Title
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Abstract

This study examined the effect of age and language structure on working memory (WM) performance in three groups of participants (7;0-8;6 9;6-11:00; 19-22 years). The findings suggest that both age and language structure have an impact on WM performance. There was an interaction between these two factors that resulted in differences in performance pattern and error type. The measures of the storage function were influenced by the length of the stimuli, whereas processing efficiency was affected by sentence complexity.

Keywords: working memory, executive functions, language comprehension, developmental study

Working memory (WM) and executive functions

There is a strong relationship between WM and executive functions across age groups and populations. WM span measures predict language comprehension (Engle & Kane, 2004). In recent years, significant individual and developmental differences have been explored in WM performance. These findings resulted in a conceptual debate regarding resource sharing. A variety of unitary and semi-unitary models (e.g., Conway & Engle, 1996; Cowan, 1997, Just & Carpenter, 1992) have been developed that challenged Baddeley's multicomponent theory (Baddeley, 1986). WM capacity tasks became closely tied to measures of attention control in contexts that involve distraction or interference (Feldman Barrett, Tugade, & Engle, 2004).

A number of researchers have found a close relationship between individual differences in WM capacity and general executive functions (e.g., Conway & Engle, 1994; Engle & Cane, 2004). WM span was constrained by controlled attention (Engle, Kane, & Tuholski, 1999), by task switching ability (Towse, Hitch, & Hutton, 1998), and by the inhibition of irrelevant information (Hasher & Zacks, 1988). According to Baddeley's model, participants may demonstrate individual variations in processing and storage independently from a general executive capacity in complex WM span tasks (Bayliss, Jarrold, Gunn, & Baddeley, 2003). The extent to which performance on complex WM span tasks depends on processing and storage functions is still subject to debate (see more detailed conceptual reviews of WM e.g., Baddeley, 2000; Engle & Kane, 2004; Miyake & Shah, 1999).

Developmental studies on WM performance evidenced that executive functions develop gradually until adolescence (DeLuca, Wood, Anderson, Bucanan, Proffitt, Mahony, & Pantelis, 2003). WM span development reflects a combination of various factors, such as the efficiency and speed of processing. Older children perform faster on the same tasks as younger children therefore, they need fewer resources to perform the required activity (e.g., counting) and have more resources available for memory operations (Case, Kurland, & Goldberg, 1982). A different interpretation of age-related changes is provided by the task-switching model (Towse & Hitsch, 1995). In linguistic span tasks, participants may use the sentence context to help reconstruct the list of words that have to be remembered. If this reconstitution process is difficult, it may take so much time that some information could be lost. Younger children may make more errors because of difficulty in attention switching. In complex WM tasks, span measures may reflect the ability to control/switch attention, whereas response times depend on retrieval speed (Hitsch, Towse, & Hutton, 2001; Kail & Salthouse, 1994). Barrouillet & Camos (2001) suggest that increases in attentional capacity and better attention switching result in developmental increases in WM span.

The present study examined whether developmental differences in WM support the theory of WM capacity and executive attention (Engle & Kane, 2004). According to this theory, individual differences in WM capacity are not about memory storage per se, but reflect executive control, the ability to maintain goal-relevant information in a context of interference. Therefore, WM measures reflect multiple constructs and indicate not only the individual's short-term storage capacity, but also their ability to switch attention during processing of task stimuli.

In the current study, this theory was tested with 2 listening span tasks in which the stimuli varied in both length and linguistic complexity. Verbal WM performance in English-speaking adults is influenced by the syntactic complexity of the sentences (King & Just, 1991). Sentences with more complex syntactic structures are more difficult to comprehend than simple sentences because they require more processing resources and attentional capacity. For example, interpolated material may decrease the quality of memory representations. Processing accuracy decreased as sentence complexity increased because of the changing amount of interpolated material (McElree, Foraker, & Dyer, 2003).

The effect of sentence length versus complexity was tested in 3 age-groups in the present study. The following research questions were examined: 1. Are various performance measures differently sensitive to changes in age and language structure? We explored whether the manipulation of the independent variables (age, sentence length, word length, sentence complexity) results in performance accuracy differences. 2. Does sentence complexity or length have a larger impact on children's WM performance in linguistic span tasks? Although there is evidence in the adult literature that syntactically complex structures have a large impact on WM performance, most developmental studies used short and/or simple sentences in linguistic span tasks with children (e.g., Cain, Oakhill, & Bryant, 2004; Gathercole, Pickering, Ambridge, & Wearing, 2004). 3. Is there an interaction in WM performance between age and language structure? Specifically, we examined the interaction between age and sentence complexity. Based on the theory of WM capacity and executive attention (Engle & Kane, 2004), we hypothesized that age-related differences in executive functions are reflected in the accuracy of processing complex linguistic structures because the efficiency of sentence processing is highly related to the demands that sentence structure variations place on memory resources (McElree et al., 2003).

