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Comparing the contribution of two tests of working memory to reading in relation to phonological awareness and rapid naming speed

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The purpose of this study was to compare the contribution of two different versions of working memory to word reading and reading comprehension in relation to phonological awareness and rapid naming speed. Fifty children were administered two measures of working memory, namely an adaptation of the Daneman and Carpenter sentence span task and Sentence Question, tests of phonological awareness, rapid naming speed, word reading and reading comprehension. The results indicated that Sentence Question accounted for unique variance over and beyond the effects of Daneman and Carpenter's sentence span task, whereas the latter did not when the effects of Sentence Question were partialled out. In addition, both phonological awareness and rapid naming were accounting for unique variance beyond the effects of working memory in predicting reading. The role of working memory on reading is discussed, and future directions for research are suggested.

There is little disagreement that phonological processing, defined as the use of the sound structure of oral language in processing written and oral information, is of paramount importance for reading acquisition (e.g. Bryant, Bradley, Maclean & Crossland, 1989; De Jong & Van der Leij, 1999; Manis, Doi & Bhadha, 2000; Muter, Hulme, Snowling & Stevenson, 2004; Parrila, Kirby & McQuarrie, 2004; Stanovich, 1992; Torgesen, Wagner, Rashotte, Burgess & Hecht, 1997). Phonological awareness and rapid naming speed, two aspects of phonological processing, have been known to be associated with reading for some years now, and this association has gained importance in understanding poor reading as well as in guiding programmes aimed at remediation of reading difficulties (e.g. Clarke, Hulme & Snowling, 2005; Kirby, Parrila & Pfeiffer, 2003; Lovett, Steinbach & Frijters, 2000; Powell, Stainthorp, Stuart, Garwood & Quinlan, 2007; Scarborough, 1998; Stanovich, 1992; Wolf & Bowers, 1999). However, several researchers have pointed out that rapid naming speed and phonological awareness alone cannot account for all that is known about reading development and reading disabilities (e.g. Das, 1995; Share & Stanovich, 1995). Subsequently, several researchers have turned their interest to more fundamental cognitive processing skills that may underlie phonological processing and, consequently, reading (e.g. Das & Papadopoulos, 1998; Goswami et al., 2002; Nation & Snowling, 2004; Nicolson & Fawcett, 1995; Savage & Frederickson, 2005; Siegel, 1993).

One of the most popular cognitive processes linked to reading comprehension is working memory (e.g. Alloway, Gathercole, Willis & Adams, 2005; Baddeley, 1986; Daneman & Carpenter, 1980; Engle, Cantor & Carullo, 1992; Friedman & Miyake, 2004; Gathercole, Brown & Pickering, 2003; Swanson & Howell, 2001). The concept is simply defined as the capacity to store information for a short period of time and manipulate or process it (e.g. Baddeley & Hitch, 1974; Gathercole, 2007). Processing rather than storage is prominently identified with a 'central executive capacity' within the short period of time that characterises working memory. The 'executive' is helped by at least two prominent capacities, a phonological loop that keeps alive the sound-related structure of the input and a visual–spatial sketch pad with its capacity for maintaining nonverbal information. This is the received view of working memory, although a recent component, episodic buffer, has been added 'which is responsible for the integration of cognitive events across different representation domains' (Gathercole, 2007, p. 234). However, several terms used in conceptualising working memory are not well understood, especially when complex executive functions such as inhibition and strategy shifting are included as integral functions of the 'central executive'. The executive has to operate within a short-term memory constraint in a limited-capacity model. Naturally, then, working memory would be one of the determinants of a complex ability, such as reading comprehension. Once word-reading skills are established, higher-level skills associated with meaning construction are expected to have important roles in comprehension (e.g. Cain, Oakhill & Bryant, 2004; Swanson & Berninger, 1995).

Despite the acknowledged importance of working memory for reading, there are still unresolved issues regarding its contribution. Studies vary greatly in terms of when working memory and reading outcomes are measured, how working memory is operationalised, what other predictors are in the regression equation and whether covariates are included. For example, most would agree that some sort of general cognitive ability measure should be included in regression analyses predicting reading ability. However, it stands to reason that if working memory is another index of general intelligence (e.g. Ackerman, Beier & Boyle, 2005; Friedman et al., 2006), then controlling for general intelligence would leave no room for unique variance from working memory.

