal of Experimental Psychology: Human Learning and Memory, 5,* 531- 545.

Shiffrin, R., & Schneider, W. (1977). Controlled and automatic information processing: Perceptual learning, automatic handling, and a general theory. *Psychological Review, 87,* 122- 190.

Shute, V.J. (1991). Who is likely to acquire programming skills? *Journal of Educational Computing Research, 7,* 1- 24.

Siegel, L.S., & Linder, B.A. (1984). Short- term memory processes in children with reading and arithmetic learning disabilities. *Developmental Psychology, 20,* 200-207.

Siegel, L.S., & Ryan, E.B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. *Child Development, 60,* 973- 980.

Siegler, R.S., & Shrager, J. (1984). Strategy choices in addition and subtraction: How do children know what to do? In C. Sophian (Ed.), *Origins of Cognitive Skills.* Hillsdale, NJ: Erlbaum.

Sikora, D.M., Haley, P., Edwards, J., & Butler, R.W. (2002). Tower of London test performance in children with poor arithmetic skills. *Developmental Neuropsychology, 21,* 243- 254.

Smith, E.E., Jonides, J., & Kroeppe, R.A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6,* 11-20.

Smith, M.M., & Scholey, K.A. (1992). Determining spatial span: The role of movement time and articulation rate. *Quarterly Journal of Experimental Psychology, 45A,* 479- 501.

Smyth, M. M., Pearson, N. A., & Pendleton, L. R. (1988). Movement and working memory: Patterns and positions in space. *Quarterly Journal of Experimental Psychology, 40A,* 497- 514.

Smyth, M.M., & Pendleton, L.R. (1989). Working memory for movements. *Quarterly Journal of Experimental Psychology, 41A,* 235- 250.

Smyth, M.M., & Scholey, K.A. (1994). Interference in spatial immediate memory. *Memory and Cognition, 22,* 1-13.

Snowling, M. (1991). Developmental reading disorders. *Journal of Child Psychology and Child Psychiatry, 32,* 49- 77.

Sokol, S., McCloskey, M., Cohen, N.J., & Aliminosa, D. (1991). Cognitive representations and processes in arithmetic: Inferences from the performance of brain damaged subjects. *Journal of Experimental Psychology: Learning, Memory and Cognition, 17,* 355- 376.

Stage, S. A., & Wagner, R. K. (1992). Development of young children's phonological and orthographic knowledge as revealed by their spelling. *Developmental Psychology, 28,* 287- 296.

Stanovic, K.E., & Siegel, L.S. (1994). Phenotypic performance profile of children with reading disabilities- a regression based test of the phonological- core variable- difference model. *Journal of Educational Psychology, 86,* 24- 53.

Sternberg, S., Monsell, S., Knoll, R.L., Wright, C.E. (1978). The latency and duration of rapid move sequences: Comparisons of speech and type writing. In Stelmach, G.E., Information processing and motor control and learning. New York: Academic press.

Sternberg, S., Wright, C.E., Knoll, R.S., & Monsell, S. (1980). Motor programs in rapid speech: Additional evidence. In R.A. Cole (Ed.), *Perception and Production of Fluid Speech* (pp 469- 505). Hillsdale, NJ: Erlbaum.

Stolzfus, E.R, Hasher, L., & Zacks, R. (1996). Working memory and aging: Current status of the inhibition view. In J.T.E. Richardson, R.W. Engle, L. Hasher, R.H. Logie, E.R. Stolzfus, & R.T. Zacks (Eds.). *Working Memory and Human Cognition* (pp 68- 88). New York: Oxford University Press.

Stothard, S.E., & Hulme, C. (1992). Reading Comprehension difficulties in children: The role of language comprehension and working memory skills. *Reading and Writing, 4,* 245- 256.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643- 662.

Stuss, D.T., Shallice, T., Alexander, M.P., & Picton, T.W. (1995). A multidisciplinary approach to anterior attentional functions. *Annals of the New York Academy of Sciences, 769,* 191- 211.