Methods

Participants

Three groups of children and young adults participated in this experiment (n=75). There were 25 participants in each group; the groups differed in age (7;0-8;6 years; 9;6-11:00 years; college students, 19-22 years; see Table 1). The rationale for choosing these age groups was based on previous findings that indicated immature executive functions, such as the maintenance of task goals, sustained attention, set shifting, and inhibition below 8-8;6 years of age. Although memory span improves between age 10 and adulthood, resistance to interference matures around 10 years of age (DeLuca, Wood, Anderson, Buchanan, Proffitt, Mahony, & Pantelis, 2003; Hale, Bronik, & Fry, 1997).

All children in Groups 1-2 were typically developing based on interviews with parents and teachers. Every participant passed a language screening (CELF-3 Screening test; Semel, Wiig, & Secord, 1995), a hearing test, and a basic measure of single nonword repetition and nonword discrimination. The primary language of each participant was English. Nonword repetition and nonword discrimination tasks were used to obtain a baseline measure of participants' WM storage function and general discrimination abilities.

Table 1: Participant Profile

		Age (years)	Nonword Repetition (%)	Nonword Discrimination (%)
Group 1	Mean	7.85	59.00	84.50
	SD	0.49	17.17	12.82
Group2	Mean	10.00	71.51	89.87
	SD	0.44	15.66	10.57
Group 3	Mean	20.00	79.17	99.17
	SD	1.10	12.09	2.18

Stimuli

To measure the relations between WM and language comprehension, we developed a Modified Listening Span task (ML). The task included 90 sentences (30 syntactically simple short sentences, 30 syntactically complex short sentences, and 30 syntactically complex long sentences) with a question for each sentence. Sentence-length was determined by the number of syllables ($M = 7.91$, $SD = 1.64$ for the short sentences; $M = 17.64$, $SD = 3.47$ for the long sentences). The complex sentences included relative clauses. The last word in each sentence was replaced with a nonword (2-, 3-, 4-syllable). The nonwords were part of the syntactic structure of the sentences. The task required that participants listen to a sentence, repeat the sentence-final nonword and answer a question about the content of the sentence. (See further details in Marton & Schwartz, 2003). This task required simultaneous processing and attention switching.

The second linguistic span task consisted of 9 sets of sentences with 5 sentences in each set (3 sets with syntactically simple short sentences, 3 sets with syntactically complex short sentences, and 3 sets with syntactically complex long sentences). Participants were asked to listen to the sentences and repeat the 5 sentence-final words in the order of presentation. The words were real words with similar phonotactic patterns, syllable length, and frequency of occurrence. Following sentence presentation, yes/no questions were randomly asked.

Results

Nonword repetition and nonword discrimination tasks were used to have a baseline measure of participants' WM storage function. There was a group effect ($F(2, 148) = 16.13$, $p < 0.001$) and a word length effect ($F(2, 148) = 39.5$, $p < 0.001$) for nonword repetition. There was no interaction between group and number of syllables; each group showed a clear word-length effect as the number of syllables increased. In nonword discrimination, there was a main effect for group ($F (2, 72) = 12.92$, $p < 0.001$). However, each group showed a high performance level in this task.

Factorial ANOVAs were used to examine the differences between and within groups for the complex linguistic span tasks. For the ML task, two different dependent variables (answers to the questions and nonword repetition) were analyzed with two separate ANOVAs: correct answers to the questions with group x sentence type as independent variables and nonword repetition accuracy with a group x sentence type x word length design. These analyses were performed to test the effects of age and stimulus length versus complexity on WM performance accuracy. The answers to the questions were expected to reflect processing capacity and executive functions, whereas nonword repetition was a measure of short-term storage. Effect sizes (d) were calculated and categorized as small effect size: d = 0.2, medium effect size: d = 0.5, large effect size: d = 0.8 for the group differences (Cohen, 1988).