Previous studies on working memory have reported contradictory findings. For example, Schatschneider, Harrell and Buck (2007) found that working memory, measured with an adapted version of Gaulin and Campbell's (1994) Competing Language Processing Task, which is similar to the reading span task developed by Daneman and Carpenter (1980), did not account for unique variance in reading comprehension once the effects of oral reading fluency and reasoning skills were controlled for. Similar to Schatschneider et al. (2007), McCallum et al. (2006) demonstrated that working memory, operationalised with a visual and an auditory letter memory task was not accounting for unique variance in reading comprehension, after controlling for age, phonological awareness, rapid naming speed and orthographic processing. However, working memory was found to account for approximately 3% of unique variance in word decoding and 12% of unique variance in silent word reading fluency. In contrast, the work of Swanson and colleagues (e.g. Swanson, 2000; Swanson & Alexander, 1997; Swanson & Howell, 2001) suggests that working memory plays an important role in both word reading and, particularly, reading comprehension. For example, Swanson and Alexander (1997) showed that working memory, operationalised with a sentence span task, a counting span task and a visual–spatial span task, was accounting for unique variance in reading comprehension, in both skilled readers and learning-disabled readers, even after controlling for age, phonological awareness and general word analysis.

Processing against storage in working memory

Working memory span tests are the measures used most widely to examine the contribution of working memory to various cognitive abilities (see Jarrold & Towse, 2006; Savage, Lavers & Pillay, 2007, for recent reviews). An important characteristic of the working memory span test is that unlike short-term memory measures (e.g. forward digit span or word span) with their emphasis on storage, these tests require simultaneous storage and processing of information. For example, the reading span test developed by Daneman and Carpenter (1980) requires the participants to remember several words (storage component) while simultaneously reading aloud or verifying the truthfulness of sentences (processing component). Under the light of this dual-task nature of working memory span tests, an examination of the relationships between storage and processing is a promising approach to understanding what working memory span tests actually measure and, most importantly, which component (processing, storage or both) is the one that is actually responsible for the working memory–reading relationship.

The distinction between processing and storage has propelled several studies and generated competing hypotheses (e.g. Daneman & Carpenter, 1980; Duff & Logie, 2001; Friedman & Miyake, 2004; Maehara & Saito, 2007; Towse & Hitch, 1995). Initially, Daneman and Carpenter (1980) suggested that there is a trade-off between processing and storage components. Specifically, an increase in the amount of processing requirements should result in a decrease in the number of memory materials able to be stored, and an increase in the number of memory materials should result in a decrease in processing efficiency. More recently, Towse and colleagues (Towse & Hitch, 1995; Towse, Hitch & Hutton, 2002) proposed an alternative hypothesis, according to which participants switch their attention from processing to storage task requirements and vice versa. In contrast to Daneman and Carpenter's hypothesis, if Towse and colleagues' hypothesis is correct, then there should be little or no relationship between processing and storage requirements in sentence span tests (the processing–storage independence assumption).

However, it is difficult to apportion the amount of contribution of each component to a reading span test. Storage in the sentence span test is critically dependent on techniques to retain the information in the articulatory/phonological loop, especially in listening rather than when digits or words are read. Could it be so, as Waters and Caplan (1996) point out, that in Daneman and Carpenter's sentence span task, only storage is measured although the task requires both storage and processing?

Daneman and Carpenter's sentence span test has also been examined in terms of the usual demands of sentence comprehension. The usual demands of sentence comprehension include the speed and accuracy of syntactic and semantic processing. Caplan and Waters (1999) have argued after reviewing a number of studies that individuals with high to low sentence span in Daneman and Carpenter's working memory test do not differ in comprehension and that low-span individuals may be more affected than high spans by some 'sentential features', such as the number of propositions in a sentence or background knowledge related to the semantic content of the sentence. These have a major influence on sentence processing.

One conclusion from the various considerations of this issue is that while comparing different working memory measures for predicting comprehension, at least these two competing influences on comprehension, working memory and linguistic operations must be jointly examined.

Planning, Attention, Simultaneous and Successive processing theory

One way of testing the nature of Daneman and Carpenter's sentence span task and its contribution to reading is to compare it with a similar task that has, admittedly, more processing demands, albeit similar storage requirements. We are doing this within the framework of PASS (Das, Naglieri & Kirby, 1994) theory, which is based on Luria's (1966) work on the functional organisation of the brain and proposes that cognition is organised in three systems. The first is the Planning system, which is the executive control system responsible for controlling and organising behaviour, selecting or constructing strategies and monitoring performance. The second is the Attention system, which is responsible for maintaining arousal levels and alertness and for ensuring focus on appropriate stimuli. The final system is the information processing system, which employs Simultaneous and Successive processing to encode, transform and retain information.

Speech Rate (the fast repetition of three simple words), Naming Time (naming rows of single letters, digits, colour strips or simple and familiar words) and Sentence Repetition and Question (the serial memory tasks for words and repeating a sentence) have been used to operationalise Successive processing. All of the above tasks demand storage and articulation more than processing of the stored information. The Sentence Question task engages both processing and storage, that is, the central processing unit and the phonological loop in terms of the working memory model (Baddeley & Hitch, 1974). We assume that it is a test of verbal working memory that is likely to be a predictor of comprehension. However, unlike Daneman and Carpenter's sentence span, Sentence Question has reduced semantic load while retaining a meaningful syntactic frame for each of its sentences.