SüB, H. –M., Oberauer, K., Wittmann, W. W., Wilhelm, O. & Schulze, R. (2002). Working- memory capacity explains reasoning ability – and a little bit more. *Intelligence, 20,* 261- 288.

Swanson, H.L. (1987). Verbal coding deficits in learning- disabled readers: Remembering pictures and words. In H.L. Swanson (Ed.), *Memory and*

Learning Disabilities (Advances in learning and behavioural disabilities,

Suppl. 2, pp. 123- 4314). Greenwich, CT: JAI Press.

Swanson, H.L. (1993). Working memory in learning disability subgroups.

Journal of Experimental Child Psychology, 56, 87- 114.

Swanson, H.L. (1994). Short- term memory and working memory: Do both

contribute to our understanding of academic achievement in children and

adults with learning disabilities? *Journal of Learning disabilities, 27,* 34-

50.

Swanson, H. L. (1996). Individual and age- related differences in children's

working memory. *Memory and Cognition, 24,* 70- 82.

Swanson, H. L. (1999). Reading comprehension and working memory in

learning- disabled readers: Is the phonological loop more important than

the executive system? *Journal of Experimental Child Psychology, 72,* 1-

31.

Swanson, H. L. (2003). Age- related differences in learning disabled and skilled

readers' working memory. *Journal of Experimental Child Psychology,*

85, 1-31.

Swanson, H.L. (2004). Working memory and phonological processing as

predictors of children's mathematical problem solving at different ages.

Memory and Cognition, 32, 648- 661.

Swanson, H. L., & Alexander, J. E. (1997). Cognitive processes as predictors of

word recognition and residing comprehension in learning- disabled and

skilled readers: Revisiting the specificity hypothesis. *Journal of*

Educational Psychology, 89, 128- 158.

Swanson, H.L., & Ashbaker, M.H. (2000). Working memory, short- term
memory, speech rate, word recognition and reading comprehension in
learning disabled readers: Does the executive system have a role?
Intelligence, 28, 1-30.

Swanson, H.L., Askbaker, M.H., & Lee, C. (1996). Learning- Disabled Readers'
working memory as a function of processing demands. *Journal of
Experimental Child Psychology, 61,* 242- 275.

Swanson, H.L., & Berniger, V.W. (1995). Working memory as a source of
individual differences in children's writing. In E. Butterfield (Ed.),
Children's Writing: Toward a Process Theory of Skilled Writing (pp. 31-
35). Greenwich, CT: JAI Press.

Swanson, H.L., & Berniger, V.W. (1996a). Individual differences in children's
working memory and writing skill. *Journal of Experimental Child
Psychology, 63,* 358- 385.

Swanson, H.L., & Berniger, V.W. (1996b). Individual differences in children's
writing: A function of working memory or reading or both processes?
Reading and Writing, 8, 357- 383.

Swanson, H.L., Cooney, J.B., & Brock, S. (1993). The influence of working
memory and classification ability on children's word problem solution.
Journal of Experimental Child Psychology, 55, 374- 395.

Swanson, H.L., Cooney, J., & O'Shaughnessy, T. (1998). Memory. In B. Wong
(Ed), *Understanding Learning Disabilities,* (pp 107- 162). San Diego,
CA: Academic Press.

Swanson, H.L., & Howell, M. (2001). Working memory, short- term memory, and speech rate as predictors of children's reading performance at different ages. *Journal of Educational Psychology, 93,* 720- 734.

Swanson, H.L., & Sachse- Lee, C. (2001). A subgroup analysis of working memory in children with reading disabilities: Domain-general or domain-specific deficiency? *Journal of Learning disabilities, 34,* 249- 263.

Swanson, H.L., Saez, L., Gerber, M., & Leafstedt, J. (2004). Literacy and cognitive functioning in bilingual and nonbilingual children at or not at risk for reading disabilities. *Journal of Educational Psychology, 96,* 3-18.

