CENTRAL EXECUTIVE FUNCTIONS IN CHILDREN WITH SPECIFIC LANGUAGE IMPAIRMENT

by

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Abstract

The present study examined the phonological and visual components of working memory, both singly and within a dual-task presentation, in order to investigate the central executive functioning of children with Specific Language Impairment (SLI). Thirteen children with SLI (age 6;1 – 9;8) were matched by age to 11 children who showed normal language development (NL). Both groups completed a Nonword Repetition task (Dollaghan & Campbell, 1998) and a visual-spatial task requiring Memory for Locations. In the latter, children saw a 4 x 4 grid in which a given number of identical monsters were randomly placed. Following a 500 ms delay, children had to recall the positions of the monsters on a blank grid by pointing. Each child's span level was ascertained on each task and then the tasks were presented "simultaneously" *at the child's own level.* Children saw a 4 x 4 grid with a "span-level" number of monsters. The screen went blank for 5 seconds and the child repeated nonwords with a "span-level" number of syllables. Finally, an empty grid appeared and the child had to recall the monsters' positions. In a control condition, children recalled locations after a 5 sec delay with no word repetition. The results of the study indicated that children with SLI had significantly lower nonword repetition "spans" than children with NL, but showed only a nonsignificant difference in "spans" for visual locations. On the dual task, there was a significant decrement in visual task performance due to delay and a further significant decrement due to interference of auditory task, but no group differences in degree or pattern of decrement. The findings imply that the combined storage load from different modalities does call on the central executive for resource management, but that this may not be a source of difference between children with SLI and children with NL.

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1. Review of the Literature

The purpose of this study is to examine the role of the "central executive" as presented in the model of working memory proposed by Baddeley (1986). This central executive is postulated to coordinate information between two slave systems: the visuo-spatial sketchpad and the phonological loop. In this study we will use Baddeley's framework to examine working memory in children with specific language impairment (SLI), focusing in particular on the interaction or lack thereof between the two slave systems as a means of further exploring the role of the central executive in explaining language and cognitive problems in this population. Secondarily, the results of this study will also be used to comment on the Baddeley model itself.

In the sections to follow, Baddeley's theory of working memory will be introduced as well as two other central theories of working memory. Then, the components of Baddeley's model will be discussed. Finally, the research surrounding specific language impairment will be introduced specifically as it pertains to research on the three components of Baddeley's model of working memory.

1.1. Working Memory Models

This project seeks to examine the nature of the working memory abilities in children with SLI using the Baddeley (1986) framework. This model of working memory is only one of several prominent models in the field, including the "capacity" theory of Just and Carpenter (1992) and the connectionist model of MacDonald and Christensen (2002). These three models will be discussed and contrasted. The reason for choosing the Baddeley model for this project will also be highlighted.

1.1.1. Baddeley (1986)

According to Baddeley (1986) working memory is the system that temporarily stores and manipulates information that is necessary for complex cognitive tasks such as language comprehension, learning, and reasoning. The concept of working memory has evolved from the concept of a unitary short-term memory system. The model of Atkinson and Shiffrin (1971) provided the groundwork for the development of the concept of working memory. This "standard model" for memory, which includes encoding, storing, and retrieving information, consisted of three components: sensory registers, a short-term store, and a long-term store. The short-term store is discussed briefly due to its role in the development of a concept of working memory.

The short-term store of the Atkinson-Shiffrin model contains "control processes" that are assumed to be under the immediate control of the person and govern the flow of information in the memory system. According to this model, control processes vary across individuals and contexts because they are used all the time in some situations and only under special circumstances in others. "Rehearsal", the overt or covert repetition of information, and "coding", the process by which information to be remembered is put in the context of easily retrievable information, are examples of these control processes. Atkinson and Shiffrin emphasize that these control processes are optional in nature. They highlight the importance of the short-term store as the central component of the overall memory system as all information flows into and out of the short-term store. Their description of the purpose of the short-term store is the point at which Baddeley and Hitch (1974) suggest there are problems with this conceptualization.

Atkinson and Shiffrin suggest that the short-term store can be equated with "consciousness" in that thoughts and information which are currently in awareness are all part of the short-term store. They argue that as consciousness is equated with the short-term store and control processes are centered in and act through it, the short-term store can be considered a working memory. For them it is a system where decisions are made, problems are solved and the flow of information is directed. However, Baddeley and Hitch argue that it is problematic to think of the short-term store as a working memory due to evidence from neuropsychological studies. Shallice and Warrington (1970; Warrington & Shallice, 1969), for example, describe a patient who had a grossly defective short-term store but nonetheless had intact learning, memory and comprehension. If the short-term store is thought to act as a working memory then patients with short-term store deficits should be expected to show many other cognitive difficulties, including impaired long-term learning but, as stated, evidence suggests this is not the case.

Therefore, Baddeley and Hitch (1974) developed a model in which the working memory system consists of a "workspace" with separate storage and processing components. This division attempts to resolve the difficulties presented by the neuropsychological findings. For example, Baddeley and Hitch (1974) argue that there was no evidence to suggest that the short-term store is an essential function in comprehension and further, that the lack of comprehension deficits shown by patients with a grossly defective short-term store adds to this argument. However, Baddeley and Hitch argue that there is more to short term memory than is captured in the traditional notion of "short term store", and that it is these non-storage aspects of STM that *are* important in comprehension. They therefore propose a model of *working* memory to account for these and other findings. In order to show that this newly conceptualised version of short-term memory, i.e. working memory, is important in comprehension, they presented participants with a digit span task concurrently with a passage comprehension task. Participants were presented with a sequence of three or six digits and then asked to recall them. Meanwhile, the experimenter read the participants a passage. When the passage was completed, the digit span task was stopped and the experimenter read out the comprehension questions. There was found to be significantly lower comprehension scores on the six digit memory load condition than on a control condition, $t(14)=19.0$, $p < .05$ but this was not true for the three digit load condition, $t(14) = 44.5$, $p > .05$. The authors concluded that a six-item memory load reliably depresses comprehension.

Baddeley and Hitch (1974) argue that these findings from studies examining the use of short-term memory in comprehension as well as other studies examining reasoning and learning point to the existence of a working memory system, which plays a central role in human information processing. As eventually formulated, Baddeley's (1986) model of working memory is comprised of three main components, which work together: a *central executive* for processing information, and two auxiliary slave systems for storing information, the *phonological loop* and the *visuo-spatial sketchpad*. Although there is a certain lack of clarity on this point, the Baddeley model seems to place separate resource limits on its storage and processing functions, thus allowing for differences in storage and processing capabilities. Research on the three main systems that make up Baddeley's working memory model and related research on language impairment will be discussed further in a later section.

The *central executive* has proven useful in removing functions such as attentional control from the slave systems (Baddeley, 1998). For example, the classic phenomenon of selective attention enables attention to one stream of information while discarding others. In order to examine this aspect of attention, Baddeley (1996) examined visual detection 1) alone, 2) with irrelevant tones, 3) with instruction to respond to both circles and tones, and 4) with a requirement to switch between circles and tones on a given cue. He found that reaction time was slowed by the presence of an irrelevant signal on the other dimension, and also by the instruction to switch channels. He interprets these results as showing that focused selective attention is one function of the central executive. However, like Atkinson and Shiffrin's short-term store the most function of working memory is to transfer information to the long-term store.

According to Thorn and Gathercole (2000) the central tenets of the Baddeley (1986) working memory model are (1) that information in the auditory and visual modalities is served by separable systems, and (2) that storage and processing functions are also separable. These related characteristics are particularly important in distinguishing Baddeley's (1986) model from other prominent models in the field; namely the model of Just, Carpenter, and colleagues (Just & Carpenter, 1992; Daneman & Carpenter, 1980; MacDonald, Just, & Carpenter, 1992) and the most recent connectionist framework proposed by MacDonald and Christiansen (2002). As the purpose of this project is to examine central executive functions in children with SLI using the Baddeley (1986) model, very little attention will be given to these other models. However, a brief summary of their central points will be given in order to highlight the main characteristics of the Baddeley framework and justify its utility in exploring the working memory abilities of children with SLI.

1.1.2. Just and Carpenter (1992): an integrated working memory

Just and Carpenter (1992) propose a "capacity" theory of working memory. Unlike the model of Baddeley (1986), their *working memory* consists of a single integrated set of processes and resources. Baddeley's (1986) working memory has three components: two storage systems and the central executive. The Just and Carpenter (1992) model most closely corresponds to Baddeley's central executive and does not include modality-specific storage areas. It also takes into account not just item storage for retrieval at a later time but also the storage of partial results in complex sequential computations.

The Just and Carpenter (1992) model integrates the storage and processing functions of working memory. This integration is seen most clearly in their notion of "limited capacity". According to the "capacity" theory, storage and processing are fuelled by activation. Capacity is the maximum amount of activation available in working memory to support either of the two functions. Therefore, if the storage demands are large, the number of processes is large or the amount of activation the processes propagate exceeds the capacity, then the process attempts are scaled back to a level that keeps the total activation within the maximum bound. This creates a trading relation between storage and processing, the central feature of the "capacity" theory.

The Daneman memory task was devised as a measure of the trading relation between storage and processing, and therefore according to the "capacity" theory, is a measure of working memory (Daneman and Carpenter, 1980). In this task the participant is given a set of sentences to read or listen to, and, at the end of the set, is asked to recall the final word of each sentence. The number of sentences in the set is incremented from trial to trial and the participants reading or listening "span" is the maximum number of sentences he can read or listen to while maintaining perfect recall of final words. As participants are required to remember sentence final words (storage) at the same time they listen to sentences (processing), this task emphasizes an examination of integrated capacity. The storage and processing demands are assumed to be in a trading relationship.

The "capacity" theory was primarily devised to explain individual differences in language comprehension, and Just and Carpenter ultimately argue that the nature of a person's language comprehension depends on working memory. Individuals vary in the amount of activation they have available for meeting the computational and storage demands of language processing, and this difference predicts differences in speed and accuracy of language comprehension. In principle, however, this model could be extended to other cognitive tasks. Just and Carpenter (1992) themselves suggest that capacity theory may apply to cognitive domains other than language, such as problem solving, complex decision making and higher level visual information processing. They argue that these domains are amenable to capacity theory analysis because, like language, they involve sequential symbol manipulation. Support for this broader view comes from the fact that similar correlations are found when simple arithmetic, combined with word recall, is substituted for sentence processing in Daneman's experimental paradigm (Turner & Engle, 1989).

1.1.3. MacDonald and Christiansen (2002): Connectionist view

MacDonald and Christiansen (2002) put forward a third view of working memory. Contrary to Baddeley (1986) or Just and Carpenter (1992), MacDonald and Christiansen do not propose working memory as being separated from the representation of knowledge. Instead, they postulate a connectionist approach to cognitive processing in which the representation and processing of language or other sorts of knowledge are merely two aspects of the same (network) system. They argue further that neither knowledge nor capacity are cognitive primitives that can vary independently but rather that they emerge as system features from the interaction of network architecture and experience. A significant amount of individual difference in language processing ability results from differences in experience with language, and the biological differences that do exist are not in the capacity of a separate working memory. Therefore, MacDonald and Christensen do not make claims about the capacity of working memory nor do they make claims about its separability, as working memory is not thought to be separated from the knowledge network.

One interesting ramification of the MacDonald and Christiansen model is that it explains impairment in a different manner than any of the other theories of working memory. They state that any change would affect an entire connectionist network, and therefore, connectionist models do not treat aphasia or other deficits, such as language impairment in children, as being a deficit in either working memory capacity or linguistic knowledge. The authors state that working memory capacity and linguistic knowledge are inseparable in these networks and that any change will have effects on both the processing capacity of the network and the nature of the representations within the network.

1.1.4. Summary

The models summarized depart from the Baddeley (1986) model in three main features: 1) whether working memory is postulated as consisting of single or segmented components, 2) whether there are capacity limitations, and the scope of these limitations, and 3) whether working memory is separate from the knowledge network. Baddeley (1986) proposes segmented components in working memory that have different functions and roles. Specifically, the central executive is the controller while the phonological loop is responsible for the storage and maintenance of language information and the visuo-spatial sketchpad is responsible for storage and maintenance of visual images. Just and Carpenter (1992) in contrast, propose a single, integrated system that handles both storage and processing functions, and MacDonald and Christiansen do not speak to the single or separate status of memory components since working memory itself is postulated merely as a function of the knowledge network.

Second, while Baddeley claims that capacity on working memory tasks can predict a range of other cognitive skills, such as reading, comprehension, and reasoning, he seems not to make specific claims regarding limitations to capacity. Contrarily, Just and Carpenter's (1992) model centres on the capacity limitations of working memory. Third, Baddeley treats working memory as a higher order process that can influence linguistic and other knowledge. Contrarily, MacDonald and Christensen (2002) view neither knowledge nor capacity as primitives that can vary independently but rather postulate that they emerge from an interaction of network architecture and experience.

Specific language impairment (SLI) is defined as a deficiency in language concomitant with normal cognition (Leonard, 1998). However, current work (Johnston, 1999) suggests this traditional view may be too simplistic since, among other things, children with SLI evidence significant memory deficits. As we have just seen, the Baddeley model (Baddeley & Hitch, 1974; Baddeley, 1986) proposes a working memory that consists of three separable components: storage components for auditory and visual information, and a third coordinating component. It thus offers the possibility of examining working memory for language separate from working memory for visuo-spatial information, as well as processing functions separate from storage functions. This characteristic would seem to allow for a more detailed description of the memory deficits observed in SLI. In the terms of the model, an examination of central executive function in SLI could indicate, for example, whether children with SLI are impaired in only "phonological loop" functions or more broadly in the attentional control processes governing both the phonological loop and the visuo-spatial sketchpad. The Baddeley model also allows us to ask whether the storage function is impaired in one or both modalities. With this application in mind, the next sections will review research on the Baddeley model in more detail.

1.2. Baddeley (1986) Model

1.2.1. Phonological Loop

Baddeley (1986) describes the phonological loop as one of two slave systems subsidiary to the central executive, or control system. He assumed that the phonological loop was responsible for storing and maintaining speech-based information. These functions consisted of a *phonological store* that can hold acoustic or speech-based information for 1 to 2 seconds, and an *articulatory control process* which either maintains information within the phonological store by subvocal repetition, or takes visually presented material such as words or nameable pictures and registers them in the phonological store by subvocalization (Baddeley, 1986; Gathercole and Adams, 1994).

Although this system may be less important with simple, clearly presented material, the phonological store serves as a crucial backup system for comprehension of speech under taxing conditions. When demand placed on this slave system is minimal, little is required of the central executive, however, when demand on the slave system is great, the central executive is critical in resolving the problem of storage (Baddeley & Hitch, 1974).

Baddeley, Gathercole, and Papagno (1998) take a somewhat different view of the functions of the phonological loop. They argue that although the evidence for the existence of a phonological loop is strong, there is not an obvious reason why it is important for human cognition. They then postulate, based on research from normal adult participants, children, and neuropsychological patients, that the function of the phonological loop is not to remember familiar words but to help learn new words.

Investigators of the role of working memory in vocabulary learning have spent considerable energy developing appropriate methodologies. Gathercole and colleagues (Baddeley et al., 1998; Gathercole and Adams, 1994; Gathercole and Baddeley, 1989; Gathercole and Pickering, 1999 Gathercole, Service, Hitch, Adams, and Martin, 1999; and Gathercole, Willis, Emslie, and Baddeley, 1991) have explored tasks that investigate the capacity of the phonological loop. For example, Gathercole et al. (1991) examine the influence of number of syllables and wordlikeness on children's repetition of nonwords. Their results suggest that both phonological loop capacity, as measured by number of syllables successfully repeated, and linguistic characteristics such as wordlikeness, influence nonword repetition. They explain these findings by arguing that when a phonological representation of an unfamiliar sequence is constructed in phonological memory, it is supported by either an abstract phonological reference frame generated from structurally similar vocabulary items or by a specific lexical analogy. Nonword repetition is thus constrained by lexical factors as well as phonological memory ones.

Further research from Gathercole and Adams (1994) indicates that familiarity with memory stimuli facilitates memory performance for remembering an unfamiliar phonological sequence. They conclude that long-term knowledge about words contributes to the repetition of unfamiliar phonological forms.

Results from these studies suggest that in order for tasks such as nonword repetition to provide valid measures of working memory for phonological information that are not constrained by long-term knowledge about words, it is important for nonwords to contain as few properties of real words as possible. In order to identify other features of a task that would provide relatively pure estimates of the capacity of short-term auditory store, Gathercole and Pickering (1999) compare the value of two techniques. A previous study (Gathercole, Pickering, Hall, & Peaker, 1999) had found little difference in the accuracy of serial recognition for lists composed of either words or nonwords, indicating that long-term knowledge may not be tapped in serial *recognition* as strongly as in serial *recall*. Therefore, Gathercole & Pickering argue that serial recognition may be a valid measure of assessing the storage capacity of phonological short-term memory that minimizes the effect of long-term knowledge. In the ensuing study, the authors found that children's scores on two tests of immediate verbal memory, recall of nonwords composed of low-probability phoneme combinations and recognition of sequences of word and nonword stimuli were indeed highly correlated with each other. They conclude that this supports the validity of serial recall of low-probability nonwords as an additional, valid method of assessing the storage capacity of phonological short-term memory.