Comments from Luria regarding memory for sentences are appropriate at this point. Luria (1976) in discussing mnemonic processes reported that whereas 7–10 isolated words could not be remembered after first presentation, the same words organised in a sentence could be recalled easily. So stable was the memory that recall did not diminish even when another sentence was read between the presentation of the first sentence and its recall. He attributed the stability to semantic organisation. As long as brain lesions did not touch the area responsible for semantic organisation (occipital-parietal and frontal regions), recall was not impaired (by lesions of the upper part of the brain-stem and pituitary tumours that produced mild mnemonic disorder). Thus, semantic organisation facilitates Sentence Repetition and questioning in our test. As we enhance the role of semantic organisation, by adding Questioning, and demanding delayed recall of the last words in a set of three or four sentences, we suggest that we are likely enhancing working memory.

Craik and Lockhart (1972) proposed the 'levels-of-processing' theory according to which learners may engage in different levels of elaboration as they process information. This is done on a continuum from perception, through attention, to labelling and, finally, meaning. Sentence Question clearly requires a deeper, semantic level of processing in line with Luria's thinking discussed above: deeper than that necessary for answering 'yes' or 'no' in Daneman and Carpenter's sentence span task; in Sentence Question the whole sentence has to be remembered and recalled in order to answer the question. Processing level is thus deeper whereas storage demands are comparable for the two tests (store the last word).

Overview of the current study

The purpose of the present study was to compare the relative contribution of two tests of working memory (Daneman and Carpenter's sentence span and Sentence Question) as direct predictors of word reading and comprehension in relation to the well-established contribution of phonological awareness and rapid naming speed. We hypothesised that:

1. Sentence Question will be a stronger predictor of reading comprehension than the Daneman and Carpenter sentence span task, because of the increased processing demands involved in the task.
2. Phonological awareness and rapid naming speed will be significant predictors of word reading and reading comprehension, and their contribution will be independent from each other and of working memory.

If working memory is an example of distal cognitive processing (Das, 1995; Siegel, 1993), then its contribution to reading should be viewed within a broader framework that includes proximal cognitive processing skills, such as phonological awareness and rapid naming speed. The relationship of rapid naming speed to both tasks of working memory is of particular importance in light of recent theoretical accounts suggesting that rapid naming speed may be an index of the effectiveness of working memory (e.g. Amtmann, Abbott & Berninger, 2007).

Method

Participants

Fifty English-speaking Canadian children attending Grades 3 and 4 (26 boys and 24 girls, ages 8 years and 10 months to 10 years and 7 months, $M = 9.27$, $SD = .67$) participated in this study. All of the children were from predominately low-SES families residing in a rural community outside Edmonton. None of the children had an official diagnosis for any reading or behavioural problems and none of them was receiving any special education services.

Measures

Working memory. Both of the working memory tasks were designed to tap storage and processing functions of working memory. Each task involved word span and sentence comprehension components. The sentences were presented in groups that ranged in size from two to five sentences per group (we refer to a group of sentences as one *item*). Word recall was prompted at the completion of each item. For each task the participant's memory span score was the item with the highest number of sentences in which all or the majorities of words were recalled accurately and in the correct order. For example, if a child correctly recalled three out of four 4-sentence-level words s/he was assigned a sentence span of (4). Additionally, we followed Daneman and Carpenter's (1980) partial scoring criteria. If the child correctly recalled only one word at a particular sentence level s/he was given a credit of (.5). For example, a child who correctly recalled two out of three 3-sentence-level words and s/he also correctly recalled one of the 4-sentence sets s/he was assigned a sentence span of (3.5).

Daneman and Carpenter memory span task. This task was adapted from Daneman and Carpenter (1980). Children listened to groups of sentences and were asked to determine if each sentence was true or false (e.g. 'All mothers work in an office'). Children were instructed to keep the last word in each sentence in their memory and then after completing a sentence group they were asked to say the last word in each sentence in the same order. For this task sentences were presented in groups that range in size from two to five. Word recall was prompted at the completion of each sentence group (see Appendix A).

Sentence Question memory span task. This task was adapted from the Cognitive Assessment System (CAS; Naglieri & Das, 1997). The children were asked to answer questions about nonsensical sentences in which the content words were replaced by colour words (e.g. 'The yellow greened the blue. Who greened the blue?'). Thus, the children could use syntactic cues, but not semantic cues to answer the questions. The sentences were all four to six words in length. After answering each question the children were instructed to keep the answer in their memory and then after answering a set of questions they were asked to say the answers given to each questions in the same order. The sentences were presented in groups that ranged in size from two to four. Word recall was prompted at the completion of each sentence-level group (see Appendix B).