Tabachnick, B.G., & Fidell, L.S. (1996). *Using multivariate statistics.* New York: HarperCollins.

Taylor, H.G., Lean, D., & Scwartz, S. (1989). Pseudoword repetition ability in learning disabled children. *Applied Psycholinguistic, 10,* 203- 219.

Thorn, A.S., & Gathercole, S.E. (1999). Language specific knowledge and short-term memory in bilingual and non-bilingual children. *Quarterly Journal of Experimental Psychology, 52A,* 303- 324.

Thorndyke, P.W. (1977). Cognitive structure in comprehension and memory of narrative discourse. *Cognitive Psychology, 11,* 82- 106.

Thorndyke, P.W., & Hayes- Roth, B. (1979). The use of schemata in the acquisition and transfer of knowledge. *Cognitive Psychology, 9,* 77- 110.

Torgeson, J.K. (1985). Memory processes in reading disabled children. *Journal of Learning Disabilities, 18,* 350- 357.

Towse, J.N., & Hitch, G.J. (1995). Is there a relationship between task demand and storage space in test of working memory capacity? *Quarterly Journal of Experimental Psychology, 48A,* 108- 124.

Towse, J.N., Hitch. G.J., & Hutton, U. (1998). A re-evaluation of working memory capacity in children. *Journal oF Memory and language, 39,* 195- 217.

Towse, J.N., Hitch. G.J., & Hutton, U. (2000). On the interpretation of working memory span in adults. *Memory and Cognition, 28,* 341-348.

Towse, J.N., Hitch. G.J., & Hutton, U. (2002). On the nature of the relationship between processing activity and item retention in children. *Journal of Experimental Child Psychology, 82,* 156- 184.

Towse, J.N., & Houston- Price, C.M.T. (2001). Combining representations in working memory: A brief report. *British Journal of Developmental Psychology, 19,* 319- 324.

Trbovich, P.L., & LeFevre, J. (2003). Phonological and visuo-spatial working memory in mental addition. *Memory and Cognition, 31,* 738- 745.

Treisman, A.M. (1991). Search, similarity, and integration of features between and within dimensions. *Journal of Experimental Psychology, Human Perception and Performance, 12,* 652- 676.

Treisman, A.M., & Gelade, G. (1980). A feature- integration theory of attention. *Cognitive Psychology, 12,* 97- 136.

Treisman, A.M., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 459- 478.

Tresch, M.C., Sinnamon, H.M., & Seamon, J.G. (1993). Double dissociation of spatial an object visual memory: Evidence from selective interference in intact human subjects. *Neuropsychologia, 31,* 211- 219.

Tuholski, S.W. (1997). Examining the relationships among attentional resources, working memory and fluid intelligence. Unpublished doctoral dissertation, University of South Carolina.

Tuholski, S.W., Engle, R.W., & Baylis, G.C. (2001). Individual differences in working memory capacity and enumeration. *Memory and Cognition, 29,* 484- 492.

Tymms, P. (1999). *Baseline Assessment and Monitoring in Primary Schools.* London: David Fulton.

Turner, M.L., & Engle, R.W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28,* 127- 154.

Vallar, G., & Baddeley, A.D. (1984). Phonological short- term store, phonological processing, and sentence comprehension: A neurological case study. *Cognitive Neuropsychology, 1,* 21- 141.

Vallar, G., & Shallice, T. (1990). *Neuropsychological impairments of short- term memory.* Cambridge: Cambridge University Press.

Van der Schoot, M., Licht, R., Horsley, T.M., & Sergeant, J.A. (2000). Inhibitory deficits in reading disability depend on subtype: guessers but not spellers. *Child Neuropsychology, 6,* 297- 312.