Using this method of research, Gathercole et al. (1999) went on to investigate working memory and development of vocabulary. They found that three measures of working memory for phonologically coded information (serial nonword recognition, nonword repetition, and digit span) predicted vocabulary knowledge. The authors examined eighteen children between the ages of 4 years 0 months and 4 years 3 months. They asked the children to complete three tests of phonological short-term memory, one vocabulary test and one test of non-verbal ability. The first memory test was nonword matching. For this task, the children listened to lists of nonwords varying in length from 1 to 4 nonwords long. The experimenter spoke two lists of nonwords and the child had to determine whether the lists were "same' or 'different'. Researchers measured both a span score, which was taken as the list below the list length where testing stopped, and the number of correct response to sequences across all list lengths. Second, the nonword repetition task was administered. The task consists of 40 nonwords, 10 each containing two, three, four and five syllables. Children were instructed to immediately repeat "funny, made-up words" given to them one at a time. Responses were scored as incorrect or correct for a total out of 40. Finally, a digit span task was administered in which the experimenter spoke aloud a sequence of digit, which the child attempted to repeat immediately in the same forward sequence. Two lists of digits were given at each list length, starting at length two. If the first two sequences at each length were correctly repeated, the length of the next list was increased by one and a further two lists were given. When a mistake was made a third list was given. Testing continued until the child failed to correctly repeat two out of a possible three lists. Span was scored as the maximum length at which the child correctly recalled at least two lists.

The researchers found correlations between all three phonological memory measures and the vocabulary measure: nonword repetition, $r(16) = .54, p < .05$; nonword recognition, $r(16) = .72, p < .001$; digit span, $r(16) = .67, p < .01$. The researchers also took a measure of articulation rate for the children, which was conducted 14 months later when the children had an average age of 5 years 3 months. The association between nonword repetition scores and vocabulary knowledge remained significant when differences associated with articulated rates were partialled out, $r(15) = .49, p < 0.05$. They conclude that short-term memory and vocabulary knowledge are independent of the speech output demands of the memory task and argue that this result is therefore consistent with the view that phonological short-term memory plays a crucial role in vocabulary acquisition.

In another study by Gathercole and colleagues, longitudinal data provide further support for the view that phonological memory contributes directly to vocabulary development (Gathercole & Baddeley, 1989). The investigators examined phonological memory by requiring children to repeat back nonwords of varying length and administered vocabulary tests at ages four and five. At both ages, the researchers found a significant and moderately high correlation between vocabulary and phonological memory score, age 4 ($r = .53$) and age 5 ($r = .57$). The authors concluded that the data clearly established a relationship between phonological memory and vocabulary knowledge since there was a stable association between vocabulary scores and nonword repetition performance that could not be attributed to intelligence or chronological age. Importantly, they found that repetition performance at age 4 is a significant predictor of vocabulary skills one year later, even when vocabulary scores at age 4 are partialled out. Gathercole and Baddeley argue that this indicates that nonword repetition performance is not simply a reflection of current vocabulary knowledge but rather that the phonological memory skills tapped by nonword repetition play a causal role in vocabulary development.

In summary, tests of nonword repetition provide valid measures of the capacity of the phonological loop. As well, relevant to the examination of working memory in SLI, these measures of working memory are found to be related to vocabulary development. However, success on tasks of nonword repetition can be influenced by linguistic knowledge and vocabulary if the nonwords are not carefully controlled. Measures of working memory capacity for phonological material are important for the study of the central executive in SLI as the phonological loop is one of the slave systems under the direction of the central executive. Deficits in the phonological loop are hypothesized to influence the central executive function as demands on the central executive are postulated to increase when the demands of the slave systems are stretched.

1.2.2. Visuo- spatial sketchpad

The visuo-spatial sketchpad is a second slave system postulated to be under the control of the central executive. While the phonological loop has undergone much exploration, the visuo-spatial sketchpad is the part of the model that is understood less well (Baddeley and Hitch, 1994). Baddeley (1986) proposes visuo-spatial memory as separate from phonological memory due to evidence from experiments using a dual-task paradigm. He states that imagery is disrupted by the requirement of performing a visuo-spatial task, such as tracking a spot of light moving on a screen. However, he finds that visuo-spatial memory, as tested by memory for complex chess positions found no disruption from a concurrent verbal task.

Baddeley and Hitch (1994) also find this same pattern of dual-task interference. They state, that as is the case with the phonological loop, selective interference effects provide a major source of evidence regarding the nature of the sketchpad. These interference effects lead them to the conclusion that visual imagery and visual perception share resources that are not used by the verbal system. In addition to evidence from dual-task studies, Baddeley and Hitch find further support for the separate status of visuo-spatial working memory from the dissociations found in neuropsychological evidence, e.g., the fact that patients with impairment of memory span for movements to different spatial locations can still have normal auditory-verbal memory spans.

The visuo-spatial sketchpad is conceived as a separate system, under the control of the central executive, that is responsible for representations of visual appearance that are organized at the level of objects (Baddeley & Hitch, 1994). They explain that the sketchpad is a workspace for loading and manipulating visuo-spatial information and suggest that the sketchpad may serve a wide range of functions, although they admit this is still somewhat speculative. They hypothesize that the sketchpad is involved in planning and executing spatial tasks, keeping track of changes in the visual perceptual world over time, maintaining orientation in space and directing spatial movement, and perhaps even in comprehending certain types of verbal information.

While the visuo-spatial sketchpad has been researched less well than the phonological loop there has been research done by Logie and colleagues and others (Logie, 1986; Logie, Della Sala, Wynn, & Baddeley, 2000; and Bruyer & Scailquin, 1998) to test this component within a multicomponent model of working memory (Baddeley, 1986). Logie (1986) provides an example of this literature. Logie investigated a technique for visual suppression in conjunction with tasks involving either visual (pegword mnemonic) or verbal (rote rehearsal) short-term processing and storage. Participants were given three tasks. The first was a task to rehearse presented words in an attempt to maintain the entire list. In this rehearsal task participants were encouraged to rehearse the presented word subvocally. They were given words one at a time with the list number preceding the word (e.g., one-book, two-dog, etc.). On presentation of the next pair, they were instructed to add this word to the previous word and rehearse the entire list. The second task involved rehearsal by visual imagery mnemonic, and subjects were instructed to create a visual image of each word from the list as it was presented by integrating it with the image of the item associated with the pegword. For example, if the pair was "one-book", the participant was to associate the number *one* with the rhyming word *bun* and form an interactive image of a book and a bun, e.g., a bun reading a book. In the third task participants were presented with a 3 x 3 matrix with boxes that were randomly filled or unfilled. Participants were asked to compare successively presented patterns, and press a response key only if the currently presented pattern was identical to the pattern presented immediately before. The author states that participants were specifically asked to avoid using verbal labels for the patterns, but also argue that labeling the patterns would have been difficult. This third task was presented as a secondary task to each of the other tasks in a dual-task paradigm. The results from the three tasks suggested that the pattern-matching task differentially affected the use of a visual imagery mnemonic more than the rote verbal rehearsal. This finding again supports the separability of visual and verbal memory. However, the investigators also found an overall drop in recall totals in both the imagery mnemonic and rote verbal rehearsal conditions, suggesting that there was also a resource in common with the matching task. These results seem to support the view that even if visual and verbal memory are separate components they may share common resources.

This experiment leads to two important conclusions relevant for the present investigation. First, regarding the issue of separate components, Logie's results are consistent with the notion of a specialized visuo-spatial sketchpad involved in both the visual processing (pattern matching) task and the imagery mnemonic. Second, regarding the issue of common resource, Logie concludes that within the working memory framework, a prime candidate for the resource common to both memory conditions is the central executive.

1.2.3. Central executive

The research on the two slave systems, while providing evidence for their separateness also suggests that there is a resource common to both. As it is the focus of the current study, Baddeley's (1986) conceptualization of this central component invites discussion. Baddeley and Hitch's (1974) early conception of working memory posited that there is a central executive component to working memory that is involved in control. They state that when memory load does not exceed capacity, little demand is placed on the central executive. However, when capacity is exceeded, the executive component must devote time to the problem of storage. Later, Baddeley (1986) also posited that the central executive is concerned with the attentional control of behaviour. Reflecting on these earlier comments, Baddeley and Hitch (1994) note that the central executive is the most complex but also the least well understood component of their working memory model. They state that they originally postulated this component as a part of the working memory model as a reminder of the importance of executive processes and the need to incorporate them in the model. Thus far, they have studied the central executive as it coordinates dual task performance, controls selective attention, selects retrieval strategies, and manipulates information from long term memory. They have not yet determined, however, whether these functions are carried out by a "unified system" or an "agglomeration of independent though interactive control processes" (Baddeley, 1996, p.5).

Thorn and Gathercole (2000), working within the Baddeley framework, provide perhaps the most explicit comments on the central executive. They state that the central executive is "a flexible but limited capacity processing resource which also serves as an interface between the two slave systems" (p. 419). They state further that the central executive should be viewed as a processing system that is not involved in temporary storage. They believe that the central executive is related to control activities such as the regulation of information flow, the control of action, planning and goal directed behaviour, and the retrieval of information from long-term memory.

Neither Thorn and Gathercole (2000) nor Baddeley (1996), however, make the scope of the posited capacity limitations entirely clear. On the one hand, they emphasize the separability of working memory components which would seem to suggest different resource pools for each of the storage systems and the central executive; on the other hand they present dual-task data that clearly indicate processing tradeoffs between the two slave systems and hence suggest a common resource pool.

This latter line of work is discussed in Baddeley (1998). Here he discusses some ways that the concept of the central executive has proven useful, which may in turn prove to be useful in an exploration of the central executive in children with SLI. He states that, among other things, the notion of the central executive has been useful in separating out attentional control from the slave systems, thus facilitating the further understanding of both phonological and visuo-spatial short-term memory. One population that has proved particularly useful in examining the central executive has been patients with Alzheimer's disease. These patients have been demonstrated to have a "dysexecutive syndrome", i.e., a marked deficit in central executive functioning (Baddeley, Logie, Bressi, Della Sela, and Spinnler, 1986). Researchers observed the ability of the patients to perform simultaneously two concurrent tasks. Patients with dementia of the Alzheimer's type (DAT) were compared to age-matched controls and young controls. The participants were required to combine performance on a tracking task with each of three concurrent tasks: a counting task with a constant rate of two numbers per second, a task involving simple reaction time to a tone, and an auditory digit span task involving repetition of a list of numbers. The level of difficulty of the tracking task and length of the digit sequences were both adjusted so that each participant worked at their own level and performance could be equated across the three groups. The investigators found that combining two tasks, even when they were equated between the groups for difficulty, produced a disproportionately large decrement in performance for the DAT patients. As noted above, despite their commitment to separable memory components, the authors conclude that this finding implicated the central executive since the DAT patients seemed to have particular difficulty in integrating and coordinating two concurrent tasks. As well as pointing to the possibility of a "dysexecutive syndrome", this study demonstrates the value of a particular methodological framework for testing central executive function, namely the dual-task paradigm. This subject will be revisited later in a discussion of the central executive in children with SLI.

1.3. Specific Language Impairment

Kail and Bisanz (1982) outline the core constructs of an information processing system and suggest areas that can change with development. They outline three major areas susceptible to change during development: cognitive processes, representations, and attentional resources. Cognitive processes undergo developmental change due to the change in procedures that children use. With increased development children learn and employ methods of solving problems that are both more sufficient and more efficient. Cognitive processes can also change in the speed at which each of the component processes are implemented. Representations undergo change in that there can be change in elements, for example new vocabulary items, or change in the relations between elements. There could also be a change from more perceptually based representations to more conceptually based representations. Attentional resources undergo change during development in that there may be an increased amount of attentional resources available for activating contents of the knowledge base. Kail and Bisanz suggest that because attentional resources are limited, an individual's performance on two simultaneous and attention-demanding tasks will deteriorate if the load imposed by one of the tasks increases.

Thorn and Gathercole (2000) suggest that all the components of working memory are present at an early age but that each goes through significant developmental changes across the early years. They state that working memory performance increases steeply up to eight years of age and reaches adult-like levels at around 11 or 12 years of age. Performance on complex working memory tasks involving both storage and processing functions shows a regular increase between the ages of 6 and 15 years. Thorn and

Gathercole suggest that developmental improvements are evidenced primarily in the central executive component of the working memory system, rather than the storage resources of the slave systems, as improvements appear to arise through increase in functional capacity rather than storage capacity. This would seem to be an instance of what Kail and Bisanz call a change in procedure or a change in available attentional resource.

Cowan (1997) states that it is clear that young children do not do as well as older children on tasks that directly measure aspects of working memory. Cowan describes the basic processes in working memory that appear to change. There are apparent developmental changes in knowledge, processing strategies, processing speed, the use of attention and processing capacity, passive memory loss over time, and passive memory storage capacity (see Cowan, 1997 for a review).

Recent work by Irwin-Chase and Burns (2000) indicates that these characterizations of the development of working memory may need further refinement. These researchers used a dual-task paradigm and, like Baddeley's study of Alzheimer's patients, equated task difficulty across children by determining single-task capacities prior to the dual-task presentation. They found no differences between 8 year olds and 11 year olds in the ability to perform two tasks simultaneously. In an extension of the experiment, the older children were better at allocating resources according to pre-set task priorities, but when the two tasks were equally important there were no age differences.

These developmental studies provide a second important context for the current investigation by posing a second possible outcome to studies of the central executive in children with SLI. Do these children with language impairment show dysexecutive problems similar to Baddeley's Alzheimer's' patients, or will the central executive prove to be a cognitive area in which developmental changes, and hence developmental delays, are not seen?

Children with specific language impairment have significant difficulties with language that can not be attributed to hearing problems, neurological status, nonverbal intelligence, or other known factors (Leonard, 1998). Johnston (1994) suggests that children with SLI pose an interesting paradox, language delays despite normal intelligence - at least as measured by traditional nonverbal intelligence tests. She further argues that in order to understand this paradox, the relationships between language and thought, or, more specifically, between verbal and nonverbal cognition must be considered. The interplay between cognition and language is invaluable as nonverbal, cognitive achievements help prepare toddlers to use words as symbolic tools of communication. However, later, this relationship shifts as language becomes a major instrument for mental representation and crucial for reasoning.

Upon review of the literature Johnston (1999) concludes that researchers have actually reported a wide array of cognitive difficulties in children with SLI. Specifically, research reports indicate that children with SLI have difficulties with perception, memory, attention, spatial cognition, conceptual development, and reasoning. Johnston (1994) argues that now that research has revealed that children with SLI do show deficits on cognitive tasks, the challenge for researchers is to understand the nature of the disorder that underlies these observations. The current study is designed to shed further light on the working memory deficits that have been reported.

In one recent study of working memory, Gillam, Cowan, and Marler (1998) manipulated input modality, response modality, and rate of stimulus presentation within a serial recall task in order to evaluate four possible hypotheses regarding the underlying deficiencies in children with SLI. The investigators examined whether working memory deficiencies were due to 1) operations underlying speech production, 2) difficulties in processing and retaining the acoustic information contained in auditory signals, 3) phonological coding deficits, characterized by difficulties converting non-linguistic information into verbal forms, or 4) a deficit in the ability to process information rapidly in time.

Gillam et al. (1998) conclude that their findings implicate the third of these factors, phonological coding. They explain that children with SLI may have difficulty retaining previously formed phonological codes during multiple mental operations or that they may avoid creating phonological representation unless such codes are necessitated by task requirements. Other researchers have explored the ability of children with SLI to utilize the phonological loop as a language-learning device as proposed by Baddeley et al. (1998) and have reached similar conclusions. Current work on the role of the phonological loop in specific language impairment will be reviewed in the following section

1.3.1. Working memory and SLI

1.3.1.1. Phonological loop and SLI.

Since it has been hypothesized that the phonological loop may be crucial in the learning of new words (Baddeley et al., 1998) explorations of this function in children with SLI were natural. Language-disordered children usually have difficulties learning new words (Gathercole, 1993). Gathercole (1993) suggests that since poor word learning plays a central role in the general profile of language deficits in SLI children it would be useful to examine the root of their word-learning difficulties.

As discussed previously, Gathercole and colleagues (Baddeley et al., 1998; Gathercole and Adams, 1994; Gathercole and Baddeley, 1989; Gathercole and Pickering, 1999; Gathercole et al., 1999; and Gathercole et al., 1991) have investigated the role of the phonological loop in vocabulary development. In addition to providing support for the view that phonological memory contributes directly to vocabulary development, Gathercole and Baddeley (1990a) demonstrated that language-disordered children were significantly poorer on nonword repetition tests than age-matched children.

In their study Gathercole and Baddeley (1990a) examined working memory capacity for phonological material in five language-disordered children and compared their performance to the performance of children of comparable nonverbal mental age, and also to that of younger children with normal language, matched on reading and vocabulary scores. The children ranged in age from 7:02 to 8:10 years. In their experiment the nonword repetition abilities of the language disordered, verbal control, and nonverbal control groups were compared. The experiment had two parts, the first part included 21 nonwords that were all one syllable in length, whereas in the second part consisted of 40 nonwords ranging from one to four syllables in length that contained either single consonants or consonant clusters. Children were asked to repeat the "funny made-up words" and each word was scored as correct or incorrect.

The repetition performance of the language-disordered children proved to be much poorer than the repetition of either of the control groups. On the first part of the experiment that included the one-syllable words, language disordered children made significantly more errors than either the verbal controls or the nonverbal controls. There was no difference between the two control groups. For the second part of the experiment the interaction between group and length was significant. Post hoc analysis found that a group difference existed only for three- and four-syllable nonwords and not for one- and two syllable nonwords. Further, only the language-disordered children were significantly influenced by length, no effect of length was found for either the verbal or nonverbal controls.

In a prior study Gathercole and Baddeley (1989) had found that phonological memory at age four also accounted for a significant amount of variance in vocabulary score at age five. They found this effect over and above the influence of vocabulary scores from the year before. Although they acknowledge that these relationships are correlational, they conclude that the data are consistent with the view that phonological memory is involved in the acquisition of new vocabulary in children.