The two working memory tasks were similar in both sentence length and syntactic complexity. However, we were concerned that prior knowledge might influence comprehension resulting in possible advantages/disadvantages for children. In the Daneman and Carpenter task children should actively access prior world knowledge in order to complete the comprehension component successfully. Additionally, this task required children to respond to the truth-value of the sentences (i.e. true/false), thus increasing the chance of receiving a correct response on the comprehension component by chance. In contrast, the Sentence Question task consisted of nonsense sentences that followed English sentence word order. Colour words replaced nouns and verbs to reduce the effects of prior world knowledge on comprehension success. A further difference relates to task demands of the span component in each task. On one hand, in the Daneman and Carpenter's task children were required to process and respond to the truth-value of the sentence while holding the last word they heard in each sentence in working memory. On the other hand, Sentence Question task required children to process and provide specific answers to questions and then hold those answers in working memory. Thus, the two tasks had different demands in both comprehension and span components.

Phonological awareness

Phoneme elision. The Phoneme Elision task from the CTOPP (Wagner, Torgesen & Rashotte, 1999) was used as a measure of phonological awareness. This task measures the extent to which an individual can say a word and then say what is left after dropping out designated sounds. The task consists of 20 items. For the first two items, the examiner says compound words and asks the examinee to say the word, and then say the word that remains after dropping one of the compound words. For the remaining items, the individual listens to a word and repeats the word, and is then asked to say the word without a specific sound. A participant's score was the number of correct responses. Wagner et al. (1999) reported test–retest reliability of .79 for Phoneme Elision for ages 8–17.

Word Segmentation. Word Segmentation task was adopted from CTOPP as well (Wagner et al., 1999). It consists of 20 items and it measures the ability of an individual to say separate phonemes that make up a word. The examinee was told to repeat a word, then to say it one sound at a time. For example, the examiner tells the examinee to say 'book' and then to say it one sound at a time. A participant's score was the number of correct responses. Wagner et al. (1999) reported test–retest reliability of .79 for Word Segmentation for ages 8–17.

Rapid naming speed

Digit naming. This task was adopted from the CTOPP (Wagner et al., 1999). This Rapid-Automatised Naming (RAN) task consists of a set of six digits (4, 7, 8, 5, 2, 3) that are displayed in random sequence six times for a total of 36 stimuli. Participants were asked to name the digits from left to right as quickly as possible and the total time to complete the RAN task was recorded. Before naming the 36 digits, each participant was asked to name the digits in a practice trial. Wagner et al. (1999) reported test–retest reliability of .80 for Digit Naming for ages 8–17.

Letter naming. This task was also adopted from the CTOPP (Wagner et al., 1999). Participants were asked to name as fast as possible the names of six letters (a, n, s, t, k, c). Letters were arranged randomly in four rows of nine letters in each row. As in the other naming speed tasks, children were asked to name the six letters in a practice trial before proceeding to the timed trials. The two pages were timed separately. Wagner et al. (1999) reported test–retest reliability of .72 for Letter Naming for ages 8–17.

Word reading. The Woodcock–Johnson Tests of Achievement (WJIII) (Woodcock, McGrew & Mather, 2001) were used to assess word reading ability. The Word Identification subtest involves the reading of individual words with some early items that require correct letter identification. All reading tests scores were calculated using the accompanying computer scoring programme. Woodcock et al. (2001) reported split-half reliability of .94 for children 9 years old.

Reading comprehension

Passage Comprehension (Woodcock et al., 2001). This subtest uses a cloze procedure that requires the subject to read sentences missing a word that is important to the meaning of the sentence or passage. Participants must supply a word that fits the meaning of each sentence or passage. The task was discontinued after six consecutive mistakes. The individual's score was the total number of correct responses. Woodcock et al. (2001) reported split-half reliability of .91 for children 9 years old.

Procedure

This study involved individually administered tests. Assessment was carried out by graduate-level students who had some training in individual psychological test administration. Testing typically took place in a quiet room within the school. In terms of test order, the children were administered first the phonological awareness and the RAN tests followed by the two working memory tasks and the reading measures. Testing lasted approximately 40–50 minutes. Parents' consent was obtained prior to testing.

Results

Descriptive statistics

Table 1 presents the descriptive statistics for all the measures used in the study. An initial examination of the distributional properties of the measures revealed that both RAN measures were moderately skewed. Log transformation was used to achieve normality (Tabachnick & Fidell, 2001). In addition, Word Segmentation was negatively skewed and kurtic. Log transformation plus reflection were used to achieve normality. Compared with

Table 1. Descriptive statistics for all the measures used in the study.