The overall results for the answers to the questions showed a main effect for both group ($F (1, 148) = 46.88$, $p < 0.001$, $d = 1.11$ for Group 1-2; $d = 1.8$ for Group 1-3; $d = 0.81$ for Group 2-3) and sentence type ($F (2, 148) = 11.23$, $p<0.001$). There was no interaction between the 2 variables ($F (2, 148) = 0.4$, $p = 0.67$). The older groups answered more questions correctly than the younger ones with each sentence type. Pair-wise comparisons reflected significant differences in response accuracy between the simple /S/ and complex sentences: ($F (1, 148) = 17.99$, $p < 0.001$, for the complex short sentences /CS/, ($F (1, 148) = 9.82$, $p < 0.01$, for the complex long sentences /CL/). There was no difference in performance accuracy between the CS and CL sentences ($F (1, 148) = 0.99$, $p = 0.32$). Participants in each group gave more correct answers following the simple sentences than the complex sentences. Performance accuracy decreased with an increase in sentence complexity regardless of sentence length (see table 2). Thus, sentence complexity had a larger effect on performance accuracy in this task than the length of the sentences.

In addition to the quantitative differences that we observed with an increase in age, the groups also showed different error patterns in their answers. The two most common error categories were omissions and interference. Participants either forgot the relevant information or they gave an answer that was related to one of the previous questions. A comparison across groups showed an interaction between group and error type ($F (2, 148) = 4.43$, $p < 0.05$) and between sentence type and error type ($F (2, 148) = 19.43$, $p < 0.001$). Post hoc Tuckey tests ($p < 0.05$) showed that children in Group 1 made significantly more interference errors than omissions with each sentence type, whereas Group 2 and 3 made more omissions than interference errors with the simple sentences, however, the number of interference errors increased with the complex sentences. The number of omissions did not differ across sentence types. Sentence complexity had a large effect on the number of interference errors; participants made significantly more interference errors with the complex sentences than with the simple ones. Interference errors reflect executive functions: either difficulty with suppressing previously relevant information or switching attention as the task requirements change. The group differences in error patterns seem to be related to the development of executive functions.

Table 2: Means and standard deviations for the answers in the ML task

	Group 1	Group 2	Group 3
S sentence			
Mean (%)	63.60	86.40	93.07
SD	26.05	14.84	8.92
CS sent.			
Mean (%)	41.33	73.87	84.27
SD	20.00	16,66	14.92
CL sent.			
Mean (%)	43.81	70.53	82.93
SD	25.57	20.27	13.59

The second dependent measure for the ML task was nonword repetition. The results showed a significant main effect for group ($F (2, 148) = 78.32$, $p < 0.001$, $d = 0.62$ for Group 1-2; $d = 1.16$ for Group 1-3; $d = 0.37$ for Group 2-3) and syllable length ($F (2, 148) = 104.81$, $p < 0.001$, but not for sentence type ($F (2, 148) = 0.69$, $p = 0.5$). There was also a group x syllable length interaction ($F (4, 148) = 4.6$, $p < 0.01$). Post hoc Tukey tests ($p < 0.05$) showed that Group 1 differed from Groups 2 and 3 at each syllable length, whereas Groups 2 and 3 differed from each other only on the 3- and 4-syllable nonwords (see table 3). The within group results showed that repetition accuracy for 2- and 3-syllable nonwords did not differ in any of the groups. Thus, nonword repetition accuracy, the measure of storage rather than processing, was influenced by the length of the words, but not by the complexity of the sentence.

Table 3: Means and standard deviations for nonwords in the ML task

	Group 1	Group 2	Group 3
2-syllable			
Mean (%)	69.93	82.47	82.10
SD	15.39	13.83	10.02
3-syllable			
Mean (%)	63.47	76.43	84.87
SD	16.46	13.94	12.03
4-syllable			
Mean (%)	39.17	55.30	65.20
SD	17.29	15.36	18.46

In the traditional listening span task, participants' WM performance was examined with two different scoring methods: with the free scoring method, participants received credit for each word, regardless of the order of recall. The results of a factorial ANOVA showed a main effect for group ($F (2, 148) = 101.67$, $p < 0.001$, $d = 1.33$ for Group 1-2; $d = 2.27$ for Group 1-3; $d = 0.9$ for Group 2-3) and sentence type ($F (2, 148) = 5.78$, $p < 0.01$). There was no group x sentence type interaction ($F (4, 148) = 0.16$, $p = 0.96$). Participants in each group recalled more words following the simple than the complex sentences. Sentence length did not influence performance accuracy, similar to participants' performance on the answers to the questions in the ML task (see Table 4).