Van der Schoot, M., Licht, R., Horsley, T.M., & Sergeant, J.A. (2002). Fronto-central dysfunctions in reading disability depend on subtype: guessers but not spellers. *Developmental Neuropsychology, 22,* 533- 5642.

van der Sluis, S., de Jong, P.F., & van der Leij, A. (2004). Inhibition and shifting in children with learning deficits in arithmetic and reading. *Journal of Experimental Child Psychology, 87,* 239- 266.

van der Sluis, S., de Jong, P.F., & van der Leij, A. (in press). Executive functioning in children, and its relations with reasoning, reading, and arithmetic.

Varnhagen, C.K., Das, J.P., & Varnhagen, S. (1987). Auditory and visual memory span: Cognitive processing by TMR individuals with Down syndrome or other etiologies. *American Journal of Mental Deficiency, 91,* 398- 405.

Vicari, S., Carlesimo, A., & Caltagirone, C. (1995). Short- term memory in persons with intellectual disabilities and Down's syndrome. *Journal of Intellectual Disability Research, 39,* 532- 537.

Wagner, R.K., & Torgesen, J.K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101,* 192- 212.

Waters, G.S., & Caplan, D. (1996). The capacity theory of sentence comprehension: Critique of Just & Carpenter (1992). *Psychological Review, 103,* 761- 772.

Waters, G.S., Caplan, D., & Hildebrandt, N. (1987). Working memory and written sentence comprehension. In M. Coltheart (Ed) *Attention and Performance XII* (pp 531- 555). Hove, UK: Lawrence Erlbaum.

Waters, G.S., Caplan, D., & Hildebrandt, N. (1991). On the structure of verbal short- term memory and its functional role in sentence comprehension: Evidence from neuropsychology. *Cognitive Neuropsychology, 8,* 81- 126.

Waters, G.S., Komoda, M.K., & Arbuckle, T.Y. (1985). The effects of concurrent tasks on reading: Implications for phonological recoding. *Journal of Memory and Language, 24,* 27- 45.

Waters, G.S., Rochon, E., & Caplan, D. (1992). The role of high- level speech planning in rehearsal- evidence from patients with apraxia of speech. *Journal of Memory and Language, 31 (1),* 54- 73.

Welsh, M.L., Pennington, B.F., & Groisser, D.B. (1991). A normative developmental study of executive function- a window on prefrontal function in children. *Developmental Neuropsychology, 7,* 131- 149.

Weschler, D. (1974). *Weschler Intelligence Scale for Children- Revised.* Windsor, England: NFER-Nelson.

Widaman, K.F., Geary, D.C., Cormier, O., & Little, T.D. (1989). A componential model of mental addition. *Journal of Experimental Psychology: Learning, Memory and Cognition, 15,* 898- 919.

Willcutt, E.G., Pennington, B.F., Boada, R., Ogline, J.S., Tunick, R.A., Chhabildas, N.A., et al. (2001). A comparison of the cognitive deficits in reading disability and attention- deficit/ hyperactivity disorder. *Journal of Abnormal Psychology, 110,* 157- 172.

Willis, C.S., & Gathercole, S.E. (2001). Phonological short- term memory contributions to sentence processing in young children. *Memory, 9,* 349- 363.

Wilson, K.M., & Swanson, H.L. (2001). Are mathematics disabilities due to a domain- general or a domain- specific working memory deficit? *Journal of Learning Disabilities, 34,* 237- 248.

Wolford, G., & Hollingworth, S. (1974). Evidence that short- term memory is not the limiting factor in tachistoscopic full-report procedure. *Memory and Cognition, 2,* 796- 800.

Yntema, D. B. (1963). Keeping track of several things at once. *Human Factors, 5,* 7- 17.

Yuill, N., & Oakhill, J.V. (1991). *Children's Problems in Text Comprehension.* Cambridge, UK: Cambridge Univ. Press.

Yuill, N., Oakhill, J., & Parkin, A. (1989). Working memory, comprehension ability and the resolution of text anomaly. *British Journal of Psychology, 80,* 351- 361.