	M	*SD*	Range
SQ_WM span	1.99	.89	1–4
DC_WM span	1.44	.45	1–3
RAN-digits	43.38	12.69	21–103
RAN-letters	48.76	17.78	26–143
Phoneme Elision	10.28	4.28	3–18
Word Segmentation	9.96	1.88	3–14
Word Identification	39.78	7.39	19–52
Reading Comprehension	21.80	3.80	11–30

Note: SQ, Sentence Question; DC, Daneman and Carpenter; WM, working memory; RAN, Rapid-Automatised Naming.

Table 2. Zero-order correlations and partial correlations (controlling for age) between all the measures in the study.

	1.	2.	3.	4.	5.	6.	7.	8.
1. SQ_WM		.37**	−.16	−.19	.31*	.39**	.37**	.39**
2. DC_WM	.37**		−.28*	−.33*	.12	.07	.28*	.31*
3. RAN-digits	−.15	−.29*		.76**	−.17	−.21	−.39**	−.32*
4. RAN-letters	−.18	−.34*	.76**		−.26	−.25	−.55**	−.39**
5. Phoneme Elision	.31*	.13	−.17	−.24		.10	.57**	.42**
6. Word Segmentation	.39**	.07	−.18	−.21	.10		.38**	.47**
7. Word Identification	.39**	.32*	−.39**	−.54**	.54**	.35*		.77**
8. Passage Comprehension	.40**	.35*	−.32*	−.36*	.38**	.45**	.74**	

Notes: Zero-order correlations are above the diagonal. Partial correlations are below the diagonal.
SQ, Sentence Question; DC, Daneman and Carpenter; WM, working memory; RAN, Rapid-Automatised Naming.
*$p < .05$; **$p < .01$.

the norms, the participants of this study were reading below grade level in both Word Identification (Grade Equivalent = 2.7, *M* standard score = 88.84, *SD* = 10.86) and Passage Comprehension (Grade Equivalent = 2.5, *M* standard score = 87.86, *SD* = 8.29). Thus, as a group it could be characterised as comprising poor readers.

Correlations between the different measures

Table 2 presents the zero-order and partial (controlling for age) correlations among the measures used in the study. Because there were no significant differences between the two types of correlations we will discuss only the zero-order correlations. The correlational analysis indicated that working memory, as measured with the Sentence Question task, was only weakly correlated ($r = .37$) with the Daneman and Carpenter sentence span task. In addition, Sentence Question was more highly correlated with Word Identification and Passage Comprehension than the Daneman and Carpenter sentence span task. Indicative also perhaps of different processing demands in the two working memory tasks were the correlations with the phonological awareness and the rapid naming tasks. Notably, Sentence Question was significantly correlated with phonological awareness, but not with rapid naming. In contrast, the Daneman and Carpenter sentence span task was significantly correlated with rapid naming but not with phonological awareness. The correlation coefficients between Sentence Question and phonological awareness were similar to the ones reported in previous studies (e.g. Oakhill & Kyle, 2002; Rohl & Pratt, 1995). Both rapid naming and phonological awareness were significantly correlated with Word Identification and Passage Comprehension. In contrast to what would have been expected, Phoneme Elision and Word Segmentation were not significantly correlated. On the other hand, the RAN measures were strongly correlated with each other, but were only weakly correlated with phonological awareness measures. This is in line with arguments put forward by many researchers that rapid naming and phonological awareness are likely independent from each other (e.g. Bowers, 1995; Compton, DeFries & Olson, 2001; Manis et al., 2000; Parrila et al., 2004; Powell et al., 2007; Savage & Frederickson, 2005; Wolf & Bowers, 1999).

Regression analyses

In order to examine the effects of working memory, phonological awareness and rapid naming speed on word reading and reading comprehension, hierarchical regression analysis was used. Table 3 presents the results of this analysis. First, we examined the effect of the two working memory tasks on the dependent variables, after controlling for age (entered at step 1 of the regression equation as a control variable). When Sentence Question was entered at the second step of the regression equation it accounted for 12% of unique variance in Word Identification and 14% of unique variance in Reading Comprehension. The Daneman and Carpenter sentence span task (entered at step 3) did not account for any unique amount of variance in any reading outcome. When the order of entry was reversed, the Daneman and Carpenter sentence span task accounted for 9% of unique variance in Word Identification and 11% of variance in Reading Comprehension. However, Sentence Question still accounted for 7% and 8% of unique variance in Word Identification and Reading Comprehension, respectively, over and beyond the effects of age and the Daneman and Carpenter sentence span task. This finding is particularly interesting and we will elaborate more on it in the Discussion.

Table 3. Results of hierarchical regression analyses.