Gathercole and Baddeley (1990a) draw on these earlier findings as well as the fact that the SLI group performed less well than the language-matched control group, to interpret their findings on nonsense word repetition. They conclude that children with language impairment suffer from basic deficits in phonological memory, and that it is impairment in these skills that is instrumental in the language problems characteristic of the disordered children.

Dollaghan and colleagues (Dollaghan, Biber, & Campbell, 1993; Dollaghan and Campbell, 1998 and Dollaghan, 1998) criticize the nonword repetition task utilized by Gathercole and Baddeley in their studies (1989, 1990a, b) and question their conclusions. In order to create a measure of working memory capacity for phonological material that is more valid and reliable, they have done a considerable amount of research on an alternate nonword repetition task. Dollaghan et al. (1993) investigated the hypothesis that the lexical status (word or nonword) of the stressed syllable in multisyllabic nonwords influences repetition accuracy. They constructed pairs of multisyllabic nonwords that were identical except for the stressed syllable. The stressed syllable in one list corresponded to a familiar real word, and the stressed syllable in the other list did not. The investigators found that nonsense words with stressed syllables corresponding with real words were recalled more accurately than nonsense words with nonlexical stressed syllables. They caution that if nonsense-word repetition tasks are to reflect the phonological processing skills in children independent of lexical knowledge, great care must be taken in their construction. The authors conclude that at a minimum, the stressed syllables of nonsense words must be scrutinized to make sure that they do not correspond to existing real words.

Dollaghan and colleagues further studied the extent to which the nonsense word repetition task could be constructed that would minimize the influence of subjects' previous language knowledge, and also investigated the utility of such a task in distinguishing between school age children with and without language impairment. Dollaghan and Campbell (1998) tested 40 children between the ages of 6;0 and 9;9, half of whom had been diagnosed as having language impairment and half of whom were age-matched controls. The stimuli included sixteen nonwords, four at each of four syllable lengths (one, two, three, four syllables). The number of phonemes repeated correctly was divided by the total number of phoneme targets, resulting in a Percentage of Phonemes Correct (PPC) at each nonword length (1PPC, 2PPC, 3PPC, 4 PPC), and for the entire set of nonwords (TOTPPC). The most interesting finding from this study is the significant Group by Length interaction. Post-hoc analyses indicated that the 3-syllable nonwords and 4-syllable nonwords, and total nonwords were significantly lower in the group with language impairment than in the group with normal language. The results from this investigation led the researchers to conclude that children with language impairments repeat nonwords less accurately than do their age peers. Dollaghan and Campbell (1998) go on to examine whether the new nonword repetition measure would be an efficient and effective means of distinguishing between children with and without language impairment.. The results of this investigation revealed that a total PPC of 70% or lower would be adequate to "rule in" the presence of a language disorder, and that a total PPC of 81% or higher would be sufficient to be rule out language impairment.

In sum, the Dollaghan and Campbell (1998) found that children with language impairments repeat nonwords less accurately than do their age peers and argue that due to the careful construction of the nonsense word stimuli, a disparity in prior lexical knowledge could not explain the observed group difference. Second, the investigators found that, when the objective is a screening measure for the purpose of identifying school-age children who are in need of further comprehensive language testing, much information can be gleaned from the nonword repetition task. They found that the working memory measure yielded much more accurate information concerning a child's language intervention status than a knowledge-dependent standardized test, and did so in much less time.

As reviewed above, Gathercole and Baddeley (1990a) found that children with SLI were significantly impaired in their phonological storage in working memory. Montgomery (1995a) has attempted to replicate findings by Gathercole and Baddeley and further extend their study by looking at the children's phonological encoding skills, perceptual processing, and rate of articulation using larger and better defined groups of SLI and matched controls. Montgomery found evidence that SLI children's inferior nonsense word repetition was a reflection of reduced phonological storage capacity. However, he found that their limitation is unrelated to deficits in phonological encoding, rehearsal and articulation rate but could not rule out a perceptual-processing impairment.

In order to further examine the nature of working memory in SLI, Montgomery and others (Montgomery, 2000a; 2000b; Ellis Weismer, Evans, and Hesketh, 1999; and reviewed in Montgomery, in press) have looked at the deficits in working memory within other working memory models and experimental paradigms. Montgomery (2000a; b), for example, looked at the role of working memory in comprehension using the Daneman memory model and task (Daneman and Carpenter, 1980), and concludes (Montgomery, 2000a) that the comprehension problems of children with SLI are related to limited functional working memory. Montgomery (in press) defines functional working memory capacity as the maximum number of sentences that can be comprehended while maintaining perfect recall of final words.

In his study, Montgomery (2000a) examines the influence of working memory on the off-line and real-time sentence comprehension/processing of children with specific language impairment. He tested 12 children with SLI (SLI) with a mean age of 9; 1 and 12 age matched and 12 language-matched controls. The study made use of a variant of the Daneman working memory task (Daneman and Carpenter, 1980) – one that, unlike the original Daneman task, systematically varied storage and processing demands. Although the task does not involve sentence comprehension, Montgomery predicted that sentence comprehension would be strongly associated with the combined functions of storage and processing rather than storage alone. Twenty-five words were chosen from five basic semantic categories. Five word lists were created varying in length from 3-7 words and each containing words from at least two semantic categories. In the first condition (no-load), children were presented with five word lists and asked to recall as many words as possible. In the second condition (single-load), children were presented with five word lists and again were asked to recall as many of the words as possible, but this time they were told to reorder the words upon recall according to physical size of the word referent (from the smallest thing to the biggest thing). In the third condition (dual-load), for each of the five word lists, children were asked to a) put the words that go together in some way in little groups and b) order each of the words inside each group according to size, starting with the smallest thing and ending with the biggest thing.

The off-line sentence comprehension task included two sets of 20 sentences, half of them longer and including modifying adjectival/adverbial lexemes and half of them shorter and not containing modifiers (e.g., "Point to the picture of the cats" versus "Point to the picture of the three cats"). Children listened to each sentence and pointed to a picture out of four that corresponded to the its meaning. The real-time sentence comprehension task was a word-monitoring task. Children were told to listen to "short stories" and to push a button as quickly as they could as soon as they heard a target word. Response accuracy and speed was stressed to the participants.

On the working memory task Montgomery (2000a) found that all children, regardless of group, performed similarly under the no-load condition and the single-load condition but that under the dual-load condition, the age-matched control children outperformed both the SLI and language-matched controls. The recall performance of the age-matched children was unaffected by processing load, whereas the recall performance of the SLI and language-matched children declined under the dual-load condition. On the off-line sentence comprehension task only the children with SLI had more difficulty with the sentences containing modifiers, and they also comprehended fewer of these sentences than did either control group. The only group differences to emerge on the real-time sentence processing task was that the age-matched control children responded more quickly than children in the other two groups. In order to ascertain the relationship between working memory and sentence comprehension, correlations were performed for the SLI children and the control children separately. For the SLI children, a significant negative correlation ($r = -.43$) was found between performance on the dual-load condition and total score on the off-line comprehension task. For the control children, the correlation was significant, but positive ($r = +.47$). No significant correlations were found for either the SLI children or the control children between performance on the working memory task and performance on the word recognition task.

Montgomery (2000a) states that the results indicate that in comprehension there is a trade off between storage and processing, as fits within the Daneman memory model. The fact that working memory scores of children in the SLI and language-match control groups were no worse in the single-load condition than in the no-load condition suggests that they had some ability to coordinate storage and processing. However, there appeared to be a cost to storage in the context of the more complex processing task. Further, the SLI children's poorer comprehension of complex sentences provides additional evidence of their difficulty storing greater amounts of input while at the same time rapidly computing new, incoming information. Montgomery concludes that while the off-line sentence comprehension difficulties of some SLI children appear to be related to their more limited functional working memory capacity and difficult coordinating storage and processing, real-time sentence processing does not appear to be associated with their working memory limitation.

Montgomery (in press) summarizes the evidence pointing to a positive association between the verbal working memory deficits shown in children with SLI and their problems with lexical and morphological learning. He concludes that difficulty with comprehension is due to a complex interaction between the native capacity of the information-processing system of the child, including the verbal working memory system, and the nature of the processing requirements needed for language comprehension.

Ellis Weismer et al. (1999) also found significant deficits in the verbal working memory capacity of SLI children using a Competing Language Processing Task (CLPT). On this task children are required to make true/false judgments on sentences while simultaneously remembering the sentence-final word. They found no significant difference between SLI and age matched peers on the true/false but found significantly poorer recall suggesting that children with SLI have a deficit in verbal working memory capacity.

The research reviewed, regardless of the model motivating the investigation, seems to point to a deficit in working memory for verbal or phonological information in children with SLI, or as Baddeley would say, in the phonological loop. The present investigation seeks to further this inquiry by including nonverbal areas of memory, namely the visuo-spatial sketchpad and ultimately the functioning of the central executive in children with SLI.

1.3.1.2. Visuo-spatial sketchpad and SLI.

In addition to all the difficulties with language, research by Stark, Tallal, and colleagues has pointed to difficulties in rapid perceptual skills and auditory temporal analysis skills in children with SLI (Tallal, Stark, & Mellits, 1985a; 1985b; Tallal, Stark, Kallman, & Mellits, 1981; Bernstein & Stark, 1985; and Stark, Tallal, Kallman, & Mellits, 1983). This research will be briefly reviewed in order to provide support for an investigation examining deficits outside of language ability in children with SLI.

Tallal et al. (1981) examined the ability to discriminate between stimuli in different modalities, visual and auditory, and found that on subtests where significant modality effects were demonstrated, they were similar for both groups: the children with SLI and age-matched controls. As well as this within group similarity in modality effects, however, Stark et al. (1983) also report that children with language impairment were significantly different from the normal children with respect to rapid rate perceptual processing, and that this difference was found in both the auditory and visual modality and on cross modal testing. Therefore, this study did not replicate the results of Tallal and

Percy (1973), who had found that the deficits shown by SLI children in processing rapidly presented stimuli, were specific to the auditory modality. The researchers attribute this difference in findings to age differences in the two samples. Tallal et al. (1985a, b) interpret these various results as indicating that children with language impairment are significantly impaired both nonverbally and in their ability to perceive and produce the temporal cues in speech. It was, however, the auditory perceptual variables that were most highly correlated with the degree of receptive language deficit.

The research reported by Tallal, Stark, and their colleagues stands as one body of work demonstrating cognitive deficits in SLI that extend beyond the auditory domain. There have as yet been no explicit studies of visuo-spatial sketchpad abilities in this population. However, in related work, Johnston and Ellis Weismer (1983) examined the mental rotation abilities in children with language impairment. The investigators argued that a significant linear relationship between degree of rotation and reaction time indicated that children in all groups were using imagery to conduct this task. The investigators found that language-disordered children did not differ from normal children on accuracy or require more training, but did respond more slowly. The researchers took these findings to suggest an impairment of visual imagery, which would presumably implicate the visual sketchpad. The present study seeks to further investigate the role of the central executive by examining working memory abilities for combined visuo-spatial and phonological information in school-age children with language impairment.

1.3.1.3. Central Executive and SLI.

An increasing number of proposals attempt to integrate linguistic and non-linguistic deficits and explain SLI as a limitation in information-processing capacity (Leonard, 1998). Despite this fact, studies of working memory in children with SLI have as yet seldom focused on central executive functions. Investigators have instead pursued the phonological storage system, presumably because of its clear connection to language learning.

The current research is beginning to break this trend. Thorn and Gathercole (2000), for example, suggest that central executive deficits can result in wide-ranging difficulties with general cognitive functioning, and for children can lead to learning difficulties within the educational setting. As has already been stated, impairments of the phonological loop are associated with difficulties in learning the phonological structure of new words. Deficits of the visuo-spatial sketchpad are less readily identifiable but could also result in difficulties in the long-term learning of visual and spatial information.

Gathercole and Pickering (2000a, 2000b, 2001) have launched an investigation of the working memory capabilities of children with special needs. Gathercole and Pickering (2001) found that children, aged seven and eight and recognized as having special educational needs, had marked impairments on the working memory measures, and in particular on the tasks tapping the central executive. These included a listening task, a version of the Daneman and Carpenter (1980) task described earlier, a counting recall task where children were required to count the number of dots presented in a series of arrays and to recall subsequently the dot totals in the order that the arrays were presented, and third, a backwards digit recall task that required children to recall the sequence of spoken digits in reverse order.

Swanson and Ashbaker (2000) also found results that were interpreted as support for the notion that the poor word recognition and comprehension performance seen in readers' with learning disabilities reflect deficits in a central executive system that are independent of any deficits in the articulatory loop. In this investigation the researchers examined performance on tasks measuring articulation speed, working memory for phonological and verbal information, visual working memory, and the central executive. They hypothesized that if central executive systems are playing an important role in the reading deficits, independent of the articulatory system, and then the measures of the central executive would predict reading performance after various measures of the articulatory system had been partialled from the analysis. This prediction was confirmed. The results clearly showed that the central executive and the visual and phonological storage systems (considered together) contributed independent variance to reading comprehension and word recognition above and beyond articulation speed and age.

In addition to these studies of the central executive with mixed groups of 'special needs' children, Ellis Weismer (1996) provides a brief summary report of a dual-task study with SLI children. She reports that these children exhibited disproportionate decrements in dual processing in comparison with the NL group. Her task, however, required children to listen to two sets of competing auditory stimuli and did not involve the visuo-spatial sketchpad. The present investigation seeks to look further at central executive functions in children with specific language impairment.

1.4. The present study

In this study a single measure of phonological loop function, namely nonword repetition, and a single visuo-spatial task will be administered both independently and in a combined dual-task presentation. I will examine whether the dual-task presentation creates increased difficulty for the children and whether children with specific language impairment (SLI) perform differently on either of the single tasks and/or in the combined task when compared to age-matched controls (NL). According to the framework of working memory proposed by Baddeley and Hitch (1974) and further developed by Baddeley (1986), the central executive is postulated to be involved in the coordination of information between the phonological loop and visuo-spatial sketchpad. Gathercole and Pickering (2000a) conclude that while the phonological loop supports performance on tasks that involve temporary verbal storage, the central executive is tapped by tasks that impose simultaneous demands on both processing and storage for brief periods of time. The tasks to be used here are primarily storage tasks, but once the children are equated on single task performance, any decrement found in the dual task presentation can be hypothesized to be the result of interference effects between the supposedly separate systems. Such interference would presumably indicate that storage capacity had been exceeded and that the central executive was involved in monitoring and coordinating the two tasks. A finding of no interference would suggest that the tasks did not require coordination from the central executive and therefore be more compatible with the Baddeley (1986) view of separate slave systems. Group differences will be evaluated both on the independent working memory tasks and on the potential interference with the dual task to examine whether children with SLI show impairment in central executive function.

1.5. Research Questions

1. Do children with specific language impairment have different levels of working memory for phonological and verbal information when compared to age-matched controls?
2. Do children with specific language impairment have comparable levels of visuo-spatial working memory compared to age-matched controls?
3. Do children (SLI and NL) show a decrement in working memory span for phonological information when there is a simultaneous requirement to store visuo-spatial information?
4. Do children (SLI and NL) show a decrement in visuo-spatial working memory when there is a simultaneous requirement to store phonological information?
5. Do children with SLI show a greater decrement in working memory capacity for phonological information in the dual task setting when compared to age-matched controls?
6. Do children with SLI show a greater decrement in visuo-spatial working memory in the dual task setting when compared to age-matched controls?

Based on the research reviewed in this chapter, I anticipate that children with SLI will evidence limitations in the storage of both phonological and visuo-spatial information. All of the children can be expected to show decrements in working memory spans in the dual-task presentation, but there are insufficient grounds to predict whether the children with SLI will show any special difficulties with central executive functions.

2. Method

The following chapter details the experimental participants, variables, and conditions employed in this study. The construction of the two tasks that engage the phonological loop and the visuo-spatial sketchpad, and the construction of the dual task are explained in detail, along with the procedure for each task. Finally, the design used for data analysis is outlined.

2.1 Participants

2.1.1. Criteria applying to all participants

Participants in the experiment were 24 children between the ages of 6;1 and 9;8 (years; months) recruited from schools and daycare centres in British Columbia. Children were divided into two groups based on language ability. Thirteen children were diagnosed as specifically language impaired (SLI) and eleven were age-matched controls. To recruit children with SLI for this study, Speech-language Pathologists in the Surrey and Salmon Arm schools districts were asked to refer potential participants. Data from five participants identified by Speech-Language Pathologists were ultimately not included because three children failed to meet the criteria for inclusion in the SLI group, and data from two others was lost due to technical problems during testing. Participants in the SLI group (n = 13) had an average age of 93.62 months (7 years, 10 months) (SD = 11.75, range 80 to 116 months) and participants in the control group (n = 11) had an average age of 93.54 months (7 years, 10 months) (SD=15.52, range 73 - 115 months). There was no significant difference between the two groups on age, $t\ (22) = 0.01, p > .05$. There were 8 girls and 5 boys in the SLI group and 6 girls and 5 boys in the NL group.

All children were required to obtain an IQ of 80 or above on the Test of Nonverbal Intelligence (TONI) (Brown, Sherbenou, & Johnsen, 1997); SLI (M = 96.46, SD = 9.20), NL (M = 102.27, SD =11.13). There was no significant difference between the groups on TONI scores, t (22) = 1.40, $p > .05$. The children exhibited normal range hearing sensitivity as determined by audiometric puretone screening at 20dbHL in the frequency region most important for speech recognition (500 to 4000 Hz) (American Speech and Language Association, 1997). The Goldman Fristoe Test of Articulation (Goldman & Fristoe, 1986) was administered to provide a measure of the children's phonological abilities. Children were required to have developmentally appropriate articulation skills as their ability to repeat nonsense words with sounds such as 'sh' and 'ch' would be compromised by articulatory errors. Children that did not have developmentally appropriate articulation skills were not included in this study. One child in the NL group was dropped from the study for failure to meet this criterion.. Additional phonological analyses indicated that all children could produce all the phonemes they were required to produce in the experimental tasks. Finally, all participants were native speakers of English.