The second scoring method involved the order of presentation. Participants only received credit if the words were recalled in the order of presentation. The results of a factorial ANOVA showed a main effect for group ($F (2, 148) = 88.21$, $p < 0.001$, $d = 1.13$ for Group 1-2; $d = 2.27$ for Group 1-3; $d = 1$ for Group 2-3) and for sentence type ($F (2, 148) = 4.3$, $p < 0.05$). There was no group x sentence type interaction ($F (4, 148) = 0.71$, $p = 0.59$). The effect of sentence type on recall was similar with both scoring methods. The increase in sentence complexity resulted in a decrease in recall accuracy. The length of the complex sentences did not influence performance accuracy. Variations in sentence structure complexity were more demanding on executive functions, such as attention switching, than the variations in the length of the sentences.

Table 4: Means and standard deviations for free and order recall in the LS task (%)

	Free			Order		
	Grp.1	Grp.2	Grp.3	Grp.1	Grp.2	Grp.3
Simple-Short						
Mean	59.95	80.00	94.67	37.60	75.13	89.40
SD	19.93	15.69	5.77	16.47	26.95	18.07
Complex-Short						
Mean	50.62	73.41	85.40	27.00	56.74	82.80
SD	17.98	16.99	12.48	16.28	25.47	18.31
Complex-Long						
Mean	48.46	73.85	84.27	25.60	55.64	80.40
SD	19.96	14.84	15.38	13.78	26.26	21.88

Further, there was a difference in recall accuracy for the groups when we compared the results with the two scoring methods. The scores significantly decreased for Group 1 when we considered the order of recall with both the simple ($F (1, 48) = 9.01$, $p < 0.01$) and the complex sentences ($F (1, 48) = 6.07$, $p < 0.05$). The scores for Group 2 only dropped with the complex sentences ($F (1, 48) = 7.37$, $p < 0.01$) across the two scoring methods. There was no difference in scores for the simple sentences between the free and the order scoring ($F (1, 48) = 2.24$, $p = 0.14$). Finally, Group 3 did not show any significant differences in their scores with the two methods for any sentence type ($F (1, 48) = 3.38$, $p = 0.72$ for the simple sentences; $F (1, 48) = 1.6$, $p = 0.21$ for the complex sentences).

As mentioned above, participants showed different performance patterns on the ML task for recall accuracy and for error type on the two dependent measures (nonword repetition & answers to the questions). The answers to the questions were highly influenced by sentence complexity, whereas nonword repetition with sentence context was not. The latter variable showed an effect of word length. These results indicate that the accuracy of question answers reflects processing and executive functions rather than storage, whereas nonword repetition accuracy reflects storage rather than executive functions. We further examined this question with a correlation analysis. A high correlation was found between single nonword repetition and nonword repetition with a sentence context ($r (75) = 0.62$, $p < 0.001$). There was also a high correlation between the answers to the questions in the ML task and the LS task ($r (75) = 0.59$, $p < 0.001$).

Discussion

The current study examined the effects of age and sentence complexity on WM performance. Previous studies that have examined age-related changes in WM structures used short and/or simple sentences in linguistic span tasks (Cain, et al., 2004; Gathercole, et al., 2004). Although the findings with adults showed an effect of linguistic complexity on WM performance in complex span tasks, to our knowledge, no previous research has examined the relations between linguistic complexity and age in children's WM performance. The current study extended previous work by exploring the effect of sentence length and complexity on WM performance in groups of participants that differed in age. We examined whether stimulus length or complexity has a larger effect on WM performance accuracy and language comprehension, and whether this relationship changes with age during childhood and adolescence. Further, this study tested the theory of WM capacity and executive attention (Engle & Kane, 2004) from a developmental perspective.

The results in each WM task showed an age effect; younger children made more errors than the older participants. Performance accuracy also differed between Groups 2 and 3, particularly with more complex items. Age-related changes were further observed in different error types and performance patterns, especially with an increase in stimulus complexity.