		Word Identification		Passage Comprehension	
Step	Variable	β	ΔR^2	β	ΔR^2
1.	Age	.354	.12*	.342	.12*
2.	SQ_WM	.351	.12**	.378	.14**
3.	DC_WM	.208	.04	.219	.04
2.	DC_WM	.302	.09*	.356	.11*
3.	SQ_WM	.294	.07*	.263	.08*
2.	SQ_WM	.351	.13**	.367	.13**
3.	Elision	.453	.18***	.268	.06*
4.	RAN-letters	−.405	.15***	−.238	.05
3.	RAN-letters	−.456	.19***	−.279	.07*
4.	Elision	.364	.11**	.219	.04
2.	Elision	.417	.41***	.297	.19***
	RAN-letters	−.410		−.270	
3.	SQ_WM	.184	.03	.268	.06*

Note: WM, working memory; DC, Daneman and Carpenter; RAN, Rapid-Automatised Naming.
*$p<.05$; **$p<.01$; ***$p<.001$.

Next, we examined the effect of phonological awareness and rapid naming speed on reading beyond the effects of age and working memory. Sentence Question, Phoneme Elision and RAN letters were chosen to represent working memory, phonological awareness and rapid naming speed, respectively, because they had the highest correlations with the reading measures. Similar to previous studies (e.g. Parrila et al., 2004) both phonological awareness and rapid naming accounted for unique variance over and beyond the effects of age and working memory. Rapid naming was still accounting for unique variance in word reading even after controlling for age, working memory and phonological awareness. Likewise, phonological awareness was accounting for unique variance in word reading even after controlling for age, working memory and rapid naming. In contrast to word reading, neither phonological awareness nor rapid naming explained unique variance in Reading Comprehension when they were entered at step 4 of the regression equation. Finally, we examined if working memory was accounting for unique variance beyond the effects of phonological awareness and rapid naming. The results indicated that working memory did not account for unique variance in Word Identification but did explain a significant 6% of unique variance in Reading Comprehension. This finding reinforces those of previous studies showing that working memory is particularly important for reading comprehension.

In summary, Sentence Question was accounting for unique variance over and beyond the Daneman and Carpenter memory span task. This raises the possibility that something else involved in Sentence Question that is not present in Daneman and Carpenter's memory span task may be important for reading. Beyond the effects of working memory both phonological awareness and rapid naming accounted for unique variance in reading outcomes. Finally, working memory was a unique predictor of Reading Comprehension, but not word reading, once the effects of phonological awareness and rapid naming were partialled out.

Discussion

The objective of the present study was to compare the contribution of two working memory tasks, namely the Daneman and Carpenter sentence span and Sentence Question, on word reading and reading comprehension in relation to the well-established contribution of phonological awareness and rapid naming speed. The results showed that the relationship between the two working memory tasks was rather weak ($r = .37$), suggesting that despite the same format of tasks, the underlying processing demands may, in fact, be different. If the Daneman and Carpenter sentence span requires more storage than processing, as suggested by Waters and Caplan (1996) and if Sentence Question requires more processing than storage, then the low correlation between the two tasks may provide evidence in support of Towse and Hitch's (1995) hypothesis for functional independence between processing and storage in working memory. Consistent with our first hypothesis, when we examined the unique contribution of each task to reading, we found that the Daneman and Carpenter sentence span test was not accounting for unique variance in reading once the effects of Sentence Question were partialled out.

We used correlations and regression analyses, treating the Daneman and Carpenter sentence span and Sentence Question as continuous variables rather than dividing groups into high or low span, as has been done in many studies that are criticised by Caplan and Waters (1999). Our overall conclusion supports the importance of working memory, measured with Sentence Question, on reading comprehension. Daneman and Merikle

(1996), in a meta-analysis of 77 studies on working memory, reported an average correlation of .41 (95% confidence interval = .38–.44) between sentence span and reading comprehension. In contrast, they reported that the correlation between comprehension and simple storage tasks, such as the word span task, are typically lower, around .28 (95% confidence interval = .23–.33). The correlations observed in this study between reading comprehension and Sentence Question ($r = .39$) but also between reading comprehension and the Daneman and Carpenter sentence span task ($r = .31$) are well within the reported range.

Despite the relatively smaller contribution of the Daneman and Carpenter sentence span to reading compared with Sentence Question, its power as a determinant of reading cannot be minimised. In the majority of the studies on working memory, the sentence span test has been entered first in the regression analyses before the effects of other cognitive processing skills are controlled (e.g. Cain et al., 2004; Leather & Henry, 1994; Rohl & Pratt, 1995). Consistent with the findings of these studies, our study has shown that the Daneman and Carpenter sentence span task was accounting for 9% of unique variance in Word Identification and 11% of unique variance in Reading Comprehension, when only the effect of age was partialled out.

