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Developmental Differences in Visual and Auditory Processing of Complex Sentences

James R. Booth, Brian MacWhinney, and Yasuaki Harasaki

Children aged 8 through 11 (N = 250) were given a word-by-word sentence task in both the visual and auditory modes. The sentences included an object relative clause, a subject relative clause, or a conjoined verb phrase. Each sentence was followed by a true–false question, testing the subject of either the first or second verb. Participants were also given two memory span measures: digit span and reading span. High digit span children slowed down more at the transition from the main to the relative clause than did the low digit span children. The findings suggest the presence of a U-shaped learning pattern for on-line processing of restrictive relative clauses. Off-line accuracy scores showed different patterns for good comprehenders and poor comprehenders. Poor comprehenders answered the second verb questions at levels that were consistently below chance. Their answers were based on an incorrect local attachment strategy that treated the second noun as the subject of the second verb. For example, they often answered yes to the question "The girl chases the policeman" after the object relative sentence "The boy that the girl sees chases the policeman." Interestingly, low memory span poor comprehenders used the local attachment strategy less consistently than high memory span poor comprehenders, and all poor comprehenders used this strategy less consistently for harder than for easier sentences.

INTRODUCTION

For nearly three decades, research in language acquisition has focused attention on the development of syntactic competence. However, this work has seldom examined on-line syntactic performance. Precise models and methods for the study of on-line sentence processing in adults (Frazier, 1987; Frazier & Fodor, 1978) have been available for over a decade. However, these techniques have seldom been applied to the study of the development of on-line sentence processing strategies in children (Cole & Perfetti, 1980; Tyler, 1983; Tyler & Marslen-Wilson, 1981). This gap in the research literature is particularly troubling, given that there are sentence processing theories postulating automatic and obligatory access to universal processing strategies for all speakers of all ages (Gibson, Pearlmutter, Canseco-Gonzalez, & Hickok, 1996). If, in fact, sentence strategies are learned incrementally (MacWhinney & Bates, 1989; Tabor, Juliano & Tanenhaus, 1997), we would need to reassess these claims regarding processing universals. The current study attempts to fill this research gap by examining the online processing of complex sentences by children.

Developmental Differences in Sentence Comprehension

Sentences with restrictive relative clauses provide excellent materials for the study of sentence processing in children. Four different types of restrictive relative clause patterns are available in English. Sentences (1) through (4) provide illustrations of these four syntactic types.

1. Subject–Subject (SS): The boy that sees the girl chases the policeman
2. Subject–Object (SO): The boy that the girl sees chases the policeman
3. Object–Object (OO): The boy chases the girl that the policeman sees
4. Object–Subject (OS): The boy chases the girl that sees the policeman

These four types of relative clause sentences vary in terms of the role of the head noun in both the main and relative clauses. The first letter in the preceding abbreviations indicates the role of the head noun in the main clause, and the second letter indicates the role of the head noun in the relative clause. When the head is the subject in both clauses, the sentence has a SS structure. When the head is the subject in the main clause but the object in the relative clause, the sentence has a SO structure. When the head is the object in the main clause and the object in the relative clause, the sentence has an OO structure. When the head is the object in the main clause and the subject in the relative clause, the sentence has an OS structure.

In a review of studies that used the enactment technique with 4- to 7-year-olds, MacWhinney and Pleh (1988) noted that children have the least difficulty with SS sentences and the most difficulty with SO sentences in terms of their off-line comprehension accuracy scores. Sentences with the OO and the OS structures are about equally hard for children and fall between the SS and SO sentences in terms of difficulty. In the present investigation, we chose to concentrate on relative clause sentences with the SS and SO structures because they represent two extremes in sentence processing difficulty. The superiority of SS comprehension over SO comprehension can be attributed to the fact that SO relatives require two shifts of perspective (Bever, 1970; MacWhinney, 1982). First there is a shift from the subject of the main clause ("the boy" in Example 2 above) to the subject of the relative clause ("the girl") and then back to the subject of the main clause ("the boy"). As King and Just (1991) have demonstrated, these shifts of perspective place a noticeable load on working memory. Working memory can be defined as the active manipulation of information in short-term memory.

Working Memory and Sentence Processing in Adults

Some investigators argue that working memory influences the processing and comprehension of sentences with complex syntactic structures. Miller and Chomsky (1963) attributed the difficulty that people have in comprehending multiple self-embeddings to problems involved in overloading memory with partial analyses of clauses. Similarly, Just and Carpenter (1992; see also Just, Carpenter, & Keller, 1996) reviewed studies indicating that individual differences in working memory predicted the ability to process complex syntactic structures. They argued that low working memory participants were less efficient at structuring sentences than high working memory participants. For example, King and Just (1991) compared the word-by-word reading reaction times for SO and SS sentences by high and low working memory participants, as measured by Daneman and Carpenter's (1980) reading span task. Low working memory participants had larger reading time differences between the beginning of the sentence and the critical relative–main clause transition than high working memory participants. This effect was especially pronounced for the more difficult SO sentences. Low working memory participants had very slow reading times for the most difficult parts of the most difficult sentences.

Other studies have found that although high working memory adults are more accurate at comprehending complex sentences, they slow down more than low working memory adults when reading certain syntactic structures. Therefore, the exact relationship between working memory and sentence processing is in need of further research. For example, MacDonald, Just, and Carpenter (1992) presented garden-path and non-garden-path sentences to adults with high and low reading spans (r-spans). The reduced relative stimuli were garden-path sentences such as "The experienced soldiers warned about the dangers conducted the midnight raid" and non-garden-path sentences such as "The experienced soldiers who were told about the dangers conducted the midnight raid." They found that the high r-span readers took longer to read the sentence final words in garden-path sentences than the low r-span readers but that the low r-span readers made more errors in answering questions presented after the sentence than the high r-span readers. MacDonald et al. (1992) interpreted these results as suggesting that low r-span readers may make an early commitment to the dominant interpretation. By excluding the subordinate interpretation, low r-span readers make more errors on the garden-path sentences. In contrast, the maintenance of both the dominant and subordinate structures allows the high r-span readers to answer the garden-path questions correctly. MacDonald et al. (1992) also suggested that the low r-span readers processed the sentence final words of garden-path sentences quickly because they were maintaining only the dominant interpretation of the sentence in working memory. In contrast, high r-span readers had longer reaction times to the sentence final words of garden path sentences because they were maintaining both the dominant and subordinate syntactic structures in verbal working memory throughout the sentence.

Others argue that working memory is not strongly related to sentence processing and comprehension (Waters & Caplan, 1996b). For example, Waters and Caplan (1996a) had readers make acceptability judgments to reduced relative sentences like the ones studied by MacDonald et al. (1992) and reviewed previously. Waters and Caplan (1996a) found that individual differences in working memory capacity, as measured by the reading span task (Daneman & Carpenter, 1980), did not explain variance in sentence acceptability judgments. Furthermore, Waters and colleagues found that Alzheimer's patients with a deficit in memory span do not show a corresponding impairment in processing syntactically complex sentences (Rochon, Waters, & Caplan, 1994; Waters, Caplan, & Rochon, 1995). These studies question the role of a single general working memory in sentence processing, although they leave open a possible role for multiple specific memories. Indeed, Waters, and Caplan (1996b) argued that there are at least two working memories, one for initial processing of sentences and one for "postinterpretative" processing. The on-line reading measures may be more sensitive to initial processing, whereas the reading span task that involves integrative questions may be more sensitive to postinterpretative processing. This may account for why only some researchers have found a strong relation between reading span and on-line processing. A measure not sensitive to postinterpretative processing like a short-term memory digit span task may show a strong relation with on-line processing. Our study presents results that argue for the role of short-term memory in on-line sentence processing in children.

Role of Memory Span in the Development of Language and Reading

No published developmental studies investigate the role of working memory in on-line sentence processing. However, several developmental studies have examined the relation between memory and the off-line comprehension of sentences. Some studies have examined working memory, as measured by a sentence span task; other studies have examined short-term memory, as measured by word, pseudoword, digit, or letter span. Focusing on working memory, Swanson (1992) found that a modified version of the Daneman and Carpenter (1980) reading span task related to reading comprehension and that this relation held up even when the contribution of vocabulary knowledge was partialled out. In addition, Siegal and Ryan (1989) showed that reading-disabled children perform significantly worse on the reading span task than normally achieving children. Focusing on short-term memory, other researchers (Cariglia-Bull & Pressley, 1990; Dixon, LeFevre, & Twilley, 1988; Mann & Liberman, 1984; Swanson, 1992, 1993) have observed strong correlations between short-term span and reading disability.

Gathercole, Baddeley, and colleagues have also used short-term memory measures such as pseudoword repetition and digit span to study language development. They use the term "phonological memory" to emphasize the role of phonological codes in short term memory. In a series of studies, Gathercole and colleagues have reported three effects. First, early phonological memory predicts later vocabulary acquisition (Gathercole & Baddeley, 1989; Gathercole, Willis, Emslie, & Baddeley, 1992). Second, children with low phonological memory learn new vocabulary more slowly than do children with high phonological memory (Gathercole & Baddeley, 1990a). Third, children with language disorders tend to have deficits in phonological memory (Gathercole & Baddeley, 1990b). Studies have shown that the amount of verbal material that can be held in phonological memory dramatically increases throughout the school years, and this increase has been attributed to an increased rate of articulatory rehearsal in the phonological loop (Hulme, Thompson, Muir, & Lawrence, 1984). Gathercole and Baddeley (1989) and Gupta and MacWhinney (1997) have proposed that children with good phonological memory produce highly discriminable and persistent phonological traces, and, as a result, these traces are more likely to become permanently linked with semantics.

