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Sentence comprehension and general working memory

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Abstract
Although the role of working memory in sentence comprehension has received substantial attention, the nature of this relationship remains unclear. The purpose of this study was to examine the interaction between general, nonverbal working memory (WM) and sentence parsing (SP) in normal English-speaking adults. Accuracy and reaction times were recorded for thirty-one young adults during three on-line tasks: nonverbal WM, SP plausibility, and lexical decision (LD). A significant positive correlation was observed between reaction times for WM and SP, but not between LD and SP. These results suggest that SP may be supported by a general WM capacity, and therefore, some sentence comprehension difficulties observed in the clinical population may potentially be related to impairment in general WM.

Keywords: *Nonverbal working memory, sentence parsing, lexical decision, sentence comprehension*

Introduction

To comprehend a sentence, an individual must assign a thematic role, which specifies who did what to whom (Mauner & Koenig, 1999). In English, sentence parsing (SP) involves not only the retrieval of individual word meanings from the lexicon, but also analysis of the syntactic structure to determine the function of the words within the sentence. Therefore, to extract the meaning from a sentence, an individual must be able to remember previous words in order to relate them to later occurring words. Thus, it seems intuitively clear that some form of memory is needed for sentence comprehension. Further, many researchers have found a correlation between SP and working memory (WM) (Daneman & Carpenter, 1983; King & Just, 1991; Friederici, Steinhauer, Mecklinger, & Meyer, 1998). However, the interpretation of this correlation remains questionable, partially due to considerable overlap between SP and the reading span tasks used to measure WM. Therefore, the nature of this relationship is still under considerable debate.

WM is thought to be a workspace in which information is maintained and manipulated for immediate use in reasoning and comprehension tasks, as well as where information is transferred to a more permanent, long-term store (Baddeley, 2003). It has been found that increasing the amount of information to be maintained in WM can result in poorer

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processing abilities (King & Just, 1991). Thus, some researchers have asserted that difficulties in sentence processing can be related to a reduced WM capacity.

For example, in the capacity theory, an extension of Daneman and Carpenter's (1983) work, both the computational processes of SP and the processes of memory are thought to competitively draw from the same pool of resources (King & Just, 1991; Just & Carpenter, 1992). Therefore, if processing of a sentence requires substantial resources, then some of the resources typically devoted to storage would be allocated to processing, resulting in decreased storage ability and "forgetting" of part of the sentence. Further, individuals who have poorer comprehension also have smaller functional storage capacity because they typically allocate more of their WM resources to comprehension processing (Daneman & Carpenter, 1983). Apart from capacity alone, individuals can differ based on how efficiently they use their resources (Vos, Gunter, Schriefers, & Friederici, 2001) or in their ability to coordinate storage and processing functions. Therefore, SP abilities are determined by both the amount of available capacity and the efficiency with which an individual allocates these available resources (Vos et al., 2001).

In contrast, Waters, Caplan, Alpert, and Stanczak (2003) suggested that the actual differences in processing speed during SP might result in functional WM differences. They found that individual differences in regional Cerebral Blood Flow (rCBF) location during a sentence plausibility task were related to differences in processing speed, and not to differences in performance on verbal WM tasks. Furthermore, they suggested that differences in rCBF between processing speed groups may reflect the degree to which supplementary cognitive mechanism are used to support SP.

Another area of disagreement relates to the cognitive construct of WM. Some researchers have suggested the existence of a separate WM system that specifically mediates sentence comprehension (Waters & Caplan, 1996; Friedmann & Gvion, 2003; Haarmann, Davelaar, & Usher, 2003). According to these theories, performance on *nonverbal* WM tasks would not necessarily be expected to correlate with SP abilities. However, Vos and Friederici (2003) found mixed results regarding specific WM components versus a more general verbal WM capacity. Just and Carpenter (1992) have asserted that WM consists of a large set of processing resources, with subsets that can be used in specific domains. Similarly, Baddeley (1986) has encouraged the notion of a WM system that is not narrowly fixed to any particular cognitive system. Clearly, more research is needed to clarify the relationship been WM and SP.