Finally, data on maternal education were obtained since studies in many domains have shown relationships between this variable and children's developmental levels (Dollaghan et al. 1999). Parents of all children were asked to give the child's mother's highest level of education reached. Dollaghan et al. (1999) argue that as maternal and paternal education levels are highly correlated, maternal education provides a valid measure of parental education. As well, logistically, some children in lower education brackets are from single-parent homes, usually the mothers, therefore, a measure of maternal education is easier to obtain. Maternal education was recorded in years (i.e., a grade 11 education would be 11 years, a high school graduate with 2 years post-secondary education would be 14 years). Mothers of children with SLI ($M = 12.61$, $SD = 1.75$) had a significantly lower level of education attained, $t\ (22) = 3.33, p < .005$, than mothers of children with NL ($M = 15.27$, $SD = 2.15$).

2.1.2. Language Criteria: CELF-3

In order to meet the criteria for the SLI group, children were required to score at least 1.3 SD from the mean on two of three expressive subtests of the Clinical Evaluation of Language Fundamentals-Third Edition (CELF-3) (Semel, Wiig, & Secord, 1995). The expressive subtests of *Formulated Sentences* and *Recalling Sentences* were administered to all children and the *Word Structure* subtest was given to children not meeting criteria after the first two. To obtain a score 1.3 SD from the mean, a score of less than seven was required on both subtests. One child deviated slightly from this criterion, scoring a '7' on *Formulated Sentences* and an '8' on *Word Structure,* but was nonetheless included in the experimental group based on her history of severe language impairment. Children in the NL group were required to have two out of three expressive CELF-3 scores at 8 or above, but most scored well above this cut-off. As expected, t-tests indicated a significant difference between children with SLI and NL on *Formulated Sentences,* $t(22) = 9.93, p < .001$ and on *Recalling Sentences*, $t(22) = 8.65, p < .001$ indicating children with SLI had a significant expressive delay compared to children with NL. Children were also given the receptive subtest, *Concepts and Directions*. Four children in the SLI group scored within low normal ranges but overall, children with SLI had significantly lower scores on this subtest as compared to children in the NL group, $t(22) = 5.50, p < .001$ indicating a receptive language delay for the SLI children overall.

Table 1 provides a summary of the criteria applying to all participants, the standardized testing results, and the means for each variable by group.

Table 1. Individual language, cognitive test scores and means by group for each variable.

Group	Age	[a]MatEd	[b]TONI	[c]CELF-FS	[d]CELF-RS	[e]CELF-WS	[f]CELF-C&D	[g]PPVT-3	[h]ITPA
SLI	6; 8	13	97	7	3	8	6	108	41
	6; 10	13	85	6	6		4	86	20
	6; 10	15	104	6	11	6	5	103	39
	7; 2	14	109	6	3		3	84	
	7; 2	12	94	5	5		4	90	
	7; 2	14	94	5	3		5	94	36
	7; 2	13	84	6	5		8	99	29
	7; 7	14	107	6	5		9	117	39
	7; 11	12	88	6	3		4	104	
	8; 8	11	84	5	5		6	81	30
	9; 3	13	98	5	4		7	99	35
	9; 7	12	108	3	3		4	73	38
	9; 8	8	102	4	4		8	99	42
M	7;10	12.62	96.46	5.38	11.18		5.61	95.15	34.90
SD	0;11	1.76	9.21	1.04	1.04		1.89	12.08	6.77
NL	6; 1	12	111	8	11		9	112	44
	6; 2	16	109	9	13		10	119	30
	6; 11	17	130	13	15		16	123	45
	6; 11	15	104	13	16		13	114	51
	7; 6	18	94	14	15		16	117	
	7; 10	16	97	11	17		10	122	
	7; 11	13	93	10	13		11	112	
	8; 8	16	100	11	10		7	125	38
	8; 11	15	93	11	9		8	107	42
	9; 0	18	100	12	13		12	113	
	9; 7	12	94	11	11		10	94	20
M	7;10	15.27	102.27	11.18	13.00		11.09	114.36	38.57
SD	1;03	2.15	11.14	1.78	2.57		2.95	8.70	10.45

Note. [a]MatEd = Maternal level of education (in years). [b]$M = 100$. [c]CELF-FS = CELF-3:Formulated Sentences, M = 10. [d]CELF-3-RS = CELF-3: Recalling Sentences, M = 10. [e]CELF-3-WS = CELF-3: Word Structure, M = 10. [f]CELF-C&D = CELF-3: Concepts and Directions, M = 10. [g]$M = 100$. [h]$M = 36 \pm 6$.

2. 2. Experimental Tasks

All children completed two experimental tasks: a visual-spatial memory task in which they needed to remember the location of a set of figures, and a nonsense word repetition task. The two tasks were also combined in a dual presentation. All experimental tasks were designed and programmed using the E-Prime software (Schneider, Eschman, & Zuccolotto, 2002a, 2002b) and were run on an HP Pavilion N5270[1].

2.2.1 Task 1: Visuo-spatial task

2.2.1.1. Stimuli.

To measure visuospatial sketchpad abilities a 4 x 4 grid was created with 5 cm^2 squares separated by 2.5 cm on the sides and 0.5 cm on top and bottom. The squares were white when unfilled and the screen background was black. In each trial, a number of identical cartoon, non-nameable monsters (http://www.microsoft.com/clipart) were distributed into some of the squares and the child's task was to remember their locations. Monsters were assigned to locations on a random basis with the restriction that there could not be three[2] or four monsters in a row of adjacent squares. All children viewed the same pairings of monsters and locations, but the trials within any given block were presented in a random order.

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[1] The HP Pavilion N5270 is a laptop computer with a Pentium III processor and a 30 by 23 cm screen size.

[2] However, two of the ten trials at level five and three of the ten trials at level six contained three adjacent monsters.

2.2.1.2. Procedure: To establish level.

On each trial, two to six monsters were presented for 3500 ms, followed by a 500 ms white screen, and then a 4 x 4 grid of white squares with a question mark in the middle of each square. Children were required to look at the monsters for the short time they were on the screen and then recall the position of the monsters when the white squares appeared by pointing to the screen. Children sat at child appropriate tables and chairs in order to be able to point to the screen at a distance of approximately 40 cm. Responses were manually recorded by the researcher using a separate keyboard attached to the laptop.

The program included feedback to the child based on their response. If the child was correct "GREAT" came up after the response in blue and if the child was incorrect "Oh NO" in red came up after the response. The investigator also provided verbal feedback of "good pointing", "Great job", "Not quite", "Try the next one", and the cue to "Look at the monsters". Language such as "Remember the monsters" and "Where were they?" was avoided due to the complexity of these concepts and the language level of the SLI children.

Children were simply instructed that they were to "Look, wait, point" in order to avoid complex language that would disadvantage the language-impaired children. The experimenter told the children that she would do the first one and show them how. All children started with trials involving only two monsters. After the demonstration item, the children were given four practice trials, out of which they were required to perform successfully on at least two in order to proceed with the experimental task. All did so.

Trials in the task proper were blocked into sets of 10, with the number of monsters increasing by one with each subsequent block. Each child progressed until they achieved less than 80% correct or until they were successful in remembering six monster locations. "Visual working memory span" was taken to be the last level at which they were successful on at least 80% of trials. Every child was at least successful at level two.

2.2.1.3. Delay condition.

After "visual working memory span" was established, a further block of 10 trials was administered at this level. However, in this condition the child had to recall locations over an unfilled 5 sec interval. New assignments of monsters to locations were generated for this condition with the same restrictions on combinations[3]. The child was told that this game would be almost the same as the last, that they were going to do the game with x (their "visual working memory span") monsters again, only it would be a bit different. They were again instructed to "Look, wait, point". Recording of responses and feedback to the child was the same as the first condition.

2.2.2. Task 2: Nonword repetition task

2.2.2.1. Stimuli.

Sixteen nonwords (Table 2), four at each of four syllable lengths (one, two, three, and four syllables), were taken from Dollaghan and Campbell (1998). The construction of these nonwords had to adhere to five constraints. First, nonwords were constructed so that none of their individual syllables (CV or CVC) corresponded to an English word.

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[3] However, one of the ten trials at level five and three of the ten trials at level six contained three adjacent monsters

Second, to minimize articulatory difficulty the consonants /s, z, l, r, ʃ, ʒ, θ, ð/ and consonant clusters were excluded. Third, nonwords contained only tense vowels. Fourth, to reduce predictability of consonant phonemes in the two possible syllable positions within the nonwords (onset or coda), consonants were assigned to occupy only those syllable positions in English in which they occur ≤ 25% of the time. Fifth, no consonants or vowels occurred more than once within a given nonword. See Dollaghan and Campbell for a more detailed description of the restrictions and reasoning for the construction of the nonword stimuli design.

Table 2. Phonetic transcriptions of the nonwords at each length

One syllable	Two syllables	Three syllables	Four syllables
/najb/	/tejvɑk/	/tʃinojtaʊb/	/vejtɑtʃajdojp/
/vowp/	/tʃovæg/	/najtʃovæb/	/dævonojtʃig/
/taʊdʒ/	/vætʃajp/	/dojtaʊvæb/	/najtʃojtaʊvub/
/dojf/	/nojtauf/	/tejvojtʃajg/	/tævɑtʃinajg/

Nonwords were spoken by a trained adult female speaker wearing a head-mounted microphone into the HP Pavilion N5270 laptop computer. Sound files were stored and edited in Cool Edit 2000 (1999-2000). Each nonword was recorded separately four or five times at a consistent rate, assigning primary stress to the second syllable of the four-syllable nonwords, and to the first syllable of all others. The nonwords were then analyzed using Cool Edit 2000, and exemplars were selected such that the nonwords at each syllable length had approximately equal durations. The duration of the entire task was 60 sec.

The sixteen nonwords were programmed into E-Prime (Schneider, Eschman, & Zuccolotto, 2002a, 2002b) in order to assure consistent presentation of the task. An external tape recorder and microphone recorded the child's responses for later scoring. The nonwords were grouped into four blocks, one for each length, and were presented in a consistent order progressing from the shortest, one syllable, to the longest, four-syllable, nonwords. Within each block, the four nonwords were presented in random order.

2.2.2.2. Procedure.

Children wore headphones that were plugged into the computer. They were instructed that they were going to hear "silly" words and that the experimenter could not hear the words so the child needed to "copy" the silly word. Children were given one word at a time starting with one-syllable words and progressing in ascending order to four-syllable words. After the child repeated a word the experimenter pushed the spacebar to start the next word. The experimenter noted whether the word was correct or incorrect. "Phonological working memory span" was taken to be the last level at which the child was successful on at least three out of four nonwords or level one if the child was not successful on at least three out of four nonwords at any level.

2.2.2.3. Reliability

Audiotapes of half of the responses from eight randomly selected participants (16% of data), four from each group with item length counterbalanced across children and groups, were transcribed independently by a second trained listener. Phoneme-by-phoneme percentages of agreement for judgments of correctness ranged from 81 - 96 %, with an average of 89%. None of the disagreements affected assignment to working memory level.

2.2.3. Dual task: Visuo-spatial task + nonword repetition

2.2.3.1. Stimuli.

For the visuospatial sketchpad portion of the dual task new distributions of monster locations were generated for each level. Monsters were again assigned to locations on a random basis with the restriction that there could not be three or four monsters in a row of adjacent squares[4]. Again monsters were presented within a 4 x 4 grid. In each trial, a number of identical cartoon, non-nameable monsters (http://www.microsoft.com/clipart), determined by the "visual working memory span" achieved in Task 1, were distributed into some of the squares. The child's task was to remember their locations. All children at the same level viewed the same pairings of monsters and locations, but the trials within any given block were presented in a random order.

For the phonological portion of the dual task, additional nonwords with 1-, 2-, 3-, and 4- syllables were created attempting to follow the Dollaghan and Campbell (1998) criteria as closely as possible. Due to the impossibility of stringently following these criteria for the creation of more words (C. Dollaghan, personal communication, May, 2002), the new nonwords did not exclude the consonants /s, z, ʃ, θ, r, ŋ/ or limit consonants to infrequent syllable positions. They also occasionally repeated consonants

[4] However, one trial at level five and two trials at level six contained three adjacent monsters and level six contained two trials with four adjacent monsters

or vowels within a given nonword[5]. However, all of the new nonwords were constructed so that none of their individual syllables (CV or CVC) corresponded to an English word, consonant clusters were excluded, and nonwords contained only tense vowels. Nonwords used in the dual task are given in Table 3.

Table 3. Phonetic transcriptions of the nonwords at each length for the dual task.

One syllable	Two syllables	Three syllables	Four syllables
/sejp/	/tejsam/	/kojpejdit/	/mejgifojvan/
/fot/	/bænaʊk/	/ʃibitʃan/	/ponadifaʃ/
/nejt/	/pojtʃan/	/fatænob/	/fejnakajzab/
/θip/	/ʃejdap/	/mækativ/	/tapogætik/
/taʃ/	/tavejtʃ/	/kojtejkaʃ/	/pagitamojk/
/gap/	/nejvat/	/businas/	/tʃodanæpiʃ/
/hatʃ/	/θaʊsar/	/gikotʃajn/	/fugæbæmik/
/bejf/	/sædiŋ/	/kejponan/	/batatejtʃin/
/mip/			
/kajd/			

2.2.3.2. Procedure.

The two tasks were combined in a dual task presentation with children given tasks at their own levels of visual and phonological memory capacity, as determined in Tasks 1 and 2. The child was presented with a 4 x 4 visual array of cartoon monsters at his "visual working memory span" for 3500 ms. Then the child repeated nonwords at his "phonological working memory span" for five sec. Finally, the child was required to recall the location of the monsters by pointing to the screen.

[5] However this only occurred three times in the 3-syllable nonwords and five times in the 4-syllable nonwords. No child attained a level on the nonword repetition task that required them to repeat 4-syllable words in the dual task.

Each level had a possibility of eight to ten nonwords. Nonwords were presented randomly from the list of nonwords but did not repeat until the entire list was exhausted. Since children repeated only 2 to 3 nonwords per trial, children virtually never heard the same nonword in two adjacent trials.

Due to the language impairment of the children in the experimental group, the task was primarily explained through modeling instead of with language. This precluded any discussion of task priorities. The first trial was modeled for every child before the child attempted two practice trials where specific feedback was provided. Data entry for the monsters was the same as the visual memory task and children's nonsense word repetitions were recorded on an external tape recorder and microphone for later transcription and scoring. Pilot testing indicated that the dual task was quite difficult for the children and giving specific feedback regarding each trial was devastating for the child. Therefore, on the dual task children were given non-specific feedback regarding performance such as "Good job" and "Great pointing". As well, children were periodically encouraged by the examiner to "Look at the monsters" in order to keep them focused on the task. Due to the structure of the task, such feedback was more likely for the visual than the nonword repetition task. The experimental task consisted of 20 trials lasting approximately ten minutes.

2.2.3.3. Reliability.

Audiotapes from half of eight randomly selected participants (16% of the data), four from each group, were transcribed independently by a second trained listener. Phoneme-by-phoneme percentages of agreement for judgments of correctness ranged from 89 - 99 %, with an average of 94%.

2.3. Additional Measures

2.3.1. PPVT-III

All children were also given the Peabody Picture Vocabulary Test-Third Edition (PPVT-III) (Dunn & Dunn, 1997). Since much of the earlier research by Gathercole and colleagues (Gathercole et al., 1999; Gathercole & Baddeley, 1989) includes correlational data between working memory span for phonological material and receptive vocabulary, this measure was included in order to compare the results of the present investigation with past research. A t-test indicated a significant difference between SLI and NL on PPVT-3 scores, t (22) = 4.39, $p < .001$, with SLI having lower receptive vocabulary than NL children. Therefore, similar to previous research our language-impaired group was significantly lower in overall receptive vocabulary.

2.3.2. ITPA

The visual sequential memory subtest of the Illinois Test of Psycholinguistic Abilities (ITPA) (Kirk, McCarthy, & Kirk, 1968) was included as a standardized method of measuring nonverbal visual memory in young children that could validate the experimental task. The ITPA was only administered to 17 of the 24 children in the study (10 SLI and 7 NL) due to time constraints in the testing sessions. A t-test indicated the groups did not differ significantly on visual sequential memory as measured by the ITPA, $t(15) = 0.88, p > .05$.

2.4. General Procedure

Participants were tested individually in 2, forty-five minute sessions. Sessions took place at the child's school, daycare, or home. The first session consisted of the language and cognitive testing. The second session consisted of the visuo-spatial memory task, nonword repetition task and dual task. Depending on time constraints the hearing screening, ITPA and GFTA were administered in either the first or second session. All the testing and experimental tasks were administered by a Masters student in Speech-Language Pathology. A registered Speech-Language pathologist had recently tested six of the language-impaired children on at least one standardized measure. The results from these tests were used rather than readministering the tests.

3. Results

The role of the central executive is postulated to be involved in coordinating the flow of information between two slave systems. Therefore, in order to examine the central executive a dual-task methodology was used. Capacity of each of the slave systems is examined separately and then compared to performance in the dual-task. A decrement in performance on either task in the dual-task condition can be interpreted as interference from the other task and therefore implicate the involvement of the central executive.