Phonological processes in short-term memory also appear to impact areas other than vocabulary acquisition. Research has shown that children who are skilled readers automatically activate phonological information during single-word reading (Booth, Perfetti, & MacWhinney, 1999). This automatic activation of phonological processes may also have an impact on sentence comprehension during reading. More generally, the ability to accurately represent and rehearse verbal information in short-term memory may be a central determinant of developmental differences in language comprehension. Therefore, we could expect short-term memory ability to explain variance in the processing of complex sentences examined in this study.

Studying On-Line Processing in Children

The first major goal of this study was to examine the extent to which children apply adult-like strategies for processing complex multi-clause sentences. The second major goal was to determine whether sentence processing in children is influenced by individual differences in either short-term or working memory. We chose to focus on the development of sentence processing for sentences with restrictive relative clauses. This is the same syntactic structure for which King and Just (1991) demonstrated working memory effects in adults. A rich off-line developmental literature in this area (see MacWhinney & Pleh, 1988) indicates that these structures are not mastered until adolescence, so we focused on children in the age range between 7 and 13. To obtain a measure of on-line processing, we chose a word-by-word sentence task. After each sentence, an off-line true–false comprehension question tested children's knowledge of which noun was the appropriate subject for the first or second verb (see Table 1). We refer to these questions as "first verb questions" and "second verb questions." Experiment 1 used a visual moving window that required reading comprehension, whereas Experiment 2 used an auditory moving window that required listening comprehension. We used the auditory moving window in Experiment 2 to be confident that the results in Experiment 1 were not due to differences in single-word decoding skill.

Table 1 Examples of SO, SS, and CVP Sentences Followed by True–False Questions Testing Either the First or Second Verb

SO sentence	
The [man that the captain] [invited] [built] [the stage] [for the] band.	
The captain invited the man	(True, First Verb)
The man invited the captain	(False, First Verb)
The man built the stage	(True, Second Verb)
The captain built the stage	(False, Second Verb)
SS sentence	
The [principal that tripped the] [janitor] [used] [the phone] [to call] home.	
The principal tripped the janitor	(True, First Verb)
The janitor tripped the principal	(False, First Verb)
The principal used the phone	(True, Second Verb)
The janitor used the phone	(False, Second Verb)
CVP sentence	
The cat chased the rabbit and enjoyed the hunt in the yard.	
The cat chased the rabbit	(True, First Verb)
The rabbit chased the cat	(False, First Verb)
The cat enjoyed the hunt	(True, Second Verb)
The rabbit enjoyed the hunt	(False, Second Verb)

Note: Brackets indicate the parts of the sentence in the moving window analysis.

Developmental Predictions

On the basis of the developmental literature just reviewed, we predicted that children would have more difficulty with SO sentences than with SS sentences because SO sentences require two perspective shifts, whereas SS sentences require no perspective shift (MacWhinney, 1982). This difference should be reflected in lower off-line comprehension scores for SO than for SS sentences and longer reading times at the critical relative–main clause transition for SO than for SS sentences (King & Just, 1991). We also expected that, for all three sentence types, second verb questions would be more difficult to answer than first verb questions because second verb questions require that the reader judge the first noun to be the subject of the second verb over an interruption in surface structure (Slobin, 1973). This predicted pattern of results would lend support to the importance of perspective shift and interruption of structure for sentence processing in children.

We also expected that children who had difficulty comprehending the sentences would be more likely to answer second verb questions incorrectly because they would rely on a simple strategy of local attachment (Ford, Bresnan, & Kaplan, 1982; MacWhinney, 1988). Using this strategy, children would incorrectly judge the second noun in the sentence to be the subject of the second verb. For example, in the SS sentence "The boy that sees the girl chases the policeman," the child may incorrectly answer true to the second verb question "The girl chases the policeman." Although this strategy fails in this case, it is successful for determining the subject of the first verb, as when the child is asked to verify "The boy sees the girl." Because this strategy is successful for first verb but not for second verb questions, we expected accuracy rates to be much lower for second verb than for first verb questions for children who had difficulty in comprehending the sentences.

Each child was also administered measures of both working memory span and short-term memory span (see Daneman & Merikle, 1996) to determine the relation between memory span and on-line comprehension. As noted earlier, the adult literature is inconclusive regarding the exact role of working memory in the on-line comprehension of complex syntactic structures (Just & Carpenter, 1992; MacDonald et al., 1992; Waters & Caplan, 1996a). Although developmental research shows that both working memory and short-term memory are related to off-line reading comprehension (Farnham-Diggory & Gregg, 1975; Perfetti & Goldman, 1976; Swanson, 1992, 1993), no developmental studies have examined the relation between memory span and on-line sentence comprehension.

On the basis of the strong relation found between phonological memory and vocabulary acquisition (Gathercole et al., 1992), we predicted that short-term memory would explain variance in the on-line processing of sentences. Because relative clause processing requires children to store sequences of words in memory, we expected children with high memory spans to be more consistent in answering comprehension questions. However, these difficult sentences are hard to process; therefore, high memory span children should slow down significantly at the transition from the relative to the main clause because they are effectively comprehending these complex sentences. In contrast, we expected low memory span children to be less consistent at answering questions because they are not able to fully process the sentences. Because they may be moving through the sentences without fully understanding them, we expected children with smaller memory spans to slow down less at the relative–main clause transition (see MacDonald et al., 1992, for a similar effect in adults with different sentence types).

Although our study did not examine sentence processing in adults, our predictions would be consistent with a U-shaped developmental function. In particular, younger and less skilled children should not slow down much during the critical relative–main clause transition because the are not fully processing the sentences as a result of their limited memory resources. The older and more skilled children should behave like the low memory span adults in that they show significant slowing at the relative–main clause transition (e.g., King & Just, 1991). These groups are relatively successful at comprehending the sentences, but the sentences are very challenging and require most of their memory resources. Adults with high memory spans easily process the sentences and therefore they should not slow down much at the relative–main clause transition.

The hypothesis that short-term memory may be important for on-line processing of sentences in children contrasts with the adult literature, which shows that short-term memory explains less variance in language comprehension than does working memory (Daneman & Merikle, 1996). However, the expected differences between the children and adults are generally consistent with the finding that phonological memory influences language acquisition less with age (Gathercole et al., 1992). Language processing in children may depend more on short-term memory in the phonological loop (Gathercole & Baddeley, 1989), whereas language processing in adults depends more on working memory in a language comprehension system (Just & Carpenter, 1992).

EXPERIMENT 1

Method

Participants

Participants were 45 third graders (M = 8.8 years, SD = .4), 50 fourth graders (M = 10.0 years, SD = .5), 30 fifth graders (M = 11.0 years, SD = .6), and 25 sixth graders (M = 12.4 years, SD = .7). The numbers of boys and girls were approximately equal, but the number of participants was not sufficient to include gender as an independent variable. All 150 children were recruited from private and parochial schools in middle class neighborhoods in the metropolitan Pittsburgh area. All participants were native English speakers and had normal hearing and normal vision or were corrected to normal vision.

Procedure

All materials administered to the children were presented on identical 15-inch MultiScan Macintosh monitors (screen resolution at 640 × 480) controlled by a Macintosh computer. All tasks were presented by using the PsyScope experimental control system (Cohen, MacWhinney, Flatt, & Provost, 1993). All children completed a short-term memory measure (digit span), a working memory measure (reading span), and a sentence task (moving window sentence comprehension).

Short-term memory. The digit span task (d-span) measures short-term memory capacity. Gathercole and Baddeley (1989, 1990a, 1990b) have argued that pseudoword repetition is a better measure of phonological short-term memory than digit span. However, these two measures are moderately correlated, and we wanted a measure that was sensitive to memory for word strings occurring in a serial order. D-span is likely to relate to on-line sentence processing in children because processing sentences requires, in part, remembering a series of words. In contrast, nonword repetition may be more related to vocabulary acquisition because word learning requires highly discriminable and persistent phonological traces (Gupta & MacWhinney, 1997).

The d-span task required children to remember numbers that were auditorily presented over earphones. All numbers, one through nine, were digitized and presented randomly by computer. Participants were asked to repeat the numbers to the experimenter in the correct order, and the experimenter typed their answers into the computer. The d-span task started with trials of two numbers and ended with a maximum of nine numbers in each trial. Five trials at each level (2–9 numbers) resulted in a total of 40 possible trials. Administration was stopped when the child got more than three out of five incorrect at a certain level or had completed all 40 trials. Participants were given one point for each trial recalled in the correct order. This resulted in a maximum score of 40.

Working memory measure. The working memory span task (w-span) was an adaptation of the Daneman and Carpenter (1980) and Swanson (1996) reading span measures. The experimenter controlled the presentation rate of sentences. The child was asked to read each sentence aloud, one after the other, without pausing between sentences. To prevent rehearsal, each new sentence was presented on the computer screen immediately after the child finished reading the previous sentence. The child's task was to recall all sentence final words in the correct order after each set of sentences. The experimenter encouraged the child to guess the sentence final words and recorded the child's verbal responses on a sheet of paper. After the children recalled as many words as they could, they were asked to answer a question about one of the sentences. This question was presented on the computer and the experimenter recorded the responses. The child did not get credit for sentence final words that were remembered after the question was presented because the question often provided a retrieval cue for a sentence final word. The experimenter emphasized that remembering the sentence final words was as important as answering the questions correctly. All participants were administered all sentence sets, which ranged in size from two to five. The sentences in each set were always presented in the same order. There were seven sets of two sentences, four sets of three sentences, three sets of four sentences, and two sets of five sentences (see Appendix A for a complete list of the sentences and questions). We used fewer sets with larger numbers of sentences because participants would rarely answer these sets correctly and these failures tend to frustrate children. All sentences were presented in 18-point Courier font and fit onto a single line on the computer screen.

A single measure was calculated from the w-span task. Points were given for a set only if all sentence final words in a set were recalled correctly regardless of order and if a correct answer to the sentence final question was given for that set. We imposed these stringent criteria because we consider working memory to involve both storage (recall of words) and processing (comprehending sentences). Points given for each qualifying set corresponded to the number of sentences in the set (2–5). Correct responses to larger sets were given more points because these sets were more difficult. The maximum number of points for the w-span measure was 48.

Sentence processing task. The moving window sentence task required children to silently read CVP (conjoined verb phrase), SS, and SO sentences (see Appendix B for a complete list of the sentences). We used a word-by-word visual moving window technique (Just, Carpenter, & Woolley, 1982) because this technique has been shown to be sensitive to on-line syntactic processing in adults (King & Just, 1991). The child controlled the presentation of each word of each sentence with the yellow button on a button box; all other words in the sentence were replaced by dashes. For example, three button presses would present the sentence "John likes Mary" in three consecutive screens at the same place on the computer monitor: "John ----- ----" "---- likes ----" "---- ----- Mary." After reading each sentence the children were required to answer a true–false question about the sentence that appeared on the computer screen. They pressed the red button on the button box if the statement was false. If the statement was true, they pressed the green button. Completion times for the sentence task ranged from 20 to 40 min, depending on age and ability level. Each child was encouraged to take breaks during the task.

There were 12 experimental sentences of each type (SS, SO, and CVP) and 16 filler sentences. All experimental sentences were 12 words in length. The filler sentences were 13 to 14 words in length and were noun- or verb-attached and noun- or verb-biased sentences (see Taraban & McClelland, 1988). All sentences were presented in 18-point Courier font, so the sentences could not be presented in a single line on the computer screen. The breaking point for the experimental sentences was between the seventh and eighth word. This point was immediately after the second verb in the sentence (see Table 1) and was past the transition between the main clause and the relative clause. There were also 10 practice sentences. During the practice sentences, the experimenter corrected participants when they made two errors in a row to make sure that the participants were taking the sentence task seriously.

All sentences were followed by a single question, but each sentence had four questions counterbalanced across four different experimental lists. These questions were either true or false and required the participant to determine the subject of the first or second verb in the sentence (see Table 1). This counterbalancing meant that each participant received three questions of each type for the SO, SS, and CVP sentences.

There were two dependent measures for the moving window sentence task: question accuracy and reading time per word. We will discuss how reading times were calculated for the sentence task in the data trimming section below.

Results and Discussion

Relation between the Individual Difference Variables

Age was significantly correlated with w-span, $r(148) = .38$, $p < .001$, and with d-span, $r(148) = .34$, $p < .001$. W-span and d-span were also significantly correlated, $r(148) = .47$, $p < .001$, even when age was partialled out of the correlation, $r(147) = .39$, $p < .001$. The correlation between w-span and d-span may result from a shared underlying short-term memory component. Because age, w-span, and d-span were partially independent, we examined whether each of these measures explained unique variance in the on-line reading times of sentences.

Data Trimming

Data trimming necessary was not necessary for the d-span or w-span tasks because these instruments did not measure reading times. For the moving window sentence task, reading times to individual words greater or less than 2.5 *SD*s from the mean for each child were equated to those values (<3%). In addition, sentences that had three or more consecutive word skips or four or more word skips for the entire sentence were eliminated (<1%). Word skips were defined as having a negative reading time and indicated that the child was pressing the button repetitively without reading the sentence for comprehension.

Typically, sentence processing research has calculated reading times by dividing the reaction time for a word by the number of letters in that word to correct for differences in string length (Frazier & Rayner, 1982). However, this correction has three disadvantages: It does not account for all variance resulting from string length; it reverses the relation between reading time and string length; and it creates a nonlinear relation between reading time and string length (Trueswell, Tanenhaus, & Garnsey, 1994). Because of the shortcomings of the millisecond/character correction method, we used a residual correction originally developed by Ferreira and Clifton (1986). For each child, we computed a linear regression in which word length in characters was regressed on reading time in milliseconds (ms). Then, the observed reading time for each individual word was subtracted from the reading time predicted on the basis of the linear regression. This subtraction removed all linear variance associated with string length so that differences in reading time between sentence types, for example, could not be accounted for by differences in string length. For ease in interpretation, however, all means presented in this paper are raw scores and not residuals.

Inferential Analysis Strategy

We conducted two basic types of analyses: on-line reading time of words in the sentences and off-line accuracy of responses to questions presented after each sentence.

We used three separate analyses of covariance (ANCOVAs) with the on-line reading times to investigate whether the covariates of age, w-span, or d-span explained unique variance in the reading time differences between SO and SS sentences. We did not examine on-line differences in CVP sentences because this sentence structure is not easily compared with the SS and SO structures. The critical parts of the SS and SO sentences contain a noun, a verb, or both, whereas the analogous parts of the CVP sentences contain a verb and the conjunction *and* (see Table 1). For all on-line ANCOVAs, the SS and SO sentence reading times were broken into four regions of interest: the beginning of the sentence (words 2–5), the end of the relative clause (word 6), the verb of the main clause (word 7), and the object of the main clause (words 8–9).

Because on-line sentence processing results could be markedly different for comprehenders and noncomprehenders (King & Just, 1991), each ANCOVA also included a dichotomous independent variable for comprehenders versus noncomprehenders. We defined noncomprehension as having an a-prime score of less than 60% based on the off-line measure. A-prime scores were used in all analyses and were calculated separately for each child and each sentence type. A-prime is a nonparametric index of a child's sensitivity that eliminates the bias factor (Pollack & Norman, 1964). This value is theoretically equal to the proportion of correct responses that can be obtained in a two-alternative, forced-choice task. Using this criterion, 30 children scored below chance on the CVP sentences, 33 scored below chance on the SS sentences, and 53 scored below chance on the most difficult SO sentences. For participants to be considered noncomprehenders, they had to score below chance on at least the SS and SO sentences. We chose these sentence types for defining comprehenders versus noncomprehenders because only these sentence types were included in the on-line analyses reported here. This criterion resulted in a total of 39 noncomprehenders and 111 comprehenders. The noncomprehenders and comprehenders were relatively equally distributed across age, w-span, and d-span. Table 2 presents the means (and numbers of children) for comprehenders and noncomprehenders with a cutoff between the groups based on a median split of age, w-span, or d-span. We used a median split for age even though there were four age groups so that the numbers of participants in the young and old groups were comparable to the number of the participants in the high and low memory groups. When we used a slightly different comprehension cutoff (a-prime < 55%) for separating the comprehenders from the noncomprehenders, we found essentially the same results in the inferential analyses, so those analyses are not presented here.

We also examined reading times for sentences that were answered correctly and those that were answered incorrectly. For sentences answered correctly, one may predict that longer reading times for the difficult region of sentences reflects on-line integration. For sentences answered incorrectly, one may predict no slowing in the difficult region but slowing in a later region of the sentences when readers realize that they are not comprehending. However, when an accuracy factor was included in the reaction time analyses, this factor did not interact with sentence type or sentence part. Therefore, those analyses are not presented here. Examining comprehension versus noncomprehension between individual children may be more valid because of the

Table 2 Experiment 1: Means and Number of Participants for Comprehenders and Noncomprehenders Divided on the Basis of a Median Split of Age, W-Span, or D-Span

	Comprehenders		Noncomprehenders	
	Young	Old	Young	Old
Age	9.2 (n = 55)	11.3 (n = 56)	9.2 (n = 21)	11.4 (n = 18)
	Low	High	Low	High
W-Span	11.3 (n = 58)	23.2 (n = 53)	11.1 (n = 18)	21.3 (n = 21)
D-Span	18.2 (n = 56)	24.5 (n = 55)	17.9 (n = 16)	25.2 (n = 23)

generally low accuracy rates in this population. The children are trying hard to comprehend these difficult sentences and may be using different strategies. Even though children may answer a question to a particular sentence incorrectly, they are still trying to comprehend that sentence.

We use the following analysis strategy to present the results. First, we present the analyses for on-line processing. Second, we present the analyses for off-line processing. In both cases, we begin with age analyses, followed by analyses of w-span and d-span. We can present only subject analyses because we are determining whether one individual difference variable explains variance when partialling for the other continuous variables, that is, age partialled for w-span and d-span, w-span partialled for age and d-span, and d-span partialled for age and w-span. We report only significant main effects and interactions.

Age Differences in On-Line Processing

A 2 (Age: old, young) × 2 (Sentence Type: SO, SS) × 4 (Sentence Part; 2–5, 6, 7, 8–9) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with w-span and d-span as covariates. There were significant main effects for sentence type, $F(1, 1199) = 26.96$, $p < .001$, and for sentence part, $F(3, 1199) = 30.96$, $p < .001$. Reading times for SS sentences were shorter than for SO sentences, and reading times for the critical relative–main clause transition (Words 6 and 7) were longer than for other regions. In addition, there was a significant interaction between sentence type and sentence part, $F(3, 1199) = 8.82$, $p < .001$. Reading times for the critical regions of SO sentences were longer than reading times for the critical regions of SS sentences (see Figure 1). This finding matches the results reported by King and Just (1991) for adults in which more syntactically complex sentences are processed more slowly at clause boundaries than simpler sentences. The interaction between sentence type and sentence part suggests that the on-line moving window technique is a useful measure of sentence processing with children of this age.

Working Memory Span Differences in On-Line Processing

A 2 (W-Span: high, low) × 2 (Sentence Type: SO, SS) × 4 (Sentence Part; 2–5, 6, 7, 8–9) × 2 (comprehension: comprehender, noncomprehender) ANCOVA was computed with age and d-span as covariates. Because these analyses (and the d-span analyses reported next) involve the same data set analyzed previously, only main effects or interactions involving the w-span variable are reported. The main effects of sentence type and sentence part, as well as their two-way interaction, do not change from those reported previously in this discussion. These analyses revealed no significant main effects or interactions involving w-span. The lack of any interactions with w-span suggests that this measure does not explain variance in the speed of processing of SS versus SO sentences. The reason for this lack of explanation may be that working memory, as measured by an adaptation of the Daneman and Carpenter (1980) w-span task, is not sensitive to on-line syntactic processing, at least in elementary school age students.