The theoretical investigation of the relationship between WM and SP can also have clinical implications. For example, persons with aphasia often have difficulty with sentence-picture matching, enacting thematic roles, and making plausibility judgements about syntactically-complex sentences (Caplan & Waters, 2003). Agrammatism is recognized as a classic symptom in Broca's aphasia; however, studies have suggested that all classifications of aphasic syndromes involve syntactic comprehension deficits even though individuals may not be agrammatic in their expression (Blumstein et al., 1998; Peach, Canter, & Gallaher, 1988; Waters et al., 2003).

In addition, several neuroimaging studies have found that areas of neural activation during WM tasks are consistent with the typical areas of damage associated with aphasia (Chein, Fissell, Jacobs, & Fiez, 2002; Osaka et al., 2004). In particular, WM tasks have been correlated with activation of the lateral prefrontal cortex, including the left inferior frontal gyrus (Brodmann's areas 44 and 45), and the adjacent areas of the dorsolateral prefrontal cortex (Brodmann's areas 9 and 46). Furthermore, Caspari, Parkinson, LaPointe, and Katz (1998) found that WM capacities of aphasic individuals were predictive of their ability to comprehend language.

However, it is likely that lexical processing deficits also play a key role in the decreased SP abilities of persons with aphasia, as all of these individuals demonstrate anomia. Similarly, because the mental lexicon stores a representation of all the words that an individual knows, lexical processing is inherently necessary for sentence comprehension. It has been suggested that syntactic information is stored in the mental lexicon under a word's entry and that sentences are parsed in accordance with the preference of the verb (McElree, 1993; Boland & Boehm-Jernigan, 1998). Furthermore, findings by Bates and colleagues (e.g. Devescovi & D'Amico, 2005; Wulfeck, Bates, & Capasso, 1991) would suggest a strong relationship between lexical processing and sentence parsing in strongly noun-inflected languages like Italian or Russian. However, this relationship should not be as robust in English where word order rather than lexical processing is thought to play a more crucial role in sentence parsing.

Nevertheless, whether the focus is language-based or memory-based, several schools of thought have sought to clarify the means by which grammatical processing and agrammatism can be explained; however, these relationships remain unclear. In addition, it is not entirely clear whether the grammatical processing difficulties that are experienced by people with aphasia are related to deficits in a specific grammatical processing component or due to a more general deficit in WM.

Moreover, much of the previous research in this area has focused on verbal WM through the use of Daneman and Carpenter's (1980) reading span task (King & Just, 1991; Friederici et al., 1998; Waters et al., 2003), which requires participants to utilize processing and storage as they read or listen to sets of sentences. After each sentence, the participants must judge the truth-value of the sentences (processing component), and after each set of sentences, the participants must recall as many sentence final words as possible (storage component). Clearly, there is considerable overlap between the reading span task and SP because the reading span task involves reading sentences and making comprehension judgements about them. Therefore, the interpretation of this widely recognised correlation between reading span and SP is difficult.

Similarly, while some theories suggest that there are separate divisions of WM that mediate SP (Waters & Caplan, 1996; Friedmann & Gvion, 2003; Haarmann et al., 2003), others consider a more generalized dependence on WM (Baddeley, 1986; Just & Carpenter, 1992; Vos & Friederici, 2003). However, little research has focused on the relationship between sentence processing and a more general measure of WM. Therefore, a question still remains regarding the role of WM in SP. Is general (as opposed to verbal) WM capacity related to SP? Moreover, is WM a central processing resource that supports cognitive functions, such as SP?