3.1. Analysis Strategy

The children with SLI in this study were successfully matched with children with NL on TONI scores, $t(22) = 1.40, p > .05$ and on Age, $t < 1$, but mothers of children with SLI had significantly lower levels of education than mothers of the NL children. Maternal education is known to predict a wide array of developmental variables (Dollaghan et al., 1999). It is thus important to ensure that differences found in the dependent variables examined in this study were not likewise due to the difference in environmental influences associated with maternal education. In the analyses to follow, whenever an ANOVA or t-test yielded a significant group effect, an ANCOVA was conducted with maternal education as the covariate[6].

[6] In principle a covariate might also be washing out a potential group difference, which might suggest an ANCOVA approach across the board. However, the anticipated effect of such analysis in the present case would be to increase the value of scores in the SLI group. Resulting differences that favored the SLI group would run counter to all prior research and most likely be misleading.

3.2. Nonword repetition

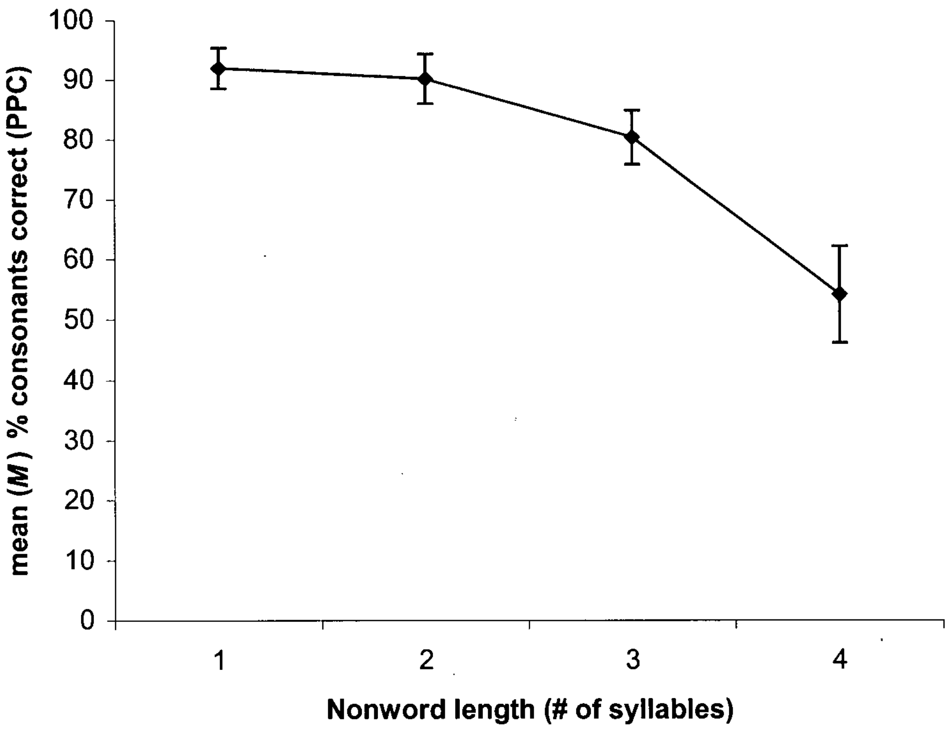
A nonword repetition task was administered in order to provide a measure of the functions of the phonological loop. Children both with specific language impairment (SLI) and with normal language (NL) repeated nonwords of increasing length (1-, 2-, 3-, and 4-syllables). Means and standard deviations for Percentage Phonemes Correct (PPC) at each nonword length, and for the task overall, appear in Table 4. Means are given separately for each group.

Table 4. Mean (SD) percentage phonemes correct at each nonword length for children with specific language impairment (SLI) and normal language (NL).

Group	SLI (n=13)	NL (n=11)
Nonword length		
1-syllable	88 (11)	95 (04)
2-syllable	84 (13)	96 (03)
3-syllable	75 (09)	88 (12)
4-syllable	49 (20)	64 (23)
Total	65 (08)	82 (12)

A Group (SLI, NL) by Length (1-, 2-, 3-, 4-syllables) repeated measures ANOVA was conducted with PPC as the dependent variable. The ANOVA revealed a main effect of Group, $F(1,22) = 9.51, p < .01$, so an ANCOVA was conducted to remove the effect of Maternal Education. This analysis indicated that Maternal Education was not significantly related to the PPC variable, $F(1,21) = 2.05, p > .05$. There were, however, two statistically significant main effects. The main effect of Group, $F(1,21) = 5.52, p < .05$, indicated that overall, children with SLI had a significantly lower percentage of phonemes correct on the nonword repetition task. As well, a significant main effect of Length was found, $F(3,63) = 4.70$, $p = .005$. Unequal N HSD post-hoc analyses with alpha set at .05 indicated a significant difference in mean percentage consonants correct between all item lengths except between 1-syllable and 2-syllable items. Therefore, percentage consonants correct declined with increasing item length past 2-syllables. Figure 1 shows the means and confidence intervals for percentage phonemes correct in 1, 2, 3, and 4-syllable nonwords across groups. The Group x Length interaction was not significant, $F < 1$.

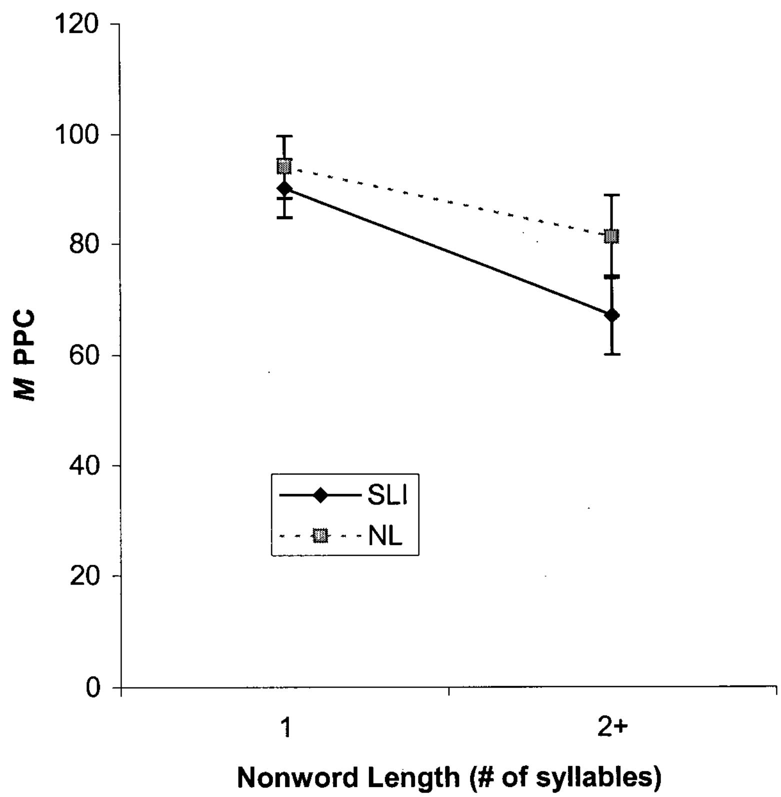
Figure 1. Mean (*M*) Percent Consonants Correct (PPC) for each nonword length (1-, 2-, 3-, 4-syllables) across Group.



An inspection of the data suggested that group differences were primarily found for the 2, 3, and 4- syllable nonwords. Therefore, 2-, 3-, and 4-syllable words were collapsed into a new category of nonwords greater than 1-syllable (2+), and a PPC for this new item category was calculated by averaging the PPCs for the 2-, 3-, and 4-syllable nonwords. A Group (SLI, NL) by Length (1, 2+) repeated measures ANOVA was again conducted with PPC as the dependent variable to examine whether there was a significant interaction between length and group. Again, the preliminary analysis yielded a Group effect, $F(1,22) = 12.61, p < .005$, so a Group by Length ANCOVA was conducted with maternal education as a covariate (Figure 2). Maternal Education was not significantly related to the PPC, $F(1,21)=1.69, p > .05$. In this analysis, the main effect of Group, $F(1,21) = 4.77$, $p < .05$, was subsumed in a significant Group by Length interaction, $F(1,21) = 4.40, p < .05$. Figure 2 shows the means and confidence intervals for the interaction. Post-hoc Unequal N HSD with alpha at $p < .05$ revealed the source of the interaction to be as expected. A significant difference between SLI and NL was found for nonwords with 2 or more syllables, $p < .05$, but no significant difference was found between SLI and NL on nonwords with 1-syllable. Children with SLI repeated 1-syllable nonsense words as accurately as age-matched peers but repeated the set of words with 2, 3, and 4-syllables less accurately than their age-matched peers. There was no significant effect of Length, $F(1,21) = 1.42, p > .05$.

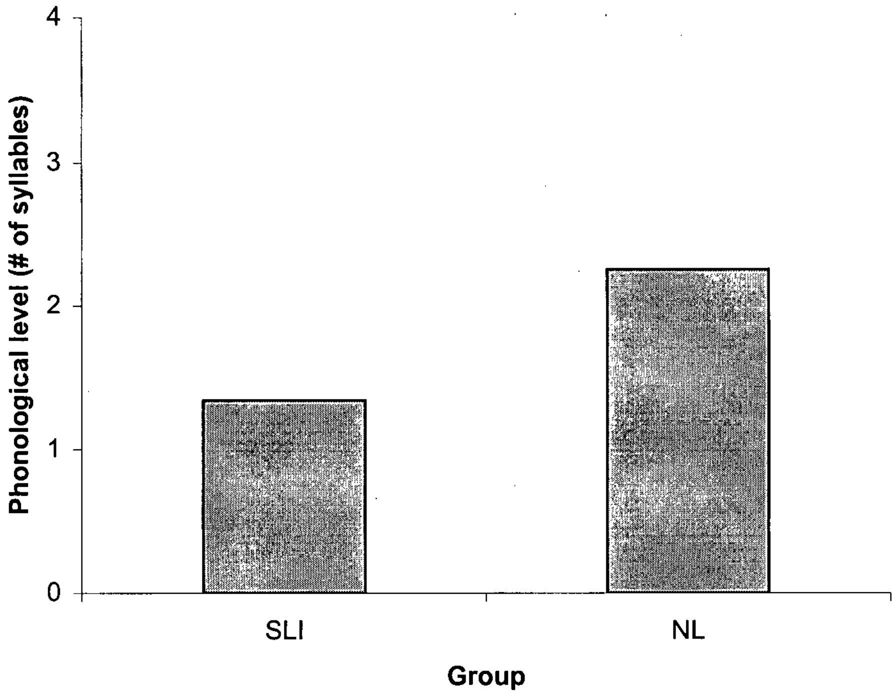
Level attained on the nonword repetition task was determined as the last level at which the child repeated at least three out of four nonwords without error. A t-test revealed a significant Group difference on level attained, t (2,22) = 5.89, $p < .001$. In order to ensure group differences obtained on the t-test were not due to maternal education, a one-way ANCOVA with maternal education as a covariate was conducted.

Figure 2. Mean (*M*) Percent Consonants Correct (PPC) for each nonword length (1-, 2+ syllables) by Group.



Maternal education was not significantly associated with memory span on the nonword repetition task, $F(1,21) = 2.96, p > .05$. The ANCOVA again indicated a significant effect of Group, $F(1,21) = 16.09, p < .001$, as shown in Figure 3.

Figure 3. Mean (*M*) phonological level attained (# of syllables) by Group.

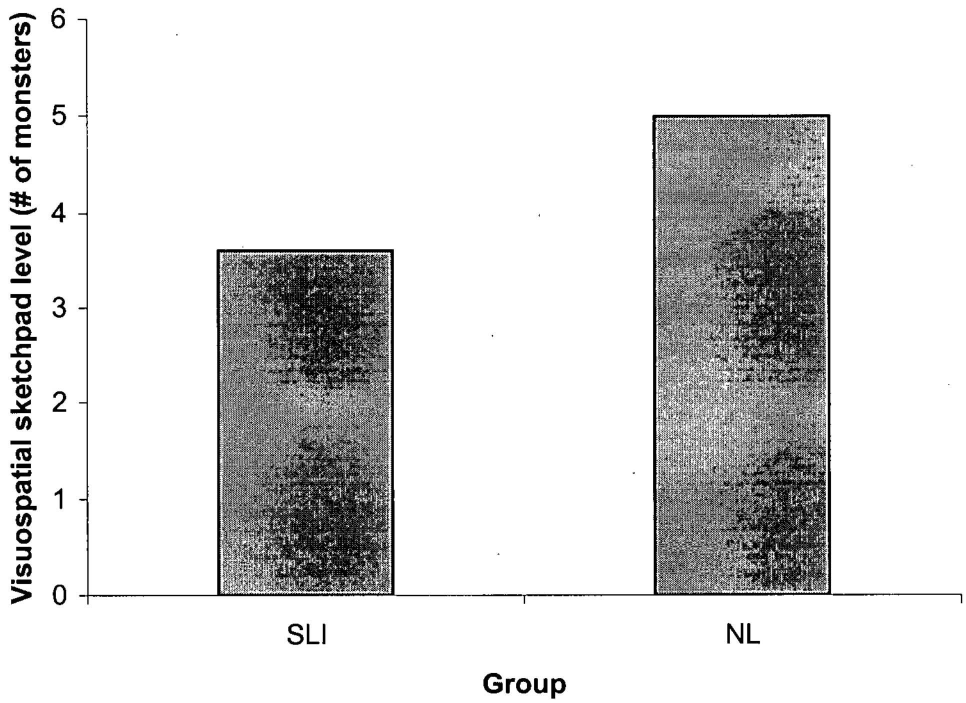


3.3. Visual working memory

Recall that this study used a span measure as an index of visual working memory. "Visual span" was defined as the highest number of monsters (between 2 and 6) that could be recalled at 80% accuracy or better. Children started with items that required memory for location of two monsters and progressed until they failed on three or more trials out of 10 at a given level. Visual working memory span was taken to be the highest level at which the child correctly responded on 80% or more trials.

A t-test was used to determine whether children in the SLI and NL groups differed significantly in their visual working memory span. The results of this analysis indicated no significant difference between SLI and NL on visual working memory span, $t(22) = 1.9, p = .07$, although performance trends favoured the children with NL.

Figure 4. Mean visuospatial sketchpad level (# of monsters) by Group.



Even though every child was required to reach between 80 and 100% at their visual working memory span, it remained possible to that children in the two groups could show differences on the percent correct at span. In order to check for differences in percent correct at visual working memory span, a t-test was performed. T-test analysis indicated no significant group difference on percent correct at span, $t < 1$, SLI ($M = 89$, $SD = 09$) and NL ($M = 87$, $SD = 08$).

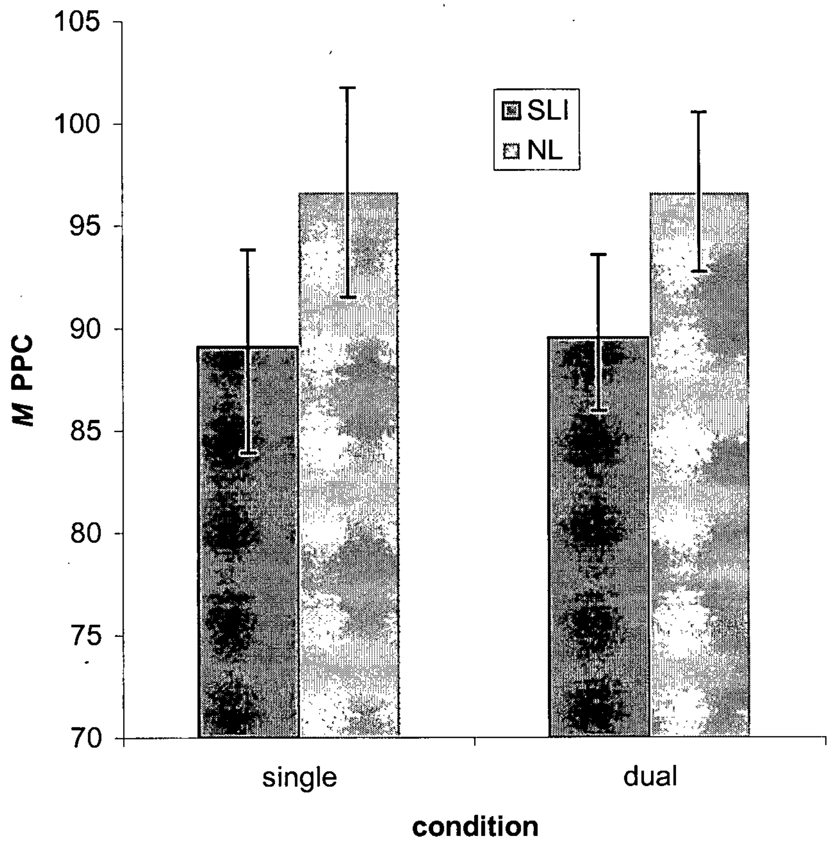
3.4. Dual task

The next set of analyses will focus on the data pertinent to the conceptualization of the central executive. As previously described, the dual-task presentation combined the two memory tasks that had been presented singly, i.e. the nonword repetition task and the memory for monsters task. As the central executive is postulated to be responsible for coordinating the flow of information from the two slave systems, examining each of the tasks within a dual-task paradigm can help shed light on the function of the central executive. A decline in performance from the single task to the dual task would indicate interference between the two slave systems. Interference on the auditory task and visual task were examined separately.