Zago, L., Pesenti, M., Mellet, E., Bricogne, S., Seron, X., Beaudoin, V., Lochon, P., Mazoyer, B., & Mazoyer, N. (1999). Functional anatomy of simple and complex mental calculation using PET. *Neuorimage, 6,* 325.

Appendices

Appendix 1: Example of the odd- one- out task at a list length of two
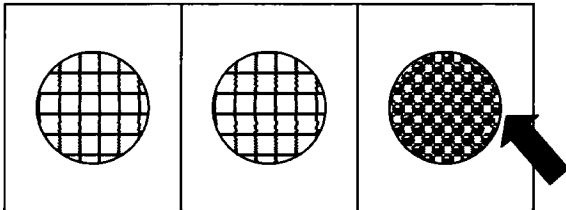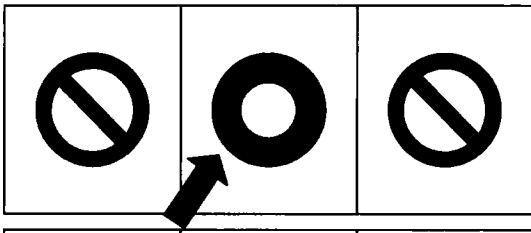
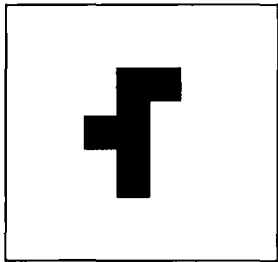Correct response
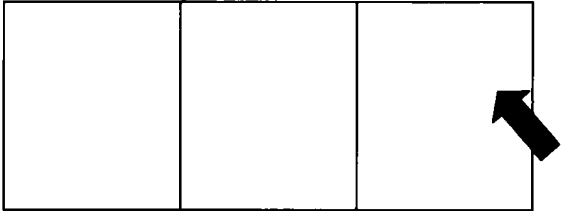
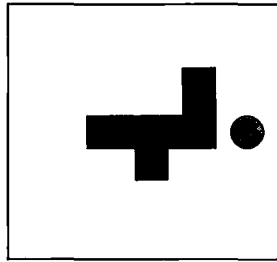Correct response
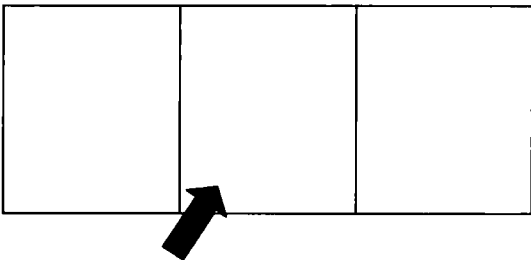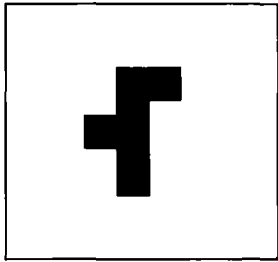
Correct response

Correct response

Appendix 11: Example of the spatial span task at a list length of two
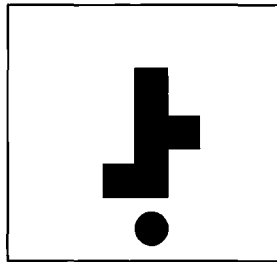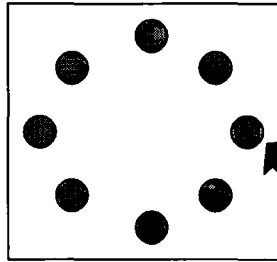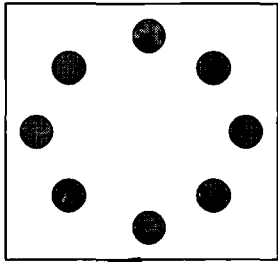

Correct response

'Normal'

Correct response

'Mirror Image'

Correct response for the

two locations