The purpose of the present study was to examine the interaction between WM and SP in normal English-speaking adults. The focus was to determine whether or not differences in nonverbal WM capacity were associated with differences in sentence-parsing abilities, as seen in the previous work employing verbal WM capacity measures. In addition, all participants completed an online control task that involved lexical decision. Although sentence parsing should inherently involve lexical processing, it should rely more heavily on WM, whether it be process specific or not.

Method

Participants

Thirty-one young adults participated in the study. All were right-handed females aged 24 ± 3 years who spoke English as their first language. Individuals were excluded from participation if they reported a history of any of the following: neurological impairments, psychiatric disorders, dyslexia, learning disabilities, or, because one of the tasks employed Chinese characters, experience with the Chinese language.

Experimental tasks

Each participant completed four tasks. Three tasks were online, and the other task was offline. The online measures included a nonverbal WM task, a sentence-parsing plausibility task, and a lexical decision control task. Accuracy and reaction times (RTs) were recorded for each participant. The offline task was an additional nonverbal WM task.

The online nonverbal WM task involved three distinct Chinese characters. For each trial, a six-item matrix composed of the Chinese characters was presented (see upper panel of Figure 1). The participants were instructed to study the image closely because they would be required to remember how often each character occurred within the matrix. Immediately following the character matrix, a second image was presented, which consisted of an addition equation involving two of the Chinese characters equalling a randomly determined value between 2 and 5 (see lower panel of Figure 1). During the presentation of the equation, the participant was required to make a decision about the mathematical correctness of the equation based on the number of times each symbol occurred within the previously presented character matrix. Participants responded by pressing buttons to indicate "yes" for correct equations and "no" for incorrect equations. An equation was considered correct if the number value stated in the equation was equal to the total number of occurrences of the two indicated characters within the preceding character matrix. For each trial, a character matrix was presented for 7 s, followed by a 3 s presentation of an addition equation. Measurements for RT began with the presentation of each equation. The online nonverbal WM task consisted of 60 trials.

The sentence-parsing task was composed of semantically-plausible and non-plausible sentences presented in a word-by-word paradigm on a computer screen (see Figure 2). Sentence constructions included 10 subject-relative clauses, 10 object-relative clauses, 10

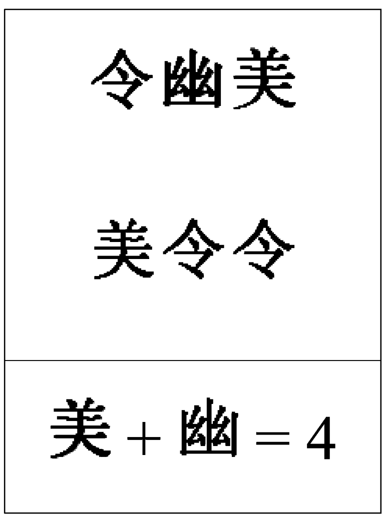

Figure 1. The upper panel shows a Chinese character matrix (displayed for 7 s), and the lower panel shows an addition equation (subsequently displayed for 3 s) from the online nonverbal working memory task.

a. [The] [goalie] [the] [team] [admired] [retired.]

b. [The] [candy] [that] [the] [boy] [craved] [ate.]

Figure 2. Serial (word-by-word) presentation of sentences in the sentence-parsing task. Each pair of brackets represents a separate presentation, with each word being displayed in isolation on the computer screen in succession. Sentence [a] is a plausible object-relative clause sentence and [b] is an implausible object-relative clause sentence.

cleft-constructed objects, 10 cleft-constructed relative clauses, 10 centre-embedded clauses, and 10 local ambiguity sentences. Each trial began with a 2.5 s presentation of a fixation cross, followed by a serial (word-by-word) presentation of the sentence. Each word in the sentence was presented for .5 s, with the exception of the last word in the sentence. The sentence-final word was presented for 4 s and was marked with punctuation and green font. Reaction time measurements began with the presentation of each sentence-final word. During the presentation of the final word, the participants were required to press one of two buttons to indicate whether the sentence was semantically plausible. A total of 60 sentences were presented in random order for this task.