We need to fractionate working memory itself beyond the three units of phonological, visual–spatial slave systems and central executive processing (Baddeley & Hitch, 1974) in order to understand the relative contribution of the two working memory tests, Daneman and Carpenter's sentence span and Sentence Question, on reading comprehension. The central executive processing unit already seems to be stretched, anyway, as adherents of original working memory model attempt to raise it to the status of a comprehensive executive processor (Clair-Thompson & Gathercole, 2006). Therefore, a forceful suggestion for fractionation of working memory, mainly central processing, by Caplan and Waters (1999) is not surprising for the purpose of sentence comprehension. Briefly, they distinguish between 'interpretive processing' for the purpose of meaning extraction, and 'post-interpretive processing' for extracted meaning to accomplish other tasks, such as for storing information in long-term semantic memory, reasoning and planning actions. Not everyone in memory research agrees with this distinction as is evident in the peer reviews that followed Caplan and Waters' (1999) article. Suffice it to say that the concept of working memory is still being debated, and alternative interpretations to account for individual differences in comprehension are being actively explored (Cowan, 2000). The aspects of comprehension that require reasoning and planning could very well encourage us to adopt a broader perspective of cognitive processes, such as the PASS processing theory that finds planning and simultaneous processing to be necessary for comprehension (e.g. Das et al., 1994).

The role of episodic buffer on text comprehension is also of particular interest. We may be reminded that although episodic buffer has limited capacity, (1) it integrates information from a range of sources into a single complex structure or episode, (2) it acts as an intermediary between the subsystems, combining them into a unitary multi-dimensional representation and (3) it engages in active binding, which is highly demanding of the central executive (Baddeley & Wilson, 2002). The implication of this fourth component of working memory for our two working memory tasks may be clear, but perhaps is not any more capable of explaining comprehension than the existing PASS components. In Luria's notion, as we have discussed, it is the semantic organisation of the contents of the two tasks that helps working memory. To elaborate further, *Successive* or sequential arrangement of the words in a syntactic structure is the prime characteristic of each of the two tasks, and the bond is strengthened by a semantic analysis of the sentences. Both processes operate on information that is already available in an integrated form, similar to a unitary multidimensional representation (zone of overlapping associations in Luria's term). To support this, consider that Simultaneous processing refers to the synthesis of separate elements into groups, these groups often taking on spatial overtones. Successive processing refers to processing information in a serial order. A system of cues consecutively activates the components in the series. Luria observed that grammatical structures, as prominent in the two tasks we have used, have to be understood in terms of simultaneous synthesis, whereas sequential structures are affected by successive synthesis (Das, Kirby & Jarman, 1979). Over and beyond this, higher-order executive functions are in the domain of Planning, broadly a function of the frontal lobes; these are also suggested as the location for executive functions of episodic buffer. Perhaps, then, we can argue that a comprehensive model of cognitive processing that involves four major cognitive processes and is not constrained by short longevity of working memory has an explanatory advantage.

The findings of this study also add to the long list of significant contributions of phonological awareness and rapid naming to reading ability (e.g. Compton et al., 2001; De Jong & Van der Leij, 1999; Kirby et al., 2003; Manis et al., 2000; Parrila et al., 2004; Powell et al., 2007). However, the findings of this study show also that phonological awareness and rapid naming speed are rather independent from each other, at least when word reading was used as a dependent variable. On the other hand, this is not the case when reading comprehension was the dependent variable as the results indicate that controlling for the effects of age, working memory and phonological awareness revealed a nonsignificant contribution of rapid naming. Similarly, controlling for the effects of age, working memory and rapid naming resulted in a nonsignificant contribution of phonological awareness.

Finally, we should stress the differential relationship between the two working memory tasks and the measures of phonological awareness and rapid naming. Interestingly, Daneman and Carpenter's sentence span showed significant correlations with only the rapid naming tasks, and Sentence Question only with phonological awareness tasks. The latter was expected on the basis of previous studies (e.g. Kirby, Begg & Martinussen, 1996; Papadopoulos, 2001), but the former was not anticipated. Perhaps this is another indication that Daneman and Carpenter's sentence span measures more storage (needed for the quick retrieval of letter/digit names) than processing (needed for phoneme isolation and blending), and that is why it is more strongly related to rapid naming than to phonological awareness.

Some limitations of the current study are worth mentioning. First, the participants were attending Grades 3 and 4 and were from predominately low-SES families. Thus, any generalisations to other grades as well as to other SES classes should be made with some caution. Second, we used the traditional span scores for the two working memory tasks. However, Friedman and Miyake (2005) have shown that the span scoring procedure results in lower correlations with reading comprehension as opposed to total number of words recalled or the proportion of words per set averaged across all sets. Thus, our correlations may be lower than if we were to use a different scoring procedure. Third, the study focused exclusively on the central executive component of working memory utilising sentence span tasks. Certainly, working memory consists of, but is not limited to, central executive (Baddeley & Hitch, 1974). Similarly, working memory is not limited to verbal responses (e.g. Jarvis & Gathercole, 2003). Future studies should examine the role of both verbal and nonverbal working memory along with a battery of broader cognitive measures in determining reading and comprehension.