In addition to an age effect, the results of the linguistic span tasks showed an effect of sentence complexity on WM performance. Participants in each group showed higher WM performance accuracy following the simple sentences than the complex sentences. Sentence length differences did not impact performance accuracy in the current study. This latter finding is similar to Willis & Gathercole (2001); the increased length of stimulus items does not affect sentence comprehension. However, syntactic complexity does matter. The two dependent measures of the ML task reflected the contribution of storage and processing efficiency separately. Sentence complexity affected the answers to the questions, but not nonword repetition. Nonword repetition accuracy was influenced by word length, but not by syntactic complexity. The idea of separate contributions of storage and processing efficiency in the ML task was further supported by the high correlation between nonword repetition in the ML task and single nonword repetition, and by the high correlation between the answers to the questions in the ML task and the LS task. These findings are similar to those of Bayliss and colleagues (2003), who suggested that processing efficiency and storage capacity constrain complex span performance independently.

The results of the linguistic span tasks (ML, LS) of the current study are also in agreement with the findings of Gathercole, Pickering, Ambridge, and Wearing (2004), and suggest that an increase in age results in the improvement of executive functions. Executive functions are used to integrate phonological, lexical, syntactic, and semantic representations in sentence span tasks. Younger children seem to rely more on storage resources and show more difficulty in attention switching and flexible adaptation to changing task requirements. In this study, this was evidenced not only by their lower scores, but also by the age-related differences in performance pattern. In contrast to the performance of the older participants, younger children produced more interference errors than omissions with each sentence type. They showed more difficulty in blocking the effects of prior sentence information. The children in Group 2 produced more interference errors only with increased sentence complexity. Most of their errors with the simple sentences were omissions. Performance accuracy in young adults (Group 3) was also influenced by sentence complexity, but they made significantly fewer interference errors than the children in Groups 1 and 2, even with the complex sentences. Young adults showed better monitoring of previously recalled items. McCormack, Brown, & Vousden (2000) also found a decrease in interference errors with age in short-term memory tasks.

A similar age-related pattern emerged when performance on the listening span task was compared using two scoring methods: free recall versus recall with order. There was no significant difference between the scores for the participants in Group 3; children in Group 2 received similar scores with the two methods for the simple sentences, but not for the complex sentences. Their scores with the free recall scoring method were higher than with the order scoring for the complex sentences. The youngest children showed score differences with each sentence type, even with the simple sentences. The finding that children in Group 1 received higher scores with the free scoring method following each sentence type shows that they were able to remember the words but not the order of presentation. This finding also supports the idea that they may rely more on storage resources than on general processing. Remembering both the items and their order of presentation requires the ability to maintain goal-relevant information and continuous attention switching. Further research is needed to decide whether the high number of interference errors in young children reflect poor inhibition, difficulty in suppressing irrelevant information, or a weakness in mental flexibility and attention switching.

Although processing efficiency was influenced by sentence complexity, but not length, nonword repetition performance -that reflects the storage function rather than processing- showed a word-length effect. Performance on both tasks, single nonword repetition and nonword repetition with sentence context, decreased with the increase of syllable length. In the ML task, there was also an interaction between word length and age. The younger children performed more poorly than the older participants at each syllable length; performance accuracy between Groups 2 and 3 did not differ with the 2-syllable nonwords, only with the longer nonwords. WM span continuous to improve between 10-11 years of age and adulthood.

Taken these results together with the findings on the linguistic span measures, the two functions of WM, storage and processing efficiency were differently affected by the structure and complexity of the stimuli. Nonword repetition, the measure of the storage function, was influenced by stimulus length, but not by the sentence type, whereas the answers to the questions and listening span, that reflect processing efficiency, were affected by sentence complexity, but not sentence length.

The results of the two listening span tasks support the theory of WM capacity and executive attention (Engle & Kane, 2004). Performance accuracy increased and the proportion of interference errors decreased with age. These age-related differences reflect better attention switching and executive control. Participants needed to switch attention continuously during the processing of complex linguistic structures in the listening span tasks. There was a gradual development in performance accuracy across groups: the listening span tasks were most demanding on WM for the youngest children, who performed more poorly than groups 2-3 with each sentence type. Group 2 differed from Group 3 only with the complex sentences. The development of executive functions and their effect on WM performance were also reflected in children's errors. Younger children showed more difficulty in blocking previously presented information, which problem resulted in a high number of interference errors. Monitoring previously recalled items requires executive functions that develop with age.

In conclusion, both age and language structure have an impact on WM performance. There is an interaction between these two factors that has an additional influence on individual performance variations in WM tasks. The findings indicate that different WM tasks do not involve the same processes and that both factors, language and age, may influence them differently.

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