The lexical decision task was included as a language-based control task. This task employed English words (e.g. mercy) and phonologically-plausible non-words (e.g. merly) that are included on the *Psycholinguistic Assessments of Language Processing in Aphasia* (PALPA; Kay, Lesser, & Coltheart, 1992). A total of 200 trials were included in this task, and each trial consisted of a 2 s presentation of a word or non-word. The participants made a word/non-word judgement by pressing one of two buttons. Measurement for RT began with the presentation of each word.

The offline WM task involved administration of the Spatial Span subtest of the *Wechsler Memory Scale-Third Edition* (WMS-III, Wechsler, 1997). This task was administered in order to establish validity for the online WM task that was constructed for the present study. The Spatial Span task required participants to tap blocks in a sequence of increasing length in both forward and reverse order as demonstrated by the examiner. A trained graduate student administered the Spatial Span task to each participant. The possible score for each section (forward and reverse) ranged from 0 to 16, making the range for the total score 0 to 32.

The order of task administration was randomized among the participants. Stimulus presentation and recording of RT and accuracy were carried out on a personal computer using E-Prime 1.0 software (Psychology Software Tools, 2000) for all three of the online tasks. All online stimuli appeared as black or green type on a white background. Instructions for each task were visually presented to the participant and a short training block was conducted before the experimental trials. Participants were instructed to use their right hand only to respond. Testing for each participant was completed during a single 1-hour session.

Data analysis

Pearson correlation coefficients were calculated using RT data to determine the relationships between performance on the various tasks. For each participant, mean RTs were calculated on each of the three online tasks. If participants did not respond to each trial within the designated time constraints of each online task, a RT of 0ms was recorded for that trial. In order to provide an accurate representation of an individual's performance, null reaction times (5% of all RT data) were omitted and replaced with the individual's mean reaction time for that task. In addition, because the items on the sentence-parsing task encompassed a broad range of difficulty, calculating RTs based solely on correct responses could skew overall performance by omitting increased RT on more difficult items. Therefore, in an effort to capture each participant's typical performance, both correct and incorrect responses were included in calculating mean RTs.

However, to ensure that an acceptable level of performance was obtained, each participant's accuracy and reaction times were analyzed. The group mean for accuracy on the online WM task was $75 \pm 12\%$). The design of the task required participants to respond within 3 s of the initial presentation of each equation. However, two of the 31 participants did not respond to 48% and 37% of the 60 trials within the allocated time. In comparison, the other participants failed to respond to only $10 \pm 7\%$ of the trials on average. Further, the accuracy of these two outliers (40% and 42%) was not better than chance guessing. Therefore, data from these two participants were removed from the analysis.

Examination of the RT data revealed two additional outliers in this task. The mean reaction time for all participants on the online WM task was 2206 ± 161ms). One participant's mean reaction time was greater than two standard deviations below the mean, and another performed greater than two standard deviations above the mean. Because it was felt that the data from these two participants did not provide a good representation of typical performance on this task, it was removed from the analysis. Therefore, the data from 27 participants were used in the analysis.

Results

Pearson correlation coefficients were calculated using mean RT data for each of the online tasks and are summarized in Table I. A significant correlation ($r=.51$, $p=.007$) was obtained between the reaction times for the online nonverbal WM and SP tasks. Therefore, individual differences in performance on the nonverbal WM task were predictive of performance on the sentence-parsing task (see Figure 3).

In contrast, the correlation between lexical decision and WM was not significant ($r=.33$, $p=.091$). The lexical decision control task certainly required participants to access words from the mental lexicon in order to make the word/non-word judgements. Although WM might be used to retrieve words from long-term memory and keep these words active, performance on this task did not appear to be strongly related to WM capacity.