3.4.1. Interference on Auditory Task

The auditory task involved repeating nonwords at a child's "level", predetermined as the number of syllables per word which they were able to correctly repeat three out of four nonwords. In order to determine whether there was interference on the auditory task a 2 (Group: SLI, NL) by 2 (Cond: Single, Dual) repeated measures ANOVA was conducted with percent correct in the single and dual conditions as the dependent variables (see Figure 5). The ANOVA revealed a significant Group effect, $F(1,22) = 8.20, p < .001$, with children with SLI ($M = 89$, $SD = 10$) being, overall, less accurate on naming nonwords than their age peers ($M = 97$, $SD = 02$). However, there was not a significant main effect of condition, $F < 1$, indicating that there was no interference from the visual to the phonological task working memory from visual working memory, and no significant interaction, $F < 1$. There was also no difference between the two groups on level of interference.

Figure 5. Mean (*M*) Percent Consonants Correct (PPC) for each Condition (Single, Dual) by Group (SLI, NL).

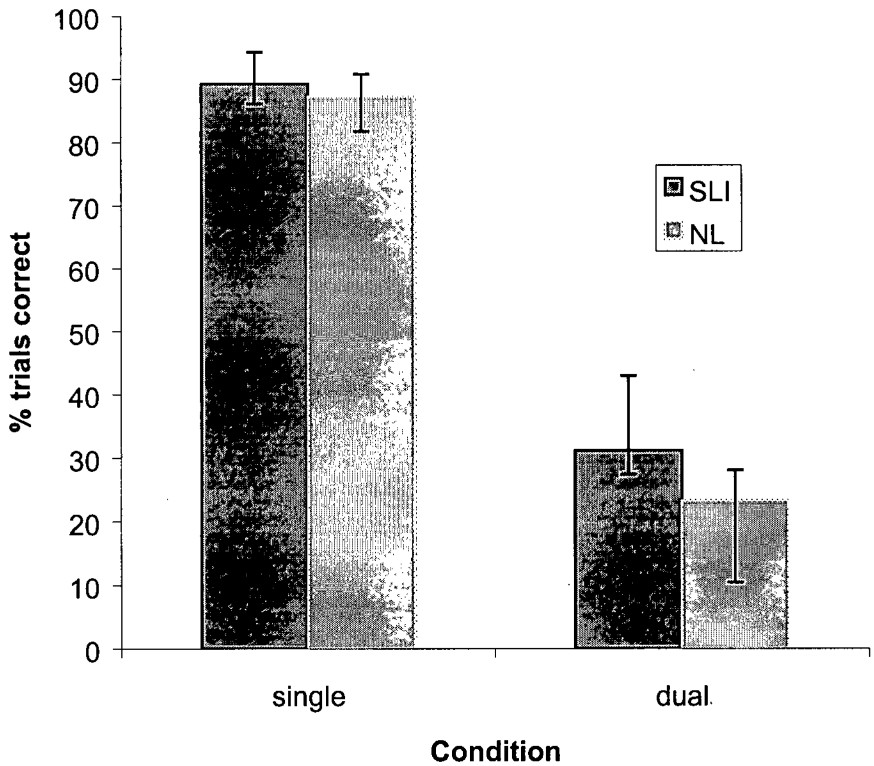


3.4.2. Interference on Visual Task

Children were required to recall the location of a predetermined number of monsters based on their individual performance levels on the single task. The dependent variable was the number of trials in which all monsters had been correctly recalled expressed as a percentage of the 20-item total. Percent correct from the single task was compared to percent correct on the dual task in a 2 (Group: SLI, NL) by 2 (Cond: Single, Dual) repeated measure ANOVA (Figure 6). The analysis yielded no main effect of

Group, $F < 1$, but did yield a significant main effect of Condition, $F(1,22) = 282.81, p < .001$, indicating that there was interference on the visual task from the auditory task (see Figure 6). The interaction between Group and Condition was not significant, $F < 1$.

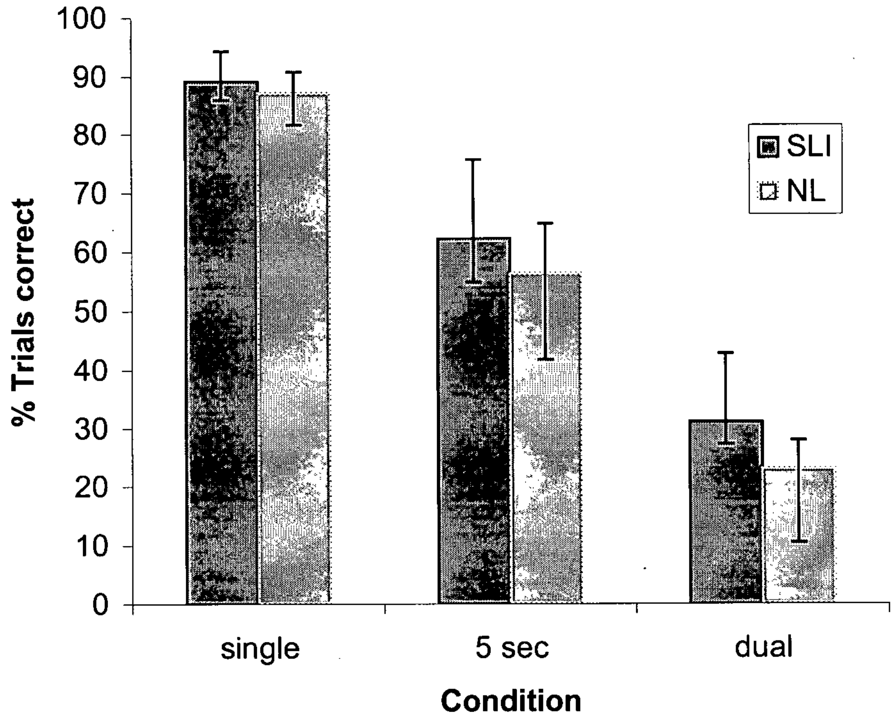
Figure 6. Mean (*M*) Trials Correct (%) for each Condition (Single, Dual) by Group (SLI, NL).



Initial analysis seemed to indicate that interference took place on the visuo-spatial task. However, the data included a confound in that the visual working memory in the dual condition involved a five second time lag that was filled with the phonological working memory task before recall was permitted, whereas the visual working memory task when presented singly required only immediate recall. The observed decrements in recall performance could simply be due to the delay in recall. To disambiguate the visuo-spatial results, children completed the visuo-spatial task in a third condition in which they were given monsters at their predetermined level, then were required to wait 5 sec before recall. This third condition allowed an examination of the effect of time separate from any interference phenomenon.

A 2 (Group: SLI, NL) x 3 (Condition: Single, 5sec, Dual) repeated measures ANOVA was conducted with the dependent variables being the percent of trials correct in each of the three conditions: immediate recall of monster locations, unfilled 5 sec delay prior to recall, and 5 sec delay prior to recall filled with nonword repetition, i.e. the dual task presentation. As can be seen in Figure 7, the SLI group performed somewhat higher than the NL group in each condition. However, the main effect of Group was not significant, $F < 1$, indicating there was no evidence that children in the SLI group performed differently from their age peers in any condition. There was also no significant interaction between Group and Condition, $F < 1$. However, a significant main effect of Condition, $F(2,44) = 109.99$, $p < .001$ indicated that there was an effect of time and/or interference on visual working memory recall. Post-hoc analyses were needed to determine the source of the main effect. Unequal N HSD with an alpha set at $p < .05$ indicated that across groups there was a significant difference between the original immediate recall condition (Single task $M = 88$, $SD = 09$) and the 5 sec delay condition ($M = 59$, $SD = 23$). This indicates that a significant decrease in accurate memory for locations was due to simple temporal delay, presumably requiring children to use rehearsal strategies in order to maintain the visuo-spatial information. As well, a

Figure 7. Mean (*M*) Trials Correct (%) for each Condition (Single, 5 sec, Dual) by Group (SLI, NL).



significant decrease in performance was found from the 5 sec delay condition ($M = 59$, $SD = 23$) to the dual condition ($M = 27$, $SD = 21$). This additional decrease seen when the two tasks were presented simultaneously indicates that the requirements of the nonword repetition task interfered with performance on the visual task.

3.5. Additional Findings

In addition to the above findings, a correlation was done between the raw score on the *Visual Sequencial Memory* subtest of the *Illinois Test of Psycholinguistic Abilities* (ITPA) and the Monster level attained by the children on the present experimental task.

The ITPA is a standardized measure of visual memory in young children and could provide external validation for the experimental task. In the ITPA task, children are shown a linear array of complex geometric forms and must recreate it with movable chips from memory. A significant correlation was found between the two visual memory tasks, $r = .61, p < .05$ indicating that our experimental task was related to standardized methods of assessing visual sequential memory.

Finally, a correlation was calculated between the number of syllables attained on the nonword repetition task in the present investigation and raw scores on the *Peabody Picture Vocabulary Test – 3rd Edition* (PPVT-III). A gamma statistic was used since there were many tied scores on the nonword repetition task variable, gamma = .78, $p < .05$. Across both groups, there was a significant and strong likelihood that children earning higher scores on the PPVT also could repeat longer nonwords. This relationship primarily reflected the poor performance of the SLI children on the repetition task.

3.6. Summary of main findings

The purpose of the present investigation was to examine the abilities of children with specific language impairment within the model of working memory proposed by Baddeley (1986). According to Baddeley's model the central executive is postulated to be involved in the coordination of information between the phonological loop and the visuo-spatial sketchpad. In order to investigate the role of the central executive in SLI, first memory spans for phonological and visuospatial information in the children with SLI were measured and compared to those in children with normal language. Second, the coordinating functions of the central executive were investigated by looking for decrements in the recall of visuo-spatial information when there is interference from a nonword repetition task and/or a decrement in the recall of phonological information when there is interference from a visuo-spatial task. Finally, the possibility that children with SLI show different patterns of decrement due to interference than children with NL was examined.

Results from this study indicated that:

1. Children with SLI repeat nonwords with one syllable as accurately as children with NL but repeat longer (2-, 3-, and 4-syllable) nonwords, taken as a set, less accurately than children with NL.
2. Children with SLI did not evidence impaired memory spans for visuo-spatial information when compared to their NL age peers.
3. There was no decrement in recall of phonological information due to interference from a visual-spatial task
4. There was a decrement in recall of visuo-spatial information due to interference from a nonword repetition task.
5. There was no difference between children with SLI and children with normal language development in the patterns or magnitude of interference in the dual-task presentation.

4. Discussion

The purpose of the present investigation was to examine the abilities of children with specific language impairment within the model of working memory proposed by Baddeley (1986). According to Baddeley's model the central executive is postulated to be involved in the coordination of information between two storage components, the phonological loop and the visuo-spatial sketchpad. In order to investigate the role of the central executive in SLI, the phonological loop and visuo-spatial sketchpad capacities of children with SLI were compared to children with normal language. Then, performance in single and dual task presentations was compared to see whether children (SLI and NL) show a decrement in visuo-spatial memory span due to interference from a phonological memory task and/or a decrement in phonological memory span due to interference from a visuo-spatial memory task. Finally, patterns of performance were also examined to see whether children with SLI show different patterns of decrement due to interference than children with NL.

4.1. Research questions

1. Do children with specific language impairment have different levels of working memory for phonological and verbal information when compared to age-matched controls?

In order to compare the phonological loop abilities of children with specific language impairment (SLI) with that of children with normal language (NL), this investigation made use of the nonword word repetition task developed by Dollaghan and

Campbell (1998). Children were required to repeat nonwords varying in length from 1-syllable to 4-syllables. A Percentage of Phonemes Correct (PPC) score was calculated for each length. Children with SLI were found to repeat nonwords with one syllable as accurately as children with NL but were found to repeat 2-, 3-, and 4-syllable words (taken together) less accurately than children with NL. In addition, the present investigation found that the "phonological working memory span" of children with SLI, as determined by the highest level at which children could successfully repeat 3 out of 4 nonwords, was significantly lower than was seen in children with NL. These findings can be interpreted as evidence that children with SLI have difficulty storing the phonological aspects of language. These general findings of impaired nonword repetition in children with SLI are supported by an extensive literature (e.g., Gathercole & Baddeley, 1990a; Dollaghan & Campbell, 1998; Gathercole & Pickering, 2000, 2001; Montgomery, 1995a). However, the findings in the present investigation varied slightly from those of other studies. Both Gathercole and Baddeley (1990a) and Dollaghan and Campbell (1998) found an interaction between group and number of syllables, with post-hoc tests pointing to significant group differences at 3 and 4, but not 1 or 2 syllable nonwords. The current investigation, in contrast, found an interaction between Group and Length when PPC were collapsed across 2-,3-, and 4-syllable nonwords. This difference may indicate that children in the present study had more difficulty with 2-syllable nonwords than has been reported elsewhere (Gathercole & Baddeley, 1990a; Dollaghan & Campbell, 1998).

If true, this divergence could reflect methodological differences between the present investigation and the studies by Gathercole and Baddeley (1990a) and Dollaghan and Campbell (1998). Whereas the present investigation examined 13 language-impaired children and 11 age-matched controls aged 6;1 to 9;8, the study by Gathercole and Baddeley (1990a) involved smaller group sizes and somewhat older children. Both these facts could have yielded relatively stronger performance on 2-syllable nonwords. In addition, Gathercole and Baddeley (as well as Montgomery, 1995a) scored the nonword repetition task in terms of overall number of nonwords correctly repeated instead of PPC, which would have accentuated group differences on longer words. There were two methodological differences between the present study and that by Dollaghan and Campbell (1998) that may have contributed to the different although not divergent results: they used intervention status rather than language testing as the criteria for group selection and their groups differed significantly on nonverbal intelligence as measured by the Test of Nonverbal Intelligence – Revised (TONI-R) (Brown, Sherbenou, & Johnsen, 1990). Despite the possible disparity in findings on 2 syllable nonwords the results of this study were consistent with the other reports in the general finding that children with SLI have more difficulty in nonword repetition than do their age peers.

Nonword repetition is widely interpreted to be a measure of ability to store language data in phonological memory (Montgomery, 1995a). Poor nonword repetition performance of the language-disordered children is hypothesized to reflect impaired phonological storage, particularly given the clear trend of difficulty in storing longer items. Within the Baddeley model, this function of storing language is handled by a slave system, the "phonological loop". Gathercole, Service, Hitch, Adams, and Service (1999) argue that one of the major constraints on an individual's ability to learn the sound patterns of new words is the ability to hold a novel sound pattern in temporary phonological memory. An extensive empirical literature pointing to the role of the phonological loop in the learning of new words (Gathercole & Baddeley, 1989; 1990b; Gathercole et al., 1999) supports this claim.

The deficits in nonword repetition observed in the present study suggest that the children with SLI had a reduced capacity to store phonological information. However, other possible explanations for the difficulty with nonword repetition are raised in the literature, and need to be considered. These include impoverished phonology, delayed lexical development, slower articulatory rate, deficient phonological encoding, and impaired perceptual processing. One explanation could be that many children with language impairment, as found in the literature (Leonard, 1999), have delays in phonological development in addition to their other language impairments. Such knowledge gaps could certainly affect performance on the repetition task. However, children in the present study were screened on the Goldman-Fristoe Test of Articulation (GFTA) (Goldman & Fristoe, 1986) which controlled for this possibility. All children were found to have all the sounds in their repertoire that were necessary to repeat all the words required in their task. As an additional check, wherever mistakes were made on nonword repetition, a search was made to determine if the child had said that sound elsewhere. This was the case for all children. Difficulty on this nonword repetition task does not seem to be attributable to the lack of availability of phonological forms.

A second explanation could be that limited lexical knowledge or lexical processing inefficiencies contribute to the inability to repeat nonwords. This is a case made extensively by Dollaghan and Campbell (1998). Gathercole et al. (1991) had found repetition accuracy in children to be sensitive to both nonword length as found in the current study and the linguistic factor of wordlikeness. Therefore, Dollaghan et al. (1993)

examined the nonwords used in the Gathercole, et al. study and concluded that the nonwords that had been used were not equally "nonsensical" in that some syllables within some nonwords actually corresponded to English words. Dollaghan et al. (1993) tested the influence of the lexical status (word or nonword) of these stressed syllables. They found that normally achieving school-age boys repeated nonwords with lexical stressed syllables significantly more accurately than nonwords with nonlexical stressed syllables. From this study, Dollaghan et al. (1993) conclude that there is a need to control, at a minimum, the lexical status of nonword syllables when constructing nonword stimuli, and they did so in their later study (Dollaghan and Campbell, 1998). These carefully constructed nonwords with minimized lexicality were the stimuli used for the present investigation. It therefore seems unlikely that prior lexical knowledge could account for group differences in repetition.

Articulation rate has been hypothesized to be a third source of difficulty with nonword repetition. However, Montgomery (1995a) found articulation rates for children with poor nonword repetition were not different from those with better nonword repetition skills. Similarly, Gathercole et al. (1999) found that speech output constraints were not related to phonological memory. They measured working memory for phonological information through a serial nonword *recognition* task in which the child simply had to indicate whether two phonological sequences were the same or different, thereby minimizing spoken output. They also measured phonological memory with more traditional measures requiring spoken *recall*; i.e., nonword repetition and digit span. They found that the relationship between working memory for phonological information and vocabulary was equally strong regardless of whether the task involved speech output skills or not. Finally, Gathercole and Baddeley (1990a) found that articulatory output problems were not the basis of poor repetition abilities, as they found no differences between nonwords with single versus clustered consonants. Taken together, these findings indicate that the difficulties of SLI children with nonword repetition are not due to difficulties articulating.