King and Just (1991) found a three-way interaction among working memory span (high versus low), sentence type (SS versus SO), and sentence part (relative to main clause transition). In particular, they found that low span adults slowed down the most at the clausal boundaries of the most difficult SO sentences. We may not have found a similar three-way interaction in children because children have difficulty processing both SS and SO sentences and because short term memory in children may be a more important determinant of on-line processing than working memory (see following discussion).

Digit Span Differences in On-Line Processing

A 2 (D-Span: high, low) × 2 (Sentence Type: SO, SS) × 4 (Sentence Part; 2–5, 6, 7, 8–9) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with age and w-span as covariates. This analysis revealed a significant main effect of d-span, $F(1, 1199) = 4.14$, $p < .05$. High d-span participants had longer reading times than low d-span participants. However, this main effect was qualified by a signifi-

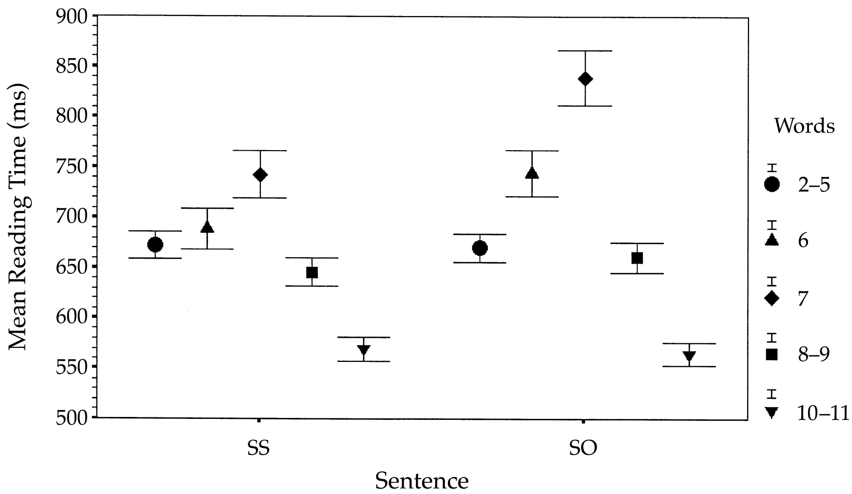

Figure 1 Mean reading time (ms) as a function of sentence region (Words 2–11) for SS and SO sentences. Word 6 is the last word of the relative clause and Word 7 is the first word of the main clause. Error bars indicate one standard error.

cant interaction between d-span and sentence part, $F(3, 1199) = 3.64, p < .05$. High d-span children slowed down more when reading the relative–main clause transition of sentences than did children with low d-span (see Figure 2). This finding suggests that high d-span children may process difficult syntactic structures more effectively than low d-span children (except for the noncomprehenders answering second verb questions as noted in the following discussion). These findings support the U-shaped developmental function discussed in the introduction. These findings are also generally consistent with other research that has found a relation between short-term memory and standardized tests of comprehension ability in young children (Farnham-Diggory & Gregg, 1975; Perfetti & Goldman, 1976), and between phonological memory and vocabulary acquisition (Gathercole & Baddeley, 1989).

Age Differences for Off-Line Comprehension Questions

A 2 (Age: old, young) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with w-span and d-span as covariates. This analysis revealed significant main ef-

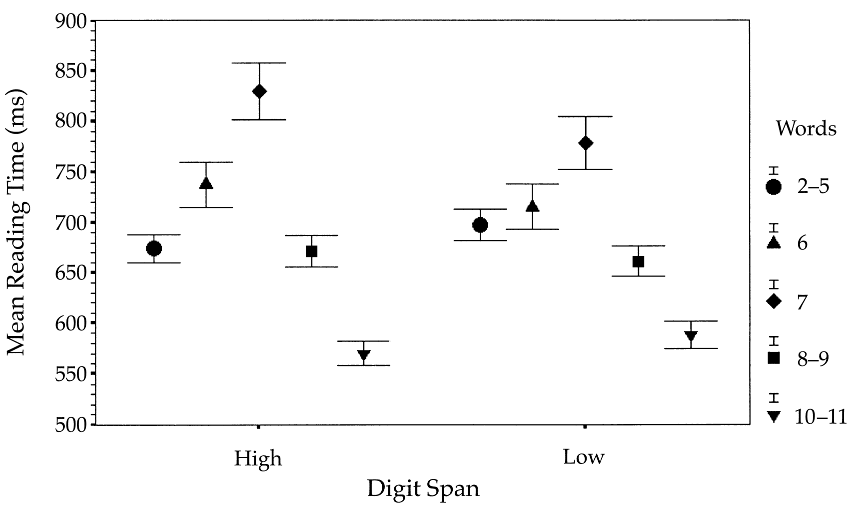

Figure 2 Mean reading time (ms) as a function of region in sentence (Words 2–11) for high and low d-span participants. Error bars indicate one standard error.

fects for comprehension, $F(1, 899) = 749.19$, $p < .001$, for sentence type, $F(2, 899) = 28.60$, $p < .001$, and for question type, $F(1, 899) = 158.64$, $p < .001$. The comprehension main effect shows that comprehenders scored higher than noncomprehenders. This is not surprising, because we dichotomized participants on the basis of whether or not they comprehended the sentences above chance (see preceding discussion). The sentence type main effect shows that participants answered SO questions less accurately than either SS questions or CVP questions. This result can be explained by the fact that SO sentences require two perspective shifts, whereas SS and CVP sentences require no perspective shift (MacWhinney, 1982). The main effect of question type shows that first verb questions were answered with greater accuracy than second verb questions. This effect can be explained by the fact that second verb questions require the participant to draw a dependency across an interruption in surface structure, whereas first verb questions do not require this (Slobin, 1973).

All of these main effects were qualified by two significant two-way interactions: comprehension by question type, $F(1, 899) = 275.54$, $p < .001$, and question type by age, $F(1, 899) = 8.75$, $p < .01$. These two two-way interactions were qualified by two three-way interactions: comprehension by question type by sentence type, $F(2, 899) = 13.03$, $p < .001$, and comprehension by question type by age, $F(1, 899) = 48.85$, $p < .001$. We parsed these three-way interactions by computing 2 (Age: young, old) $\times$ 3 (Sentence Type: SO, SS, CVP) $\times$ 2 (Question Type: first verb, second verb) ANCOVAs separately for comprehenders and noncomprehenders.

Comprehenders. This analysis produced main effects for sentence type, $F(2, 665) = 7.00$, $p < .001$, and for question type, $F(1, 665) = 8.74$, $p < .01$. The sentence type main effect showed that comprehenders answered SO questions less accurately than either SS questions or CVP questions. The question type main effect showed that first verb questions were answered with greater accuracy than second verb questions (see Figure 3). These results can be explained by the principles of perspective shift for SO sentences and interrupted structure for second verb questions (MacWhinney, 1982; Slobin, 1973).

Noncomprehenders. This analysis produced a significant main effect for question type, $F(1, 233) = 228.48$, $p < .001$. Noncomprehenders had lower accuracy levels on second verb questions than on first verb questions. In addition, there were significant interactions between age and question type, $F(1, 233) = 30.29$, $p < .001$, and between sentence type and question type, $F(2, 233) = 13.38$, $p < .001$. The pattern of age and sentence type effects for second verb questions differed from the pattern for first verb questions. For first verb questions, younger noncomprehenders had lower accuracy levels than older noncomprehenders (see Figure 4 for a similar effect with w-span instead of age as the independent variable). In addition, the more difficult SO questions had lower accuracy rates than the easier SS and CVP questions (see Figure 3). In general, the pattern of question type and

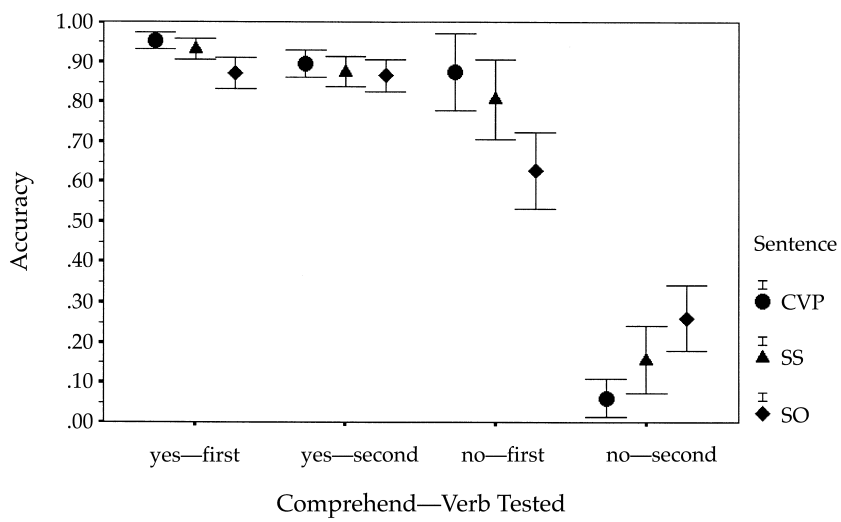

Figure 3 Mean a-prime scores to questions for the CVP, SS, and SO sentences in the reading experiment. First and third clusters represent questions testing the first verb (first), whereas second and fourth clusters represent questions testing the second verb (second). First and second clusters represent participants who comprehended the sentences (yes), whereas third and fourth clusters represent participants who did not comprehend the sentences (no). Error bars indicate one standard error.

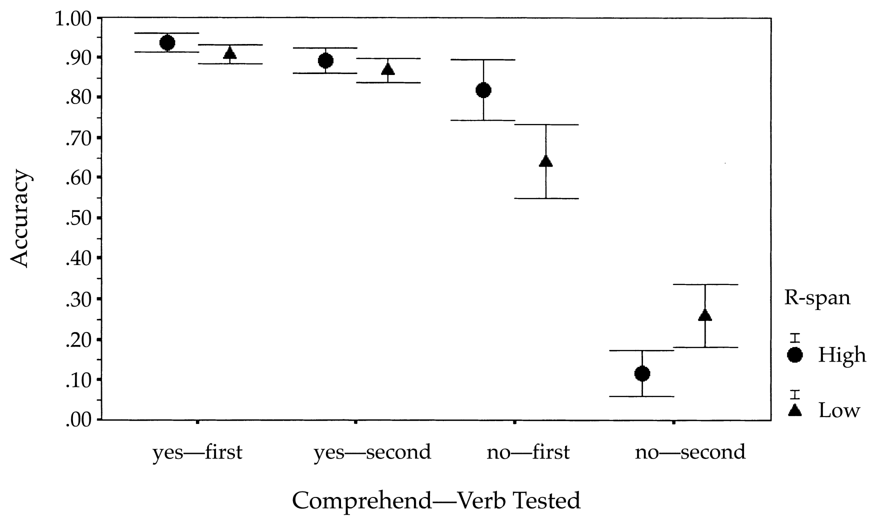

Figure 4 Mean a-prime scores to off-line questions for high and low w-span participants in the reading experiment. First and third clusters represent questions testing the first verb (first), whereas second and fourth clusters represent questions testing the second verb (second). First and second clusters represent participants who comprehended the sentences (yes), whereas third and fourth clusters represent participants who did not comprehend the sentences (no). Error bars indicate one standard error.

sentence type differences for the first verb questions for noncomprehenders was similar to, but more marked than, the pattern found for comprehenders.

In contrast to first verb questions, accuracy levels for noncomprehenders on second verb questions were very low. Noncomprehenders often incorrectly chose the second noun as the subject of the second verb. For example, in the SS sentence "The captain that invited the man built the stage," the noncomprehenders often answered that "The man built the stage." When referring to Figures 3 and 4, a-prime scores below .50 on the second verb questions indicate an incorrect choice of the second noun as the subject of the second verb. For these questions, older noncomprehenders had lower accuracy levels than younger noncomprehenders (see Figure 4 for a similar effect with w-span instead of age as the independent variable). In addition, the easier CVP and SS questions had lower accuracy rates than the more difficult SO questions (see Figure 3). Crucially, both of the effects for second verb questions were in the opposite direction to those found for first verb questions.

These results suggest that older noncomprehenders were actually worse at understanding second verb questions than younger noncomprehenders. To better understand this effect, we contrasted the responses for true versus false questions after collapsing across sentence type. Second verb questions that are false correspond to a structural interpretation based on a local attachment strategy—"choose second noun as subject of second verb." For these questions, we would expect that non-comprehenders would consistently produce incorrect responses. For second verb questions that are true, this effect should not be so strong because the question itself provides a hook into the alternative correct interpretation. In fact, younger noncomprehenders scored at chance levels on true questions (51%), whereas they were more consistent at applying the incorrect local attachment strategy on false questions (17%, $p < .01$). The older noncomprehenders answered both true and false questions at below chance levels, but they were also more consistent at applying the local attachment strategy on false questions (13%) than on true questions (29%, $p < .01$).

We can account for this pattern of results for the noncomprehenders by assuming a developmental trajectory in which children begin with a local attachment strategy that is inconsistently applied. Because this strategy is highly labile in this younger group, the veridicality of the question has a strong effect. In the case of false questions, where the form of the question is compatible with the strategy, young noncomprehenders are fairly consistent in applying the incorrect local attachment strategy. However, in true questions, where the form of the question does not match up with the strategy, young noncomprehenders are less consistent in applying the incorrect local attachment strategy. For older noncomprehenders, the form of the question is relatively less important. Older noncomprehenders are consistent in applying the incorrect local attachment strategy for answering true and false questions. This indicates a consolidation of this incorrect strategy across development for the noncomprehenders.

Working Memory Span Differences for Off-Line Comprehension Questions

A 2 (W-Span: high, low) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with age and d-span as covariates. Because these analyses (and the d-span analyses reported below) involved the same data set analyzed above, only main effects or interactions involving the w-span variable are reported. Therefore, the main effects of comprehension, question type, and sentence type, as well as the comprehension by question type interaction and the comprehension by question type by sentence type interaction, do not change from what was reported above.

This analysis revealed a significant interaction between question type and w-span, $F(1, 899) = 10.22$, $p < .01$, and between comprehension, question type, and w-span, $F(1, 899) = 24.63$, $p < .001$. This three-way interaction parallels the interaction between comprehension, question type, and age reported and discussed above. The unique predictive power of w-span showed that the noncomprehenders with high w-span scores were more consistent in their application of the incorrect local attachment strategy (see Figure 4). This finding suggests that the larger or more efficient working memories of the high w-span noncomprehenders allowed them to consistently apply an incorrect local attachment strategy. Their ability to keep all lexical items in memory in the order in which they were presented allowed them to consistently answer that the second noun was the subject of the second verb.

Digit Span Differences for Off-Line Comprehension Questions

A 2 (D-Span: high, low) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with age and w-span as covariates. This analysis produced no significant main effects or interactions involving d-span.

EXPERIMENT 2

Experiment 1 yielded five major findings. First, reading times for the relative–main clause transition in SO sentences were longer than reading times for these regions in SS sentences. This effect supports the principle of perspective shift (MacWhinney, 1982). Second, high d-span children slowed down when reading the relative–main clause transition of SO and SS sentences more than did low d-span children. This is the first demonstration to show that short-term memory is related to on-line sentence processing and supports the U-shaped developmental function discussed in the introduction. Third, noncomprehenders consistently applied a local attachment strategy, which led to errors on second verb questions, particularly for the easier SS and CVP sentences. Second verb questions are especially hard for noncomprehenders because of an interruption in surface structure (Slobin, 1973). Noncomprehenders may have been able to more consistently apply the local attachment strategy to easier CVP and SS sentences because these sentences require fewer resources than SO sentences. Fourth, older and high w-span noncomprehenders had lower accuracy levels on second verb questions than younger and low w-span noncomprehenders. We interpret this finding as indicating that a local attachment strategy can be used more effectively in high memory span children because a decreased load on processing capacity allows a more consistent application of this strategy. Fifth, these first four effects show that the moving window technique is appropriate for studying on-line sentence processing in children. This is the first study to use this technique with children.

Despite the good match of these findings to the existing adult and developmental literature, one could question whether the moving window reading methodology is appropriate for children. Because the children in Experiment 1 are still learning to read, these various effects could be due not to differences in sentence processing strategies but rather to problems with visual word decoding. One way to assess this alternative account is to replicate the experiment by using a technique that does not rely on reading. If the same effects obtain with an auditory version of the sentence task, then we cannot attribute these sentence-level effects to poor single-word decoding. One technique that can be used in this context is the auditory moving window task that has been shown to be sensitive to lexical frequency differences in adults (Ferriera, Henderson, Anes, Weeks, & McFarlane, 1996). This task seems appropriate for the study of sentence processing in children because it does not rely on reading.

Our second experiment used the same stimuli as in Experiment 1 but with auditory presentation. We expected to replicate the first three findings in Experiment 1, and the results of Experiment 2 supported this expectation. However, we also expected the shift from the visual to the auditory modality to be accompanied by a greater involvement of short-term phonological memory. To the degree that auditory sentence processing relies at least partially on the phonological loop (Gupta & MacWhinney, 1997), we expected the comprehension of auditorily presented sentences to have a stronger relation to the digit span measure (d-span) than to the working memory span measure (w-span).

Method

Participants

Participants were 15 second graders (M = 7.9 years, SD = .4), 24 third graders (M = 8.9 years, SD = .4), 23 fourth graders (M = 9.7 years, SD = .5), 22 fifth graders (M = 10.6 years, SD = .5), and 16 sixth graders (M = 11.7 years, SD = .5). The numbers of boys and girls were approximately equal, but the number of participants was not sufficient to include gender as an independent variable. All 100 participants were recruited from private and parochial schools in middle class neighborhoods in the metropolitan Pittsburgh area. All participants were native English speakers and had normal hearing and normal vision or were corrected to normal vision.

Procedure

The d-span measure was the same as the one used in Experiment 1. However, the working memory measure (w-span) and the sentence task were now presented auditorily, rather than visually. The sentences and questions in these tasks were the same as in Experiment 1.

Working memory measure. A female graduate student read all sentences and questions with normal prosody. These stimuli were digitized for presentation on a computer through earphones. During each trial in the auditory w-span task, there was a 400-ms interstimulus interval between each sentence in each set. This short interstimulus interval was used to prevent rehearsal of sentence final words. As in the visual w-span task, the experimenter controlled presentation of the question after the participant had recalled as many sentence final words as possible. The participant controlled presentation of each set by pressing a yellow button on a button box.

Sentence processing task. The same female read all the individual words in the sentences by speaking each word independently in an alphabetical list. Because the words were spoken independently, the sentences were absent of coarticulatory and prosodic cues. Reading the words in this manner avoided the problem of dividing continuous speech into segments. If continuous speech is divided into segments, then it sounds unnatural because coarticulation and prosodic cues are violated. In contrast to the sentences, the questions were read as a continuous stream because they were presented as wholes during the sentence task. The questions and sentences were digitized for computer presentation.

The participants controlled the presentation of each word of each sentence with a yellow button on a button box. This button press produced a reaction time for each word in the sentence. After listening to each sentence, the participants heard a beep and were asked to press the yellow button to present a true–false question. They pressed the red button if the question was false. If the question was true, they pressed the green button.

Results and Discussion

Relation between the Individual Difference Variables

Age was significantly correlated with w-span, $r(98) = .29$, $p < .01$, and with d-span, $r(98) = .38$, $p < .001$. W-span and d-span were also significantly correlated, $r(98) = .46$, $p < .001$, even when this relation was partialled for age, $r(97) = .39$, $p < .001$. Because age, w-span, and d-span were partially independent, we examined whether each of these measures explained unique variance in the on-line listening times for sentences.

Data Trimming

The same data trimming procedure used in Experiment 1 was used for the auditory moving window data in Experiment 2. In particular, for each child, a linear regression was computed in which word duration in milliseconds was regressed on listening time in milliseconds. The observed listening time for each individual word was then subtracted from the predicted listening time based on the linear regression. To our knowledge, this procedure has not been used before in the literature to adjust listening times, therefore, we conducted parallel analyses with the raw listening times. We do not report these results, however, because they produced similar results to the adjusted listening time analyses. In addition, listening times for individual words greater or less than 2.5 *SD*s from the mean for each child were equated to those values (<3%) and sentences that had three or more word skips in a row or four or more word skips for the entire sentence were eliminated (<1%).

Inferential Analysis Strategy

The same analysis strategy for Experiment 1 was used in Experiment 2. Using an a-prime criterion of

Table 3 Experiment 2: Means and Number of Participants for Comprehenders and Noncomprehenders Divided on the Basis of a Median Split of Age, W-Span, or D-Span

	Comprehenders		Noncomprehenders	
	Young	Old	Young	Old
Age	8.8 (n = 32)	10.8 (n = 35)	8.7 (n = 11)	10.7 (n = 12)
	Low	High	Low	High
W-Span	11.9 (n = 34)	23.0 (n = 33)	11.0 (n = 13)	21.2 (n = 10)
D-Span	16.1 (n = 30)	22.9 (n = 37)	15.4 (n = 13)	22.5 (n = 10)

greater than 60% to separate comprehenders from noncomprehenders, 19 participants scored below chance on CVP sentences, 22 scored below chance on SS sentences, and 28 scored below chance on SO sentences. For participants to be considered noncomprehenders, they had to score below chance on at least the SS and SO sentences. This resulted in totals of 23 noncomprehenders and 77 comprehenders. The noncomprehenders and comprehenders were relatively equally distributed across age, w-span, and d-span. Table 3 presents the means (and number of participants) for comprehenders and noncomprehenders divided on the basis of a median split of age, w-span, or d-span. Young and old groups were formed by a median split of age, even though there were five age groups, so that the results of Experiment 1 and 2 could be directly compared.

Age Differences in On-Line Processing

A 2 (Age: old, young) × 2 (Sentence Type: SO, SS) × 4 (Sentence Part; 2–5, 6, 7, 8–9) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with w-span and d-span as covariates. There were significant main effects for sentence type, $F(1, 799) = 4.97$, $p < .05$, for sentence part, $F(3, 799) = 3.41$, $p < .05$, and for comprehension, $F(1, 799) = 5.35$, $p < .05$. In addition, there was a significant interaction between sentence type and sentence part, $F(3, 799) = 3.09$, $p < .05$. Listening times for the relative–main clause transition in SO sentences were longer than listening times for this region in SS sentences (see Figure 5). This effect replicates the interaction between sentence type and sentence part for the visual moving window in Experiment 1, and indicates that the auditory moving window technique provides a sensitive measurement of on-line sentence processing in children even though the sentences were absent of contextual and prosodic cues. There was also an interaction between age and sentence type $F(1, 799) = 5.68$, $p < .05$. Younger children listened to SS and SO sentences at similar rates. In contrast, older children listened to SS sentences more quickly than SO sentences. This suggests that older children are more sensitive to the general processing differences between sentence types.

Working Memory Span Differences in On-Line Processing

A 2 (W-Span: high, low) × 2 (Sentence Type: SO, SS) × 4 (Sentence Part; 2–5, 6, 7, 8–9) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA

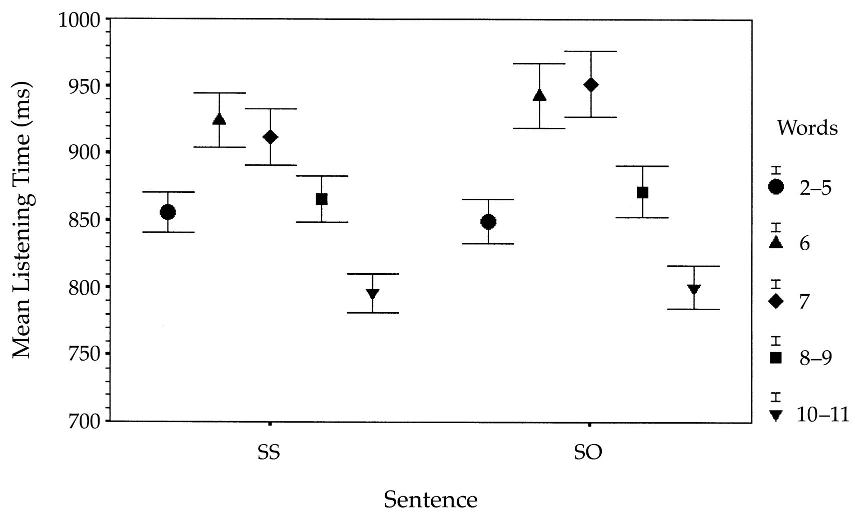

Figure 5 Mean listening time (ms) as a function of region in sentence (Words 2–11) for SS and SO sentences. Error bars indicate one standard error.

was computed with age and d-span as covariates. As with the analyses of the on-line effects in Experiment 1, these analyses revealed no significant main effects or interactions involving w-span.

Digit Span Differences in On-Line Processing

A 2 (D-Span: high, low) × 2 (Sentence Type: SO, SS) × 4 (Sentence Part; 2–5, 6, 7, 8–9) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with age and w-span as covariates. This analysis revealed a significant interaction between d-span and sentence part, $F(3, 799) = 3.76$, $p < .05$. High d-span children slowed down when listening to the relative–main clause transition in sentences more than did children with low d-span (see Figure 6). This effect replicates the interaction between d-span and sentence part for the visual moving window in Experiment 1 and supports the U-shaped developmental function discussed in the introduction.

Age Differences for Off-Line Comprehension Questions

A 2 (Age: old, young) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with w-span and d-span as covariates. This analysis revealed significant main effects for comprehension, $F(1, 599) = 307.32$, $p < .001$, for sentence type, $F(2, 599) = 35.33$, $p < .001$, and for question type, $F(1, 599) = 23.77$, $p < .001$. In addition to these main effects, there was a significant comprehension by question type interaction, $F(1, 599) = 27.91$, $p < .001$. However, this two-way interaction was qualified by a three-way comprehension by question type by sentence type interaction, $F(2, 599) = 6.63$, $p < .01$.

We parsed this complex three-way interaction by computing 2 (Age: young, old) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) ANCOVAs separately for comprehenders and noncomprehenders. For comprehenders, there were main effects for sentence type, $F(2, 461) = 7.19$, $p < .01$, and for question type, $F(1, 461) = 5.10$, $p < .05$. Comprehenders answered SO questions less accurately than either SS or CVP questions. Comprehenders also answered first verb questions with greater accuracy than second verb questions (see Figure 7). These results are consistent with Experiment 1 and support the sentence processing principles of perspective shift and interrupted surface structure (MacWhinney, 1982; Slobin, 1973).

For noncomprehenders, there was a significant main effect for question type, $F(1, 137) = 21.53$, $p < .001$. Noncomprehenders had lower accuracy levels on second verb questions than on first verb questions. This is evidence that the interrupted surface structure effect held for noncomprehenders as well as for comprehenders. In addition to this main effect, there was a significant interaction between sentence type and question type, $F(2, 137) = 4.20$, $p < .05$. For first verb questions, the more difficult SO questions had lower accuracy rates than the easier SS and CVP questions. In contrast, for second verb questions, the easier CVP and SS questions had lower accuracy rates than the more difficult SO questions (see Figure 7). These effects for the noncomprehenders replicate the effects in Experiment 1 that found the noncomprehenders used the incorrect

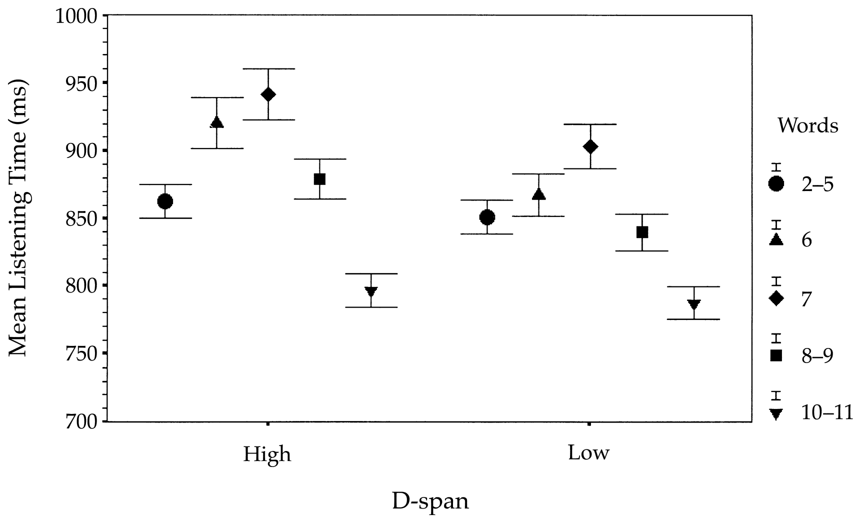

Figure 6 Mean listening time (ms) as a function of region in sentence (Words 2–11) for high and low d-span participants. Error bars indicate one standard error.

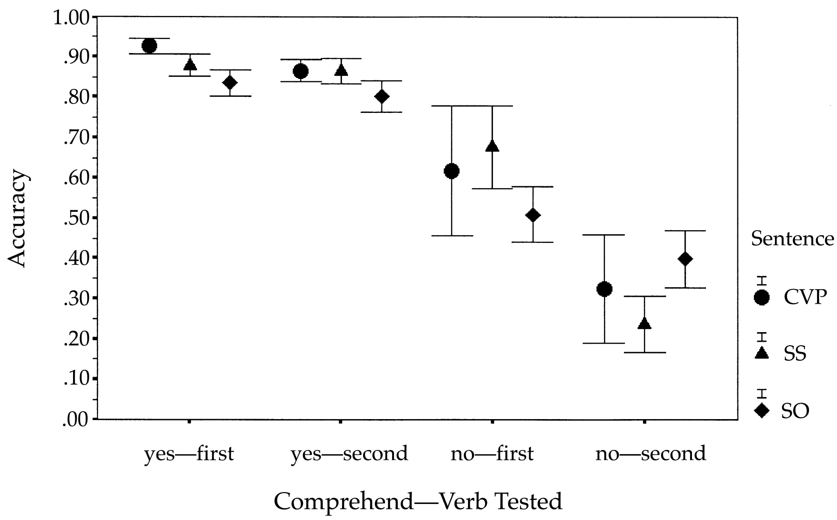

Figure 7 **Mean a-prime scores to questions for the CVP, SS, and SO sentences in the listening experiment. First and third clusters represent questions testing the first verb (first), whereas second and fourth clusters represent questions testing the second verb (second). First and second clusters represent participants who comprehended the sentences (yes), whereas third and fourth clusters represent participants who did not comprehend the sentences (no). Error bars indicate one standard error.**

local attachment strategy more effectively for the easier sentences.

Working Memory Span Differences for Off-Line Comprehension Questions

A 2 (W-Span: high, low) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with age and d-span as covariates. This analysis produced no significant main effects or interactions involving w-span. The absence of a relation between w-span and auditory comprehension of off-line questions contrasts with the presence of a relation between w-span and visual comprehension in Experiment 1. We interpret this difference as reflecting a lesser role for working memory, as measured by the w-span task, in auditory sentence processing as compared with visual sentence processing (a discussion of this effect follows).

Digit Span Differences for Off-Line Comprehension Questions

A 2 (D-Span: high, low) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) × 2 (Comprehension: comprehender, noncomprehender) ANCOVA was computed with age and w-span as covariates. This analysis revealed a significant interaction between comprehension and d-span, $F(1, 599) = 6.53$, $p < .05$, and between comprehension, question type, and d-span, $F(1, 599) = 8.49$, $p < .01$. We parsed this complex three-way interaction by computing 2 (Age: young, old) × 3 (Sentence Type: SO, SS, CVP) × 2 (Question Type: first verb, second verb) ANCOVAs separately for comprehenders and noncomprehenders.

For comprehenders, there was a significant interaction between d-span and question type, $F(1, 461) = 6.06$, $p < .05$. High d-span children were more accurate at answering second verb questions than low d-span children, whereas both high and low d-span children were comparable in accuracy levels on first verb questions (see Figure 8). For noncomprehenders, there was also a significant interaction between d-span and question type, $F(1, 137) = 3.39$, $p < .05$. High and low d-span children had comparable accuracy levels on first verb questions. In contrast, for second verb questions, high d-span children had lower accuracy levels than low d-span children (see Figure 8). This interaction suggests that the larger short-term memory capacity of the noncomprehenders with high d-span scores allowed them to more consistently apply a local attachment strategy than those children with low d-span scores. This two-way interaction is generally consistent with Experiment 1. However, the visual moving window experiment found that accuracy in responses to off-line questions for the noncomprehenders was modulated by w-span and not d-span as in Experiment 2. Short-term phonological memory may have a more important role in auditory than in visual sentence comprehension because auditory sentence comprehension and digit span involve processing a series of words presented phonologically. In contrast, working memory, as

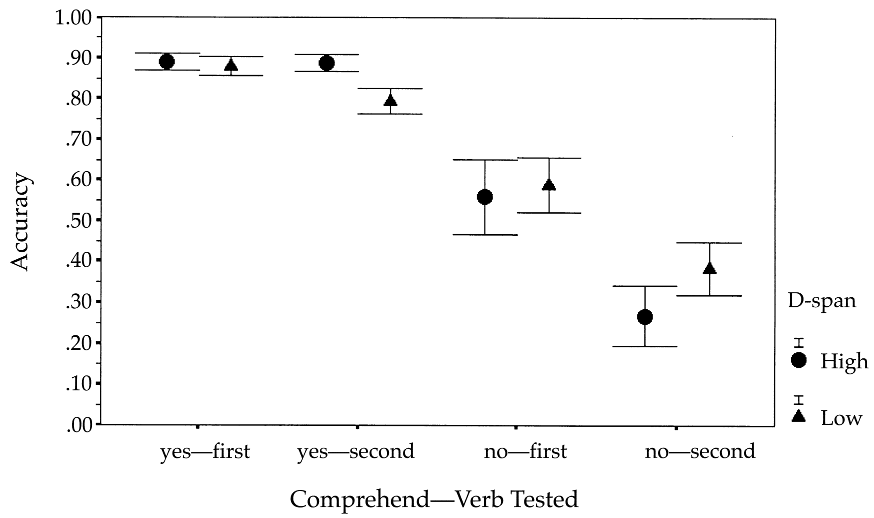

Figure 8 **Mean a-prime scores to off-line questions for high and low w-span participants in the listening experiment. First and third clusters represent questions testing the first verb (first), whereas second and fourth clusters represent questions testing the second verb (second). First and second clusters represent participants who comprehended the sentences (yes), whereas third and fourth clusters represent participants who did not comprehend the sentences (no). Error bars indicate one standard error.**

measured by the reading span task, may be more related to visual sentence comprehension because reading is a more demanding process than natural language comprehension and requires more processing resources.

GENERAL DISCUSSION

This study had two major goals. The first was to determine the extent to which children have succeeded in acquiring adult-like strategies for processing complex multiclause sentences. The second was to examine ways in which sentence processing in children might be influenced by individual differences in either short-term or working memory. Working memory was measured by a modified version of the w-span task (Daneman & Carpenter, 1980; Swanson, 1996) and short-term memory was measured by an auditory digit span task. We studied the relation between memory span and the processing of three types of sentences by 250 children in the second through sixth grades (see Tables 2 and 3). Children read or listened to sentences with SO and SS relative clause structure, as well as to sentences with conjoined verb phrases (see Table 1). Our experiment included both an on-line measure of word-by-word processing and an off-line measure of question accuracy. The data for children who comprehended the sentences were analyzed separately from the data for those who did not comprehend the sentences.

We observed a consistent pattern of findings for both on-line and off-line processing across the two experiments, whether processing was in the visual (Experiment 1) or auditory (Experiment 2) modality. Moreover, the findings matched up well with predictions derived from the developmental literature and the adult sentence processing literature. We first discuss the results for on-line processing.

On-Line Processing of Restricted Relative Clause Sentences

Our results showed that the moving window technique is appropriate for assessing on-line syntactic processing in children. In fact, this is the first application of the technique to children. Moreover, it is the first study to demonstrate effects of sentence structure on on-line auditory processing in children or adults (see Ferierra et al., 1996).

We found a significant interaction between sentence type and sentence part for both the visual and auditory moving window. The difference in reading and listening times between the relative–main clause transition and the rest of the sentence was larger for SO sentences than for SS sentences (see Figures 1 and 5). Both SS and SO sentences may have forced children to slow down at the relative–main clause boundary because the relative clause interrupts the structure of the main clause (Slobin, 1973). SO sentences may have shown more slowing than SS sentences at this boundary because there are two perspective shifts in SO sentences and no perspective shifts in SS sentences (MacWhinney, 1982). This finding supports past reading studies with adults that have found syntactically complex sentences to exhibit more slowing at clause transitions than simpler sentences (King & Just, 1991).

Our results also support a role for short-term memory in the on-line processing of sentences by children. Specifically, high d-span children slowed down more during the relative–main clause transition than did low d-span children (see Figures 2 and 6). This larger difference in the listening and reading times for the most difficult syntactic sequence suggests that high d-span participants may have been using their ability to store words in short-term memory as a way of processing these difficult sentence segments. Low d-span participants do not have this option because they cannot store words effectively in short-term memory. These results are consistent with the hypothesis of a U-shaped developmental function in on-line processing discussed in the introduction. In addition, these results are generally consistent with research that shows a strong relation between short-term phonological memory and vocabulary acquisition in young children (Gathercole & Baddeley, 1989, 1990a, 1990b), and between short-term memory and off-line measures of reading skill (Dixon et al., 1988; Farnham-Diggory & Gregg, 1975; Mann & Liberman, 1984; Perfetti & Goldman, 1976).

We did not find a relation between working memory, as measured by the w-span task, and the on-line processing of sentences. Our results are at odds with some adult studies that have found working memory differences in on-line sentence processing (King & Just, 1991), but our results are in agreement with other adult studies that have found no working memory span differences in acceptability judgments (Waters & Caplan, 1996a).

One interesting finding in the on-line results that deserves further research is that sentence processing in the visual modality seemed to slow down later than processing in the auditory modality. In particular, for the visual modality, a slowdown occurred from the end of the relative clause to the verb of the main clause for SS and SO sentences and for high and low d-span children. In contrast, for the auditory modality, most of the slowdown occurred on the last word of the relative clause and not on the verb of the main clause. This finding suggests that auditory processing is more immediate and places demands earlier on the language and memory systems. However, to more accurately test this hypothesis, modality of presentation must be manipulated within participants.

Off-Line Sentence Comprehension

We also studied the final representation of the sentence by asking children to verify sentences that asked for information about the subject of either the first verb or the second verb in the sentence (see Table 1). In a review of previous research on the comprehension of sentences with relative clauses by 4- to 7-year-old children, MacWhinney (1982) suggested that the principle of perspective shift most accurately accounted for the data. The present investigation extends the findings on perspective shift to older children by showing that comprehenders had lower accuracy rates in their responses to SO questions than to SS or CVP questions (see Figures 3 and 7). This finding can be explained by the fact that CVP and SS sentences require no perspective shift, whereas SO sentences require two perspective shifts. The analyses for the comprehenders also showed that responses to first verb questions had higher accuracy rates than responses to second verb questions. Second verb questions may be more difficult to answer than first verb questions because answering second verb questions requires the child to make an attachment across a clausal interruption (Foss, Bias, & Starkey 1977; Slobin, 1973).