The correlation between the reaction times for lexical decision and SP was not statistically significant ($r=.37$, $p=.058$). However, this relationship approached statistical

Table I. Pearson correlations for mean reaction times between working memory, sentence parsing, and lexical decision.

	Sentence parsing	Working memory
Lexical decision	.37 (p=.058)	.33 (p=.091)
Working memory	.51** (p=.007)	

**Correlation significant at the .01 level.

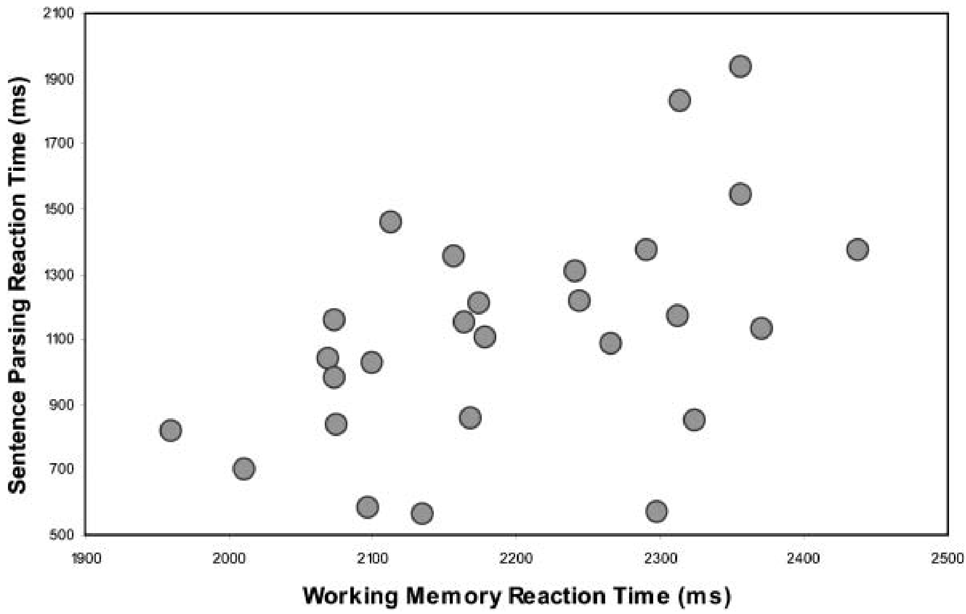

Figure 3. Reaction times for working memory and sentence parsing.

significance at the .05 level. It is important to note that the relationship between lexical decision and SP was weak despite the fact that they are both language tasks.

The spatial span task was included in the design of this study in order to provide validity for the online WM task. However, the correlation between the raw scores on the spatial span task and accuracy on the WM task was only $r=.27$, $p=.174$. Perhaps this lack of relationship was attributable to the different nature of these two tasks. In particular, the spatial span task was offline, and consequently, had no time constraints. Participants were able to respond as quickly or as slowly as they desired, and scores were determined based on accuracy alone. Conversely, the online WM task was much more demanding due to the continuous presentation of stimuli and the time limitations for responding. It is important the note that the online task was more representative of how individuals actually process language in everyday situations.

Discussion

Previous research has suggested that sentence comprehension is related to WM; however, most of these studies utilized a language-based WM task. Therefore, the question still remains whether sentence comprehension is related to a more general, nonverbal WM. The positive moderate correlation found between nonverbal WM and SP implies that these cognitive processes are related. Individual differences in nonverbal WM are related to differences in SP efficiency. Although a correlation of .51 is usually classified as moderate, the relationship between these variables should not be overlooked (cf. Spencer, 1995). Because this study investigated complex cognitive processes, individual variations should be expected among participants regarding recruitment and utility of supplementary cognitive processes; and therefore, even moderate correlations can be meaningful.