Fourth, phonological-encoding abilities have been hypothesized as the source of the working memory deficits in SLI (Montgomery, 1995a). To look at this finding, Montgomery tested whether children with SLI would demonstrate a similarity effect, independent of articulatory rehearsal. Children heard lists of words and were then shown a picture array in which they were asked to point to the pictures in the same order. The lists contained words that were phonologically similar or dissimilar. He found that both groups recalled more phonologically dissimilar words than similar thereby finding a similarity effect for both groups. Overall, children with SLI recalled fewer of both types of words than children with NL. Montgomery argues that the overall similarity effect suggests that all of the children were using phonological encoding abilities and the overall group effect suggests a deficit attributable to storage. As well, he argues that the nonsignificant interaction indicates that children with SLI were using adequate phonological encoding as distinct from deficient articulatory rehearsal. These results led him to the interpretation that children with SLI have comparable phonological encoding abilities and that therefore, their phonological memory deficit did not arise from phonological encoding difficulties.

However, Gillam et al. (1998) came to the opposite conclusion in their study of information processing by school-age children with SLI. They found poorer recall when a visual stimulus was paired with a pointing response than when it was paired with a speech response. Since the pointing response seemed to require a further manipulation of phonological codes, i.e., translation into visual print codes, they conclude that poor phonological representation is an important contributor to working memory deficiencies in SLI. These two examples highlight a current uncertainty over the phonological encoding abilities of children with SLI. It remains possible that their poor nonword repetition performance is due to poor phonological encoding abilities.

Finally, it has been proposed that impaired nonword repetition results from a difficulty with perceptual processing (Montgomery, 1995a; Dollaghan, 1998). Montgomery examined the factor of stimulus length in a nonword repetition task to determine whether a perceptual-processing deficit might be a contributing factor to the SLI children's difficulties in repeating multisyllabic nonwords. Forty-eight nonwords varying in length from 1- to 4-syllables were paired with either identical nonwords or a nonword that differed in either the initial, medial, or final phoneme. Half the pairings were the same and half were different. Children were required to listen to the nonword pairs and respond, "yes" or "no" to the question, "Were those words the same?" A significant Group x Length interaction indicated that the children with SLI discriminated equally well on the 1-, 2- and 3-syllable nonword pairs but made more errors in discrimination of the 4-syllable nonword pairs. Montgomery (1995a) interpreted these results as evidence that children with SLI may have a perceptual-processing difficulty, especially when analysing and segmenting lengthy and unfamiliar phonological input. This logic can be followed if the task is taken as a measure of perceptual, i.e., bottom-up, processing abilities. Such interpretation assumes that a task requiring only the recognition of nonwords is more amenable to phonetic analysis (as opposed to phonological analysis) than a task requiring repetition. This assumption seems reasonable if arguable. In any case, Montgomery interprets the task as one that examines perceptual processing and therefore concludes that at least some of the difficulty with nonword repetition results from perceptual dysfunction.

Stark et al. (1983) examined rate of perceptual processing and found children with language delay to be significantly different than normal children. Leonard, McGregor, and Allen (1992) build on this hypothesis and conclude that their results suggest that identifying perceptual contrasts are problematic for children with SLI. In their task children with SLI had considerable difficulty with certain syllable-final consonant contrasts as well as weak syllable contrasts. They suggest this difficulty was due to difficulty discriminating speech stimuli whose contrastive portions had shorter durations and thus were perceptually less salient than the noncontrastive portions.

In a further study of the perceptual processing abilities of children with SLI, Dollaghan (1998) presented children with auditory time-gatings of unfamiliar words; familiar, phonologically related words; and familiar, phonologically unrelated words. She found that the groups did not differ significantly in the point at which they recognized *familiar* words, but also that the subjects with SLI required more of the acoustic-phonetic signal to recognize *unfamiliar* words than did their peers. She argues that these findings suggest that poor representation and perceptual inefficiencies may contribute to slowed lexical access. As this task requires retrieval of lexical items, it is clearly a measure of higher level processes. However, as described, other research studies in this realm point to lower level perceptual processing as the source of the difficulties found with nonword repetition in children with SLI.

In summary, the findings from this study, as supported by others in the literature, suggest that children with SLI do have poorer function in the phonological loop that forms one component of the model of working memory proposed by Baddeley (1986). However, reference to difficulties with phonological loop function does not completely describe the nature of the problem. As stated, phonological loop deficiencies could be interpreted as indicating a "pure" deficit in storage (Gathercole & Baddeley, 1990a), or as indicating poor phonological encoding or inefficient perceptual processing. Further research is needed to clarify the nature of this deficit.

2. Do children with specific language impairment have different levels of working memory for visuo-spatial information when compared to age-matched controls?

Results from the current study found that children with SLI did not have significantly impaired visuo-spatial sketchpad functions when compared to their NL age peers, although there was a trend in that direction. The literature on SLI has emphasized the phonological memory deficits of children with SLI (Gathercole & Baddeley, 1990a; Dollaghan & Campbell, 1998; Montgomery, 1995b; Ellis Weismer et al., 1999). However, trends in the current study are compatible with findings such as those of Tallal et al. (1981) and Doehring (1960) that indicate that children with SLI can also have deficits outside of language. Within the framework of the Baddeley (1986) model, such results suggest that children with SLI may not have deficits that are limited to the phonological loop but rather may have difficulties in the visuo-spatial sketchpad that are analogous to, but less severe than, those seen in the phonological loop.

Even if significant group difference on the visuo-spatial task had emerged, interpretation of this finding would not be straightforward. While the children were asked to recall visual positions, we do not actually know what type of knowledge and/or processes supported this performance. One possibility is that children were using visual imagery, and hence the "sketchpad" to remember the positions. As described in Chapter One, Johnston and Ellis Weismer (1983) examined mental rotation abilities in children with language impairment and found that performance on a mental rotation task was significantly slower in children with SLI than in children with NL. Based on the pattern of performance across various degrees of rotation, the researchers took these findings as evidence of impairment in visual imagery. Lower performance on the visuo-spatial task in the current study could be seen as further evidence of such difficulty. However, the children may have used other strategies to support recall on this task. Some children were observed to use verbal coding, e.g., "it looks like a man" (referring to the configuration of monster locations); "3 over, 1 down, and in the corner"; and "This one is easy there are four in the corner". Other children seemed to encode the locations motorically by manually pointing to the monsters when they were viewing them and repeating this motoric pattern to rehearse the spatial information. Although the visual working memory task was intended to be visual-spatial, some children clearly transformed it into some other sort of memory task. Others probably did not. The difficulty in determining the cognitive processes used to solve spatial tasks has been discussed by Olson (1975), among others. Until a task is designed with better methods for determining what children are actually doing to recall visual and spatial information, the results from visual working memory tasks cannot be definitive. The current results do at least support the value of further work in this area.

Now that the phonological loop and visuo-spatial sketchpad have been considered separately, we can consider the dual-task presentation. Recall that in the final experimental task, children were required to perform the two tasks simultaneously. This presentation of the tasks allows for an examination of the role of the central executive since this component of working memory is hypothesized to be involved in the coordination of information in the modality specific storage systems. A decrement in performance in either of the slave systems compared to single task performance would suggest involvement from the central executive. Therefore the following two research questions will be considered together.

3. Do children (SLI and NL) show a decrement in working memory span for phonological information when there is a simultaneous requirement to store visuo-spatial information?
4. Do children (SLI and NL) show a decrement in working memory span for visuo-spatial information when there is a simultaneous requirement to store phonological information?

In the present study the relative demands placed on each of the component storage systems was controlled by presenting each of the memory tasks at the child's own span level. The findings indicated no decrement in performance on the nonword repetition task within the dual task presentation but there was a decrement in performance on the visuo-spatial task. Recall that children also completed the same visuo-spatial memory task at their span with a five second unfilled delay interval. Comparison of this condition to the dual task condition indicated that although a portion of the decrement could be attributed to the demands implicit in a fading signal, an additional significant decline in performance could be attributed to difficulties coordinating the two tasks simultaneously. Two further aspects of this interpretation will be discussed here: the apparent fact that interference was seen only in one modality and the apparent fact that interference occurred at all. In considering these findings, I will also review pertinent aspects of the Baddeley model, particularly as it treats the notion of limited capacity, and the functions of the central executive.

As argued by Baddeley (1986) the capabilities of each slave system in some ways determine the functions of the central executive. When demand placed on the slave system is minimal, little is required of the central executive. However, when demand on the slave system is great, the central executive is critical in resolving the problem of storage. The results of the current study suggest that resources were allocated in favour of the phonological task over the visual task.

An investigation of reasons why the phonological task took precedence leads first to an exploration of task structure. In the dual-task presentation, children were presented with a visual stimulus, then were asked to repeat nonwords, and finally were asked to recall the positions of the monsters from the aforementioned visual stimulus. This task construction logically created a bias toward better performance on the phonological task rather than the visual task, as the phonological task required an immediate response whereas the visual task required delayed recall. Providing feedback to the children regarding their performance on the visual task might have reduced this bias. However, as discussed in chapter 2, pilot testing indicated that the difficulty of the visual task made this feedback too devastating for the children. Therefore, the present investigation did have a task bias and it is likely that the attentional bias inherent in the overall structure of this specific dual-task presentation accounts for some of the performance asymmetry.

In addition to task structure, the precedence of the phonological task could be due to the automaticity of language. The cognitive schemes involved in the nonword repetition task may be more familiar and well practiced and hence require less attention than those involved in the visual working memory task. Even though they were presented in novel combinations, the individual phonemes were well known and were probably produced many times a day. The visual-spatial information could not be coded with similarly familiar visual schemes. It could thus be hypothesized that the visual task required relatively greater attentional resources. When the available resources were reduced by the need to perform a second task the system was not able to expend the resources needed to maintain the visuo-spatial information at the same level as in the single task. Note that both of these explanations for the modality asymmetries found in the present investigation are a function of task rather than a reflection of inherently differing abilities or capacities.

Regardless of the direction of interference, the finding of interference of any sort in the dual task presentation also invites explanation. Under the Baddeley model (1986) this function of allocating attentional resources is postulated to be under the control of the central executive. This component of working memory is involved in attending selectively to one stream of information while discarding others, as well as in the coordination of multiple tasks. In his discussion of findings from older adults, Baddeley (1996) suggests that age may be a variable that influences executive processes. Applying this same argument to early development, it may be that 7-9 year olds do not have efficient executive processes and that this explains the current observed decline in recall of visual information from the single to the dual task presentation. Young children may not be able to attend to the visual information while simultaneously attending to phonological information – at least not when both experimental tasks are challenging.

Kail and Bisanz (1982) argue that one area of developmental change is in the amount of attentional resources available for activating contents of the knowledge base. They state that when total attentional resources are limited, an individual's performance on two, simultaneous and attention-demanding tasks will deteriorate if the load imposed by one of the tasks increases. In support of this view, Kail and Bisanz cite evidence that seven year old children show greater interference in dual task experiments than do 11- and 20-year olds (Manis, Keating, & Morrison, 1980). In Baddeley's terms, this evidence could also be explained by inefficient or ineffective central executive functions.

Both the current study and the one reported by Irwin-Chase and Burns (2002), confirm the Kail and Bisanz conclusion that dual task presentation leads to a decrement in performance. However, unlike Manis et al. (1980), Irwin-Chase and Burns find no age differences in central executive function. The 11-year olds in their study show a performance decrement in the dual-task that is similar to that of the 7-year olds. This finding suggests that there may not be a developmental explanation for the decrement in dual-task performance observed in the present study. Although some uncertainty remains, the fact that both the current study and that of Irwin-Chase and Burns control for task difficulty and Manis et al. does not, makes this conclusion seem likely.

A study of older children and adults that examined dual-task performance on tasks matched for level might help to resolve this issue, especially if a wider range of tasks were included. When Duff (2000) examined adult performance on the storage and processing components of working memory separately and in combination, he found no decrement in performance in a dual-task when storage tasks were combined but he did find a decrement in performance when processing tasks were combined.

In summary, findings from this study indicate that even when the component tasks are equated for difficulty, simultaneous presentation leads to performance decrements. This decrement would seem to implicate central executive function, but it is not yet clear whether it reflects limitations in the amount of resource or inefficiencies in coordination. Further research is also needed to determine whether the observed decrements would disappear with increasing age

The final research questions focus on whether there is a difference in central executive function in children with SLI. The questions posed were as follows.

5. <u>Do children with SLI show a greater decrement in working memory capacity for phonological information in the dual task setting when compared to age-matched controls?</u>
6. <u>Do children with SLI show a greater decrement in working memory capacity for visuo-spatial information in the dual task setting when compared to children with NL?</u>

There was no difference for children with SLI in the decrement from single to dual task performance that was observed in either working memory task when compared to children with NL. Children with SLI showed impairment in the storage within the phonological loop and some possible minor impairment in the visual spatial sketchpad functions but the source of these difficulties was not apparently in the central executive. Once the relative difficulty of the two component tasks was controlled, the SLI and NL groups were not different in the degree of interference observed. SLI children did not evidence the dysexecutive syndrome seen in Alzheimer's patients.

These findings initially seem to be at odds with another study utilizing dual task methodology with SLI children that is described briefly by Ellis Weismer (1996). In this study children with SLI did exhibit disproportionate decrements in dual processing in comparison with the NL group. However, in her task, children were required to listen to two competing auditory stimuli. In one ear, the child heard a woman give one instruction and in the other ear they heard a man give an instruction. Children were instructed to listen and do what the woman told them to do, and then what the man told them to do. Although the Ellis Weismer study finds group differences in a dual task presentation these findings are not out of line with the current study if the results are considered within the Baddeley (1986) model.

The Baddeley model posits that auditory and visual data are stored in separate modality-specific slave systems. Since an extensive literature points to difficulties within the phonological loop for children with SLI, increased difficulty in a dual-task presentation when *both* tasks involve language is scarcely surprising. In such a dual-task, there would be both more information to store and a competition for resources within the *same* memory system. Presumably the central executive was involved in the eventual sorting out of the two messages as well as in attempting to manage the resource demands. The present investigation gave only one task in each modality, and tested children at their own level of both phonological working memory and visuo-spatial working memory, thereby burdening neither of the slave systems differentially between the groups. The finding that children with SLI were not disproportionately impaired in the dual-task may well reflect this difference in design. For all of the children, central executive functions were challenged by the need to coordinate more information, but in contrast to Ellis Weismer (1996), when the additional information was visual rather than auditory SLI children were not disproportionately affected.

Thus far I have argued that the performance decrements observed in this study are evidence of interference between tasks that occurred both for children with SLI and for children with normal language development. It is possible, however that children with SLI and children with NL showed similar decrements in visual working memory performance but for *different* reasons. In the single task, the children with NL may have used language to code the visual positions of the monsters. If so, in the dual task presentation the phonological repetition task would have interfered with this verbal coding of the visual stimuli, leading ultimately to a decrement in performance. By this line of reasoning, the performance decrement for the NL children would reflect a change in coding strategy rather than difficulty with the allocation of resources by the central executive. In contrast, the children with SLI were unlikely to be coding the visual stimuli through the use of language. They may then have experienced a decrement in visual working memory span due to a deficit in the ability of the central executive to coordinate these two systems as argued above. The current data do not allow us to choose between these alternative explanations.

The results of the current investigation do not lead to a definitive position on the role of the central executive in children with SLI. While the results point to comparable "central executive" functioning in both groups of children, the decrement in visuo-spatial recall observed in both groups also could have occurred for different, group-specific reasons. As well, even though the studies by Irwin-Chase and Burns (2002) and Manis et al. (1980) suggest that there is no groups difference for children between the ages of seven and nine, there could be group differences at age 11 or older. If so, this later development would again open the possibility that children with SLI fail to develop fully mature central executive functions, or are delayed in doing so.

4.2. Theoretical Implications

4.2.1 Implications for the Baddeley model

As well as raising important questions about the nature of SLI, the dual task results have clear implications for working memory theory. The finding of interference would seem to suggest that the resources used by the visuo-spatial sketchpad are not completely separate from the resources utilized by the phonological loop. The decrement in visual recall suggests that there is a common resource pool, and that once these resources are spent, a central system is needed to coordinate resource demands. In a model such as Baddeley's that proposes separate modality-specific storage devices each with its own resources, a decrement would not be expected if, as was true in the present study, the individual tasks were presented within available memory spans. These results may fit better within other working memory models.

4.2.2 Implications for other models

Just and Carpenter (1992) propose a working memory model that consists of a single, integrated set of processes and resources. This integration is clearly seen with respect to their notion of "limited capacity". In their "capacity" theory, storage and processing are fuelled by a limited amount of activation available in working memory. They argue that when capacity is reached, a trading relation will be seen between storage and processing. This formulation would seem more compatible with the present findings than is the Baddeley model. In the dual-task condition of the current study, each of the modality-specific tasks is presented at or near capacity since further increments in task load resulted in poor performance in the single task conditions. When the tasks are combined in a dual-task presentation, the limited amount of activation available to fuel working memory is exceeded thereby creating the interference effect observed in the visuo-spatial task. For this reason, the current study would seem to support the notion of a working memory system with an overall "limited capacity".

Using a very different theoretical conceptualization, MacDonald and Christiansen would handle the findings from the present investigation similarly to Just and Carpenter (1992) in that they too would argue for overall resource limitations, albeit formulated in terms of decreased activation within a connectionist network. Connectionists such as MacDonald and Christiansen do not, however, consider working memory to be separated from the representation of knowledge. For them, knowledge and capacity are complementary system features that emerge from the interaction of network architecture and experience. From this point of view, resource limitations cannot be considered in the abstract but must be considered as a function of connection strengths within the particular knowledge representations that are activated by particular tasks. They would want to interpret the present results with respect to connection strengths and argue that the observed decrements in recall reflect the fact that young children have weaker connections in the networks activated by these particular experimental tasks. However, in so far as generalizations about working memory can be made by talking at a more global level about "modalities", "limited resources", and "executive functions", this examination of underlying network properties may be unnecessary.

Even though they can explain interference effects, both the traditional integrated working memory model and the connectionist network model would seem to have difficulty explaining the apparent dissociations between visual and phonological/verbal memory, or between processing and storage functions, that recur in the literature. There may yet be no model that captures both the differentiation and the integration that seem to characterize working memory.

4.4. Directions for future research

In order to further examine both the role of the central executive and the separability of the slave systems, it would be fruitful (as in Duff, 2000) to use visuo-spatial and phonological tasks that tax the processing abilities of the independent systems rather than merely the storage capabilities. In the current investigation, tasks requiring phonological and visual *storage* were examined separately and within a dual-task presentation and the results suggested that central executive functions may not be a source of impairment for children with SLI. An examination of phonological and visual *processing* both separately and within a dual-task presentation (as in Duff, 2000), might lead to a different conclusion.

Duff (2000) uses a dual-task methodology to examine the nature of the central executive component of Baddeley's (1986) working memory model. He argues that dual-task studies are useful in examining the model of working memory because interference effects can indicate which tasks are controlled by the phonological loop and the visuo-spatial sketchpad and which tasks are controlled by the central executive. Duff assessed 20 undergraduate students on single and dual task performance on two pairs of memory tasks, with the phonological loop involved on one member of the pair and the visuo-spatial sketchpad on the other. One task pair required only storage of information, while the other task pair required processing of information.

Duff's storage tasks required the active maintenance of material for later serial recall while his processing tasks required an immediate response. The six tasks (four single and two dual) were, briefly, as follows. To measure phonological/verbal storage, participants were presented with double-digit numbers in the centre of a computer screen one at a time and were then asked to serially recall the presented numbers orally, 500 ms after the last number. To examine visuo-spatial sketchpad storage participants were presented with a grid consisting of 16 squares. The squares were change from black to white in a random sequence. Participants were asked to watch the display and after each trial recall the positions of the white squares by marking them on data sheets. Similar to the phonological loop storage task, white squares were activated sequentially and after a

500 ms interval the participants were prompted to recall. The dual storage task combined the phonological and visual storage tasks in that it involved the same 16 square grid except that now the randomly filled squares contained two-digit numbers. Again participants were asked to recall orally the two-digit numbers and recall the serial position of the filled squares on the data sheets. On the storage tasks, the investigators found no difference in performance for the single and dual task conditions.

For the processing task that involved the phonological loop, participants were presented aurally with stimuli lists containing monosyllabic words and nonwords. The task was to repeat the real words and ignore the nonwords. The processing task for visuo-spatial information required participants to locate a dark bordered square of approximately 2 cm^2 on a 33 cm computer screen and respond to the target by using the mouse to place the cursor anywhere with the square and click once. This caused the square to disappear and another trial to commence. In order to gradually increase the work required by the task the duration allowed to locate and respond to the stimulus was decreased from 3 seconds to 2 seconds to 1 second to 0.5 seconds. The dual task required participants to perform the two tasks; phonological loop processing and visuo-spatial sketchpad processing concurrently. No difference was found between the single and dual task performance for the phonological processing task, but on the visuo-spatial single task performance was reliably greater than dual task performance at certain target durations.

Duff (2000) takes the results from this experiment to indicate that storage of phonologically encoded material and storage of visuo-spatially encoded material uses two separate pools of resources. Processing tasks, on the other hand, seem to use a central pool of resources that is shared by both of the phonological loop and the visuo-spatial sketchpad.

Duff's study suggests at least two lines of future investigation. First, recall that processing abilities are considered to be vulnerable in children with SLI (Gillam, Cowan, & Marler, 1998; Leonard, 1999). It would therefore be interesting to examine whether a dual-task presentation of visual and phonological information requiring processing would create an increased performance decrement for these children when compared to children with NL.

Second, it would be interesting to examine the abilities of older children and adults on the current experimental tasks involving the only the storage of visual and phonological information. The findings of the current investigation seem to disagree with the findings of Duff (2000) and Swanson and Ashbaker (2002) who found that storage from one modality does not interfere with storage in the other modality. However, in these studies participants were high school students or adult, undergraduate students. The present findings may reflect cognitive limitations that are present only in younger children.

Finally, in order to determine whether the precedence placed on phonological working memory over visual working memory in the present study was due to task design, it would be useful to conduct a similar investigation in which the order of the tasks within the dual-task condition was reversed. For example, instead of viewing the visual stimulus, repeating nonwords, and then recalling the visual locations of the monsters, the task could require children to listen to a nonword, view and immediately recall the visual location of monsters, and then recall the nonword. If the precedence placed on phonological working memory in the current investigation were due to task design, the opposite finding would be expected.

4.4. Clinical Implications

The results from this study corroborate the existing evidence that children with SLI show deficits in phonological working memory as evidenced by poorer nonword repetition accuracy on nonwords greater than 2 syllables long. This suggests as argued by Dollaghan and Campbell (1998) and Ellis Weismer et al. (2000) that nonword repetition may be useful in screening school-age children for language impairment.

As well, if it is true that children with SLI have similar central executive functioning as children with NL when level of difficulty is controlled, it clearly becomes important to teach at a child's own level both in, and outside, the classroom. Within the classroom it is important to reinforce directions for material and learning at a child's level so that they are able to benefit from the instruction. Within language therapy sessions children likewise need to be supported at their level in order to progress to the next level. In fact, to assure adequate central executive function, it would be advisable to drop below the child's level in all task domains other than the one where new material is being presented.

If further research provides evidence that the central executive is deficit in children with SLI, we can focus on teaching coordinating strategies in order to make use of visual and auditory modalities simultaneously. As well, if is the storage devices that are deficient, we would focus on providing experiences that would enhance encoding abilities and improve storage.

4.5 Conclusions

The current investigation combined two modality specific storage tasks within a dual task presentation in order to examine the coordinating function of the central executive. Children with SLI exhibited deficient nonword repetition implicating the storage system responsible for speech based information, the phonological loop. Children with SLI did not show a statistically significant limitation in visual memory storage as measured through memory for object locations. There was however a trend with SLI achieving a lower visual working memory span than children with NL. Finally, in the combined task, both groups showed a decline in recall for the visuo-spatial information, implying that working memory resources had been inadequate and that there had been a need for coordinating activity in the central executive. However, there were no differences between groups in the size of the decline. This result suggests that children with SLI do not have a deficit in central executive functions, and that the working memory problems that have been reported are due to a deficit in storage. This conclusion must be treated as preliminary since alternative interpretations remain possible. In particular further research is needed on the later course of development for executive functions, the modality specificity of working memory limitations, and the differing demands of storage and processing tasks.

References

American Speech and Language Association. *Guidelines for Audiologic Screening: ASHA Desk Reference: 1997.* (Volume 4) [Electronic data].

Atkinson, R., & Shiffrin, R. (1971). The control of short-term memory. *Scientific American, 225,* 82-90.

Baddeley, A. (1986). Working memory. *Science, 255,* 556-559.

Baddeley, A. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology, 49A*, 5-28.

Baddeley, A. (1998). The central executive: A concept and some misconceptions. *Journal of the International Neuropsychological Society, 4,* 523-526.

Baddeley, A., & Hitch, G. (1974). Working memory. In G. A Bower (Ed.)., *The Psychology of Learning and Motivation, Volume 8* (pp. 47-89). New York: Academic Press.

Baddeley, A. D., & Hitch, G. J. (1994). Developments in the concept of working memory. *Neuropsychology, 8,* 485-493.

Baddeley, A., Gathercole, S. E., and Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105,* 158-173.

Baddeley, A. D., Logie, R., Bressi, S., Della Sela, S., & Spinnler, H. (1986). Dementia and working memory. *Quarterly Journal of Experimental Psychology: Human Experiment Psychology, 38A,* 603-618.

Bernstein, L. E., & Stark, R. E. (1985). Speech perception development in language impaired children: A four-year follow-up study. *Journal of Speech and Hearing Research, 50,* 21-30.

Brown, L., Sherbenou, R., & Johnsen, S. (1990). *Test of Nonverbal Intelligence 2 (TONI-2).* Austin, TX: Pro-Ed.

Brown, L., Sherbenou, R. J., & Johnsen, S. K. (1997). *Test Of Nonverbal Intelligence-Third Edition (TONI-3).* Austin, TX: Pro-Ed.

Bruyer, R., & Scailquin, J. C. (1998). The visuo-spatial sketchpad for mental images: Testing the multicomponent model of working memory. *Acta Psychologica, 98,* 17-36.

Cool Edit 2000 [Computer software]. (1999-2000). Massachusetts Institute of Technology, MA: Syntrillium Software Corporation.

Cowan, N. (1997). The development of working memory. In N. Cowan (Ed.), *The Development of Memory in childhood: Studies in Developmental Psychology*. (pp. 163-200). Hove East Sussex: Psychology Press.

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

Doehring, D. (1960). Visual spatial memory in aphasic children. *Journal of Speech and Hearing Research, 3,* 138-149.

Dollaghan, C. (1998). Spoken word recognition in children with and without specific language impairment. *Applied Psycholinguistics, 19,* 193-207.

Dollaghan, C., Biber, M., & Campbell, T. F. (1993). Constituent syllable effects in a nonsense-word repetition task. *Journal of Speech & Hearing Research, 36,* 1051-1054.

Dollaghan, C., & Campbell, T. F. (1998). Nonword repetition and child language impairment. *Journal of Speech, Language, and Hearing Research, 41,* 1136-1146.

Dollaghan, C., Campbell, T. F., Paradise, J. L., Feldman, H. M., Janosky, J. E., Pitcairn, D. N., & Kurs-Lasky, M. (1999). Maternal education and measures of early speech and language. *Journal of Speech, Language, and Hearing Research, 42,* 1432-1443.

Duff, S. C. (2000). What's working in working memory: A role for the central executive. *Scandinavian Journal of Psychology, 41,* 9-16.

Dunn, L. M., & Dunn, L. M. (1997). Peabody Picture Vocabulary Test-Third Edition (PPVT-III).Circle Pines, MN: American Guidance Service.

Ellis Weismer, S. (1996). Capacity limitations in working memory: The impact on lexical and morphological learning by children with specific language impairment. *Topics in Language Disorders, 17,* 33-44.

Ellis Weismer, S., Evans, J., & Hesketh, L. J. (1999). An examination of verbal working memory capacity in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 42,* 1249-1260.

Ellis Weismer, S., Tomblin, J. B., Zhang, X., Buckwalter, P., Chynoweth, J. G., & Jones, M. (2000). Nonword repetition performance in school-age children with and without language impairment. *Journal of Speech, Language, and Hearing Research, 43,* 865-878.

Gathercole, S. E. (1993). Word learning in language-impaired children. *Child Language Teaching and Therapy, 9,* 187-199.

Gathercole, S. E., and Adams, A. M. (1994). Children's phonological working memory: Contributions of long-term knowledge and rehearsal. *Journal of Memory and Language, 33,* 672-688.

Gathercole, S. E., and 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., and Baddeley, A. D. (1990a). Phonological memory deficits in language disordered children: Is there a causal connection? *Journal of Memory and Language, 29,* 336-360.

Gathercole, S. E., and Baddeley, A. D. (1990b). 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., and Pickering, S. J. (1999). Estimating the capacity of phonological short-term memory. *International Journal of Psychology, 34,* 378-382.

Gathercole, S. E., and Pickering, S. J. (2000a). Assessment of working memory in six- and seven-year old children. *Journal of Educational Psychology, 92,* 377-390.

Gathercole, S. E., and Pickering, S. J. (2000b). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *British Journal of Educational Psychology, 70,* 177-194.

Gathercole, S. E., and Pickering, S. J. (2001). Working memory deficits in children with special educational needs. *British Journal of Special Education, 28,* 89-97.

Gathercole, S. E., Pickering, S. J., Hall, M., & Peaker, S. M. (2001). Dissociable lexical and phonological influences on serial recognition and serial recall. *The Quarterly Journal of Experimental Psychology, 54A,* 1-30.

Gathercole, S.E., Service, E., Hitch, G.J., Adams, A.M., & Martin, A. J. (1999). Phonological short-tem memory and vocabulary development: Further evidence on the nature of the relationship. *Applied Cognitive Psychology, 13,* 65-77.

Gathercole, S. E., Willis, C., Emslie, H., and Baddeley, A. D. (1991). The influences of number of syllables and wordlikeness on children's repetition of nonwords. *Applied Psycholinguistics, 12,* 349-367.

Gillam, R. B., Cowan, N., & Marler, J.A. (1998). Information processing by school-age children with specific language impairment: Evidence from a modality effect paradigm. *Journal of Speech, Language, and Hearing Research, 41,* 913-926.

Goldman, E., & Fristoe, M. (1986). *Goldman-Fristoe Test of Articulation – Revised.* Circle Pines, MN: American Guidance Service.

Irwin-Chase, H., & Burns, B. (2000). Developmental changes in children's abilities to share and allocate attention in a dual task. *Journal of Experimental Child Psychology, 77,* 61-85.

Johnston, J. R. (1994). Cognitive abilities of children with language impairment. In R. V. Watkins & M. L. Rice (Eds.), *Specific Language Impairments in Children: Vol. 4. Communication and Language Intervention Series.* (pp.107-121). Baltimore: Paul H. Brooks Publishing.

Johnston, J. R. (1999). Cognitive deficits in specific language impairment: Decision in spite of uncertainty. *Journal of Speech-Language Pathology and Audiology, 23,* 165-172.

Johnston, J. R., & Ellis Weismer, S. (1983). Mental rotation abilities in language-disordered children. *Journal of Speech & Hearing Research, 26,* 397-403.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99,* 122-149.

Kail, R., & Bisanz, J. (1982). Information processing and cognitive development. *Advances in Child Development and Behavior, 17,* 45-81.

Kirk, S. A., McCarthy, J. J., & Kirk., W. D. (1968). Illinois Test of Psycholinguistic Abilities-Revised Edition (ITPA). Urbana, IL: University of Illinois Press.

Leonard, L. B. (1998). *Children With Specific Language Impairment.* Cambridge, MA: MIT Press.

Leonard, L. B., McGregor, K. K., & Allen, G. D. (1992). Grammatical morphology and speech perception in children with specific language impairment. *Journal of Speech and Hearing Research, 35,* 1076-1085.

Logie, R. H. (1986). Visuo-spatial processing in working memory. *The Quarterly Journal of Experimental Psychology, 38A,* 229-247.

Logie, R. H., Della Sala, S., Wynn, V., & Baddeley, A. D. (2000). Visual similarity effects in immediate verbal serial recall. *The Quarterly Journal of Experimental Psychology, 53A,* 626-646.

MacDonald, M. C., & Christiansen, M. H. (2002). Reassessing working memory: Comment on Just and Carpenter (1992) and Waters and Caplan (1996). *Psychological Review, 109,* 35-54.

MacDonald, M. C., Just, M. A., & Carpenter, P. A. (1992). Working memory constraints on the processing of syntactic ambiguity. *Cognitive Psychology, 24,* 56-98.

Manis, F. R., Keating, D. P., & Morrison, F. J. (1980). Developmental differences in the allocation of processing capacity. *Journal of Experimental Child Psychology, 29,* 156-169.

Montgomery, J. W. (1995a). Examination of phonological working memory in specifically language-impaired children. *Applied Psycholinguistics, 16,* 355-378.

Montgomery, J. W. (1995b). Sentence comprehension in children with specific language impairment: The role of phonological working memory. Journal of Speech and Hearing Research, 38, 187- 199.

Montgomery, J.W. (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. W. (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. W. (in press). Understanding the language difficulties of children with specific language impairments: Does verbal working memory matter. *American Journal of Speech-Language Pathology.*

Olson, D. (1975). On the relations between spatial and linguistic processes. In J. Eliot & N. Salkind (Eds.), *Children's spatial development.* Springfield, IL: Charles C Thomas.

Schneider, W., Eschman, A., & Zuccolotto, A. [Software manual]. (2002a). *E-Prime User's Guide.* Pittsburgh, PA: Psychology Software Tools, Inc.

Schneider, W., Eschman, A., & Zuccolotto, A. [Software manual]. (2002b). *E-Prime Reference Guide.* Pittsburgh, PA: Psychology Software Tools, Inc.

Semel, E., Wiig, E. H., & Secord, W. A. (1995). *Clinical Evaluation of Language Fundaments-Third Edition (Celf-3).* San Antonio, TX: The Psychological Corporation.

Shallice, T., & Warrington, E. K. (1970). Independent functioning of verbal memory stores: A neuropsychological study. *Quarterly Journal of Experimental Psychology, 22,* 261-273.

Stark, R. E., Tallal, P., Kallman, C., & Mellits, E. D. (1983). Cognitive abilities of language delayed children. *Journal of Psychology, 114,* 9-19.

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.

Tallal, P., & Piercy, M. (1973). Developmental aphasia: Impaired rate of non-verbal processing as a function of sensory modality. *Neuropsychologia, 11,* 389-398.

Tallal, P., Stark, R. E., Kallman, C. & Mellits, E. D. (1981). A reexamination of some nonverbal perceptual abilities of language-impaired and normal children as a function of age and sensory modality. *Journal of Speech and Hearing Research, 24,* 351-357.

Tallal, P., Stark, R. E., & Mellits, E. D. (1995a). Identification of language-impaired children on the basis of rapid perception and production skills. *Brain and Language, 25,* 314-322.

Tallal, P., Stark, R. E., & Mellits, E. D. (1995b). The relationship between auditory temporal analysis and receptive language development: Evidence from studies of developmental language disorder. *Neuropsychologia, 23,* 527-534.

Thorn, A. S. C., & Gathercole, S. E. (2000). The development and impairment of working memory. *Revue de Neuropsychologie, 10,* 417-439.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28,* 127-154.

Warrington, E. K., & Shallice, T. (1969). The selective impairment of auditory verbal short-term memory. *Brain, 92,* 885-896.