The pattern of question accuracy results for the noncomprehenders also supports the roles of perspective shift and interrupted structure in sentence processing difficulty. In support of perspective shift, for the first verb questions, the noncomprehenders scored significantly lower for the SO sentences than for either the SS or CVP sentences. In support of interrupted structure, the noncomprehenders scored significantly lower on second verb questions than on first verb questions. Indeed, the noncomprehenders were scoring consistently below chance on second verb questions. The noncomprehenders were incorrectly choosing the second noun as the subject of the second verb. For example, in the SS sentence "The captain that invited the man built the stage," the noncomprehenders often answered that "The man built the stage."

We argue that the noncomprehenders were relying on a simple strategy of local attachment (Ford et al., 1982). Using this strategy, children take the second verb of these complex sentences and then look in their memories to the most recent noun that is a potential subject. In these sentences, this is the second noun and the choice of this noun as the subject of the second verb is always an error. In effect, noncomprehenders are taking the noun that is locally available over the noun that is syntactically correct. The local attachment strategy allows noncomprehenders to perform well on the first verb questions. This strategy leads to correct role assignment, because the first noun is the subject of the first verb in these sentences. A local attachment strategy account would predict that noncomprehenders would have comparatively little trouble comprehending OS structures like "The boy chases the girl that sees the policeman," because the subject always immediately precedes the verb in these sentences. Future research could address this prediction.

Two additional results emerged from the analyses of the noncomprehenders' answers to the second verb questions. Both point to the need for additional microgenetic studies (Siegler & Crowley, 1991) to examine the details of the development of sentence processing. In the visual sentence task of Experiment 1, high w-span children had significantly lower accuracy levels than did low w-span children (see Figure 4). In the auditory sentence task of Experiment 2, high d-span children had significantly lower accuracy levels than did children with low d-span (see Figure 8). We believe that these memory span differences show that high span noncomprehenders make more consistent use of an incorrect local attachment strategy than do low span noncomprehenders. Paradoxically, high span noncomprehenders make this consistent error precisely because they have more memory processing resources. Microgenetic studies would be interesting to conduct with this group because noncomprehenders with high memory spans might benefit from instruction more than those with low memory spans. Furthermore, these results indicate that working memory span (w-span) may be a more sensitive indicator of individual differences in visual sentence processing because reading may require more strategic memory resources as measured by the reading span task. In contrast, short-term memory span (d-span) may be a more sensitive indicator of individual differences in auditory sentence processing because both require processing in the phonological loop (Gupta & MacWhinney, 1997).

Recently, functional magnetic resonance imaging (fMRI) studies have investigated sentence type differences and comprehension differences in patterns of activation during the processing of SO, SS, and CVP sentences. Just, Carpenter, Keller, Eddy, and Thulborn (1996) found that more activation occurs in the language centers of the brain (Broca's area and Wernicke's area) during the processing of SO sentences as compared with SS and CVP sentences (see also Booth et al., 1999, in press). This increase in activation was particularly pronounced for Wernicke's area and its right homologue. These findings suggest that more difficult sentence structures require the recruitment of more brain tissue to aid in the comprehension process. Just, Carpenter, Keller, Eddy, and Thulborn (1996) only examined activation patterns in adults with relatively high accuracy levels on all sentences, so they could not examine differences between comprehenders and noncomprehenders. Booth et al. (1999) have recently examined differences in activation patterns between adults, children, and pediatric patients. They found that participants who comprehended the sentences at chance levels (40%–60%) showed very little activation, whereas participants who scored above chance (greater than 60%) showed more activation. Most interestingly, participants who were consistently using a local attachment strategy (i.e., they scored less than 40%) showed the most activation, which implies that they were trying hard to comprehend the sentences. Unfortunately, the design of the Booth et al. (1999) study did not allow for an examination of the relation between individual differences in memory span and activation patterns. Functional MRI holds great promise for elucidating the mechanisms underlying individual differences in sentence processing. For example, high and low memory span noncomprehenders may reveal quite different activation patterns that could provide insight into how they process these sentences differently.

CONCLUSION

The goals of this study were to determine whether children have learned adult-like strategies for processing complex multiclause sentences and whether this processing is affected by individual differences in shortterm or working memory. The first major finding of this study was that both the visual and auditory sentence tasks provided sensitive measures of both on-line and off-line processing in children. For the children who comprehended the sentences, SO sentences were more difficult to process than the SS or CVP sentences, as predicted by the principle of perspective shift (MacWhinney, 1982). In addition, the fact that second verb questions were more difficult to understand than first verb questions supports the principle of interrupted structure (Slobin, 1973).

The second major finding was that the noncomprehenders revealed a different pattern of accuracy scores from the comprehenders. Noncomprehenders consistently answered second verb questions incorrectly, which indicates that they were using a local attachment strategy that took the second noun as the subject of the second verb (Ford et al., 1982). Interestingly, memory span predicted how consistently noncomprehenders used a local attachment strategy. Noncomprehenders with a large memory span applied this strategy more consistently, presumably because they were able to store several words in memory and use those stored words to select a candidate for local attachment. We expect that these noncomprehenders are children who are poised to move into the group of comprehenders as they acquire understanding of the right way to process these sentences.

The third major finding of our developmental study is that short-term memory was more predictive of on-line processing differences than was working memory. Adult studies have suggested that the amount of working memory individuals possess influences their on-line processing of sentences (Just & Carpenter, 1992). Others have questioned the exact role of working memory in syntactic processing in adults (Waters & Caplan, 1996b). The data from our developmental study indicate that differences in working memory did not impact on-line processing in children. We did, however, observe a significant effect of short-term phonological memory ability on processing at the relative–main clause transition. These results should serve to inspire other researchers to begin studying the details of the development of on-line sentence processing in children.

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ADDRESSES AND AFFILIATIONS

Corresponding author: James R. Booth, Department of Communication Sciences and Disorders, Northwestern University, 2299 North Campus Drive, Evanston, IL 60208-3560; e-mail: j-booth@nwu.edu; Yasuaki Harasaki is also at Northwestern University; and Brian MacWhinney is at Carnegie Mellon University, Pittsburgh, PA.

APPENDIX A

SETS OF SENTENCES FOR THE W-SPAN TASK

The sets of sentences, ranging from 2 to 5, for the w-span task are followed by the question testing comprehension for one of the sentences in the set.

Two sentences

1. Many animals live on a farm.
   People have used masks since early times.
   What have been used since early times?
2. The television was on all day long.
   The doctor called the nurse on the phone.
   Who called the nurse?
3. The ball rolled down the stairs.
   You should brush your teeth at night.
   Where did the ball roll?
4. The boy ran up the steep hill.
   It stormed that night in the country.
   When did it storm?
5. It was the warmest day of summer.
   The test was given in the classroom.
   What was given?
6. Mary tried to tell her teacher the right street.
   Sarah wants you to give her a dollar.
   Who did Mary try to tell?
7. Both of the games were canceled because of trouble.
   Jennifer says she doesn't have time.
   What was canceled?

Three sentences

1. Bob will not leave until he finishes the meal.
   The desk in the classroom was full of junk.
   The pond had fish of different colors.
   What did the pond have?
2. We saw many deer on our long ride.
   Carol will make cookies for the party.
   Our class has written letters to the president.
   What will Carol make?
3. The cheerleader does not seem to have friends.
   Beth can't go because she didn't get shoes.
   Bob doesn't want to tell the teacher.
   Who can't go?
4. We waited in line for an hour.
   Sally thinks we should give the bird its freedom.
   My mother said she would write an excuse.
   Where did we wait?

Four sentences

1. The baby's toy rolled under the bed.
   They walked around to the back of the house.
   It was so cold, the snow crunched under his feet.
   The squirrel hid the acorns in the tree.
   What did the squirrel hide?
2. My little brother went in the wrong restaurant.
   I have talked to my parents about the idea.
   You will be sorry if you break the window.
   My friend wants to learn about snakes.
   Who will be sorry?
3. If you work hard you can make a discovery.
   We didn't buy the car because of the cost.
   I would like to know your opinion.
   It is important to think about safety.
   What didn't we buy?

Five sentences

1. Sam is having problems with his memory.
   The teacher wanted to see me about my book.
   John is not in a very good mood.
   The broken doll was not my fault.
   They were all happy to be at the event.
   What was broken?
2. I can study if you give me a pencil.
   I will give Cindy the candy in a bowl.
   Children like to read books about animals.
   The good news gave Ann a feeling of happiness.
   Jeff likes to do homework in ink.
   What will I give to Cindy?

APPENDIX B

TYPES OF SENTENCES IN THE MOVING WINDOW SENTENCE TASK

Examples of the three types of sentences (SO, SS, and CVP) in the experimental moving window sentence task are presented here (see Table 1 for examples of the question types).

SO sentences

The pig that the dog jumped ate the trash in the street.
The prince that the king taught rode the car to the palace.
The man that the captain invited built the stage for the band.
The waiter that the manager blamed carried the suitcase up the stairs.
The player that the Indian helped smashed the vase on the table.
The mother that the robber hated dropped the glass on the floor.
The painter that the boyscout knew noticed the problem after the meeting.
The deer that the tiger watched entered the field from the side.
The guard that the skier touched held the door open for customers.
The president that the cashier splashed loved the flowers in the pictures.
The turkey that the snake scared drank the water from the bucket.
The child that the artist drew broke the chair in the office.

SS sentences

The principal that tripped the janitor used the phone to call home.
The goat that found the mouse surprised the farmer in the barn.
The author that disliked the police refused the award for his action.
The lawyer that upset the prisoner stopped the fight just in time.