Of course, correlation does not equal causation. However, these results suggest that sentence-parsing abilities may be related to a general WM capacity, not exclusively a language-specific WM. If SP relied only on a language-specific WM, a correlation would not be expected between SP and a non-language task, such as the online nonverbal WM task in this study. On the other hand, if a language-specific component exists within the WM mechanism that supports SP, this component might still be limited by the general WM capacity of the individual. This would be consistent with capacity theory in which all storage and processing functions must draw from the same limited pool of WM resources (Daneman & Carpenter, 1983; Just & Carpenter, 1992).

Nevertheless, the current results evoke an interesting question. By what means could general WM capacity affect SP? Perhaps, the relationship between SP and WM is contingent on a central executive control as conceived by Baddeley (2003). In a study aimed at investigating the neural basis of WM through fMRI, Osaka et al. (2004) gave support to the idea that there is a modality-nonspecific system of central executive control that is responsible for resource allocation within WM. If WM is a resource-limited system, then it seems reasonable that the allocation of these resources might play an integral role in the efficiency of the entire WM system regardless of the modality or nature of the task at hand.

In the present study, the WM task was a dual task in which the participants were required to simultaneously maintain and manipulate information. Specifically, participants were required to balance resources between remembering the number of character occurrences within the matrix and performing a mathematical calculation with those number values in order to make a judgement about correctness. Therefore, the task required a division of resources within WM. A plausible explanation for the relationship between nonverbal WM and SP found in the present study is that the central executive control that mediates the allocation of resources for complex WM tasks also mediates the divided demands of SP. Namely, in order to assign thematic roles, SP requires a balance within WM between the ability to remember the words while simultaneously analyzing the syntactic structure.

Aside from the correlation obtained between SP and nonverbal WM, no other relationships were found to be statistically significant. Nevertheless, a correlation of .37 ($p=.058$) between SP and LD suggests there is a trend towards statistical significance. Thus, the present data support Bates and colleagues (Caselli, Casadio, & Bates, 1999; Dick, Bates, Ferstl, & Friederici, 1999; MacWhinney, Bates, & Kliegl, 1984) who suggested that SP and LD are closely related, even in speakers of languages such as English that no longer rely on case marking of nouns. However, it is apparent that participants whose RT tended to be short on the WM task also tended to have shorter RT on the SP task; clearly this relationship was not as strong for SP and LD suggesting that "fast" sentence parsers were not necessarily as proficient at lexical processing. Although SP involves the access and retrieval of individual words from the lexicon, the current findings suggest that SP is not typically limited by lexical performance.

In addition, the overall reaction time of each participant was not significant. In other words, the differences in correlations between the tasks revealed that there was not a consistent pattern of reaction times across the participants. Those who performed quickly on one task did not necessarily perform quickly on all other task. Therefore, the observed differences among participants seemed to be a factor of the cognitive processes measured, not the overall reaction time of each participant.

The present study only involved native English speakers. Sentence parsing in English relies heavily on word order and less on lexical processing. It is possible that a stronger relationship between LD and SP would be found in native speakers of languages that rely more heavily on case marking of nouns such as in Italian, Russian, or the Scandinavian languages. It is also a caveat that the present study did not include language tasks that were matched for difficulty. Future studies could ameliorate this limitation by including a LD task that involved greater processing demands. As a result, it would be possible to more clearly rule out the influence of task difficulty in the present findings.

In summary, the results of this study suggest that general WM capacity, as measured by a non-language task, is related to sentence-parsing abilities. This relationship implies that the WM mechanisms that are involved in SP may extend beyond the isolated, language-specific WM entities that have been proposed previously (Waters & Caplan, 1996; Friedmann & Gvion, 2003; Haarmann et al., 2003). The current findings are consistent with a general capacity explanation (Engle, Cantor, & Carullo, 1992) and theories of a single WM capacity that is responsible for all types of language processing (King & Just, 1991; Just & Carpenter, 1992). Perhaps, this mechanism involves the efficiency of a central executive control that is responsible for the allocation of resources within WM regardless of the task modality.

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