A child reads to understand. Understanding utilises both storage and processing. A deeper level of processing, semantic level, strengthens comprehension. Thus, a simple message for improving comprehension is to encourage the learner to engage in a deeper level of processing.

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Appendix A. Sentence truthfulness memory span task

Item	Sentences	Sentence response	Recall response
2 Sentence Level			
1	It gets cold in winter.	Y	
2	At night the sky is blue.	N	
Recall Test	Now tell me the last word in each sentence I just said in the same order I said them.		winter 1–0 blue 1–0
3	Children cannot read books if they cannot read words.	Y	
4	Both airplanes and birds have wings for flying.	Y	
Recall Test	Now tell me the last word in each sentence I just said in the same order I said them.		words 1–0 flying 1–0
3 Sentence Level			
5	All mothers work in an office.	N	
6	Babies learn how to walk.	Y	
7	Giraffes are very small.	N	
Recall Test	Now tell me the last word in each sentence I just said in the same order I said them.		office 1–0 walk 1–0 small 1–0
8	Boys and girls both use their feet to swim.	Y	
9	Some people may not like to smell flowers.	Y	
10	All men lose their hair when they get old.	N	
Recall Test	Now tell me the last word in each sentence I just said in the same order I said them.		swim 1–0 flowers 1–0 old 1–0
4 Sentence Level			
11	Rabbits sleep all the time. True or false.	N	
12	Many cities have large buildings.	Y	
13	Some babies can laugh.	Y	
14	Boys grow up to be men.	Y	
Recall Test	No N Now tell me the last word in each sentence I just said in the same order I said them.		time 1–0 buildings 1–0 laugh 1–0 men 1–0
15	We don't sleep with a lion unless it's a toy.	Y	
16	People, trees and rocks are all living things.	N	
17	Some girls grow up to be tall and pretty.	Y	
18	Cats are slow except when they are running.	Y	
Recall Test	No N Now tell me the last word in each sentence I just said in the same order I said them so.		toy 1–0 things 1–0 pretty 1–0 running 1–0
5 Sentence Level			
19	Money grows on trees.	N	
20	Many dogs love chewing a bone.	Y	
21	All hats are yellow.	N	
22	Boys and girls love playing.	Y	
23	Cats are larger than mice.	Y	
Recall Test	Now tell me the last word in each sentence I just said in the same order I said them.		trees 1–0 bone 1–0 yellow 1–0 playing 1–0 mice 1–0
24	Even small cars have more wheels than a bike.	Y	
25	A fish cannot live long out of water.	Y	
26	All bees look for flowers to make honey.	N	
27	When some people feel very happy they cry.	Y	
28	Some butterflies are colourful and large.	Y	
Recall Test	Now tell me the last word in each sentence I just said in the same order I said them.		bike 1–0 water 1–0 honey 1–0 cry 1–0 large 1–0
Sentence Span Score			/28

Appendix B. Sentence questions memory span task

Item	Questions	Child answers	Recall score 1 or 0	Question answers
2 Sentence Level				
1	White is bluing a red. Who is bluing a red?			White
2	Yellow pinked brown. Who was pinked by yellow?			Brown
Recall Test	Now tell me the answers you just said in the same order you said them.			White Brown
3	Blue browned in the red. Who browned in the red?			Blue
4	Green is pinking a purple. Who is green pinking?			Purple
Recall Test	Now tell me the answers you just said in the same order you said them.			Blue Purple
3 Sentence Level				
5	Blue is yellowing a white. Who is yellowing a white.			Blue
6	Red blacked a green in the blue. Who was blacked in the blue.			Green
7	Tan is whiting a red. Who is whiting a red?			Tan
Recall Test	Now tell me the answers you just said in the same order you said them.			Blue Green Tan
8	Green pinked red in the blue. Who was pinked in the blue.			Red
9	Two reds blued black. Who was blued by two reds?			Black
10	Yellow greened a white. Who greened a white?			Yellow
Recall Test	Now tell me the answers you just said in the same order you said them.			Red Black Yellow
4 Sentence Level				
11	Red is whiting a blue. Who is whiting a blue?			Red
12	Pink browned a yellow. Who was browned by pink?			Yellow
13	Brown blued in the white. Who blued in the white?			Brown
14	Purple is greening a pink. Who is greening a pink?			Purple
Recall Test	No N Now tell me the answers you just said in the same order you said them.			Red Yellow Brown Purple
15	Two yellows are bluing a red. Who are two yellows bluing?			Red
16	Green is pinking a black. Who is pinking a black?			Green
17	Red greened a white. Who was greened by red?			White
18	Pink blued yellow. Who blued yellow?			Pink
Recall Test	Now tell me the answers you just said in the same order you said them.			Red Green White Pink
Sentence Span Score Total (see Instructions to Scorer below)				
Questions Score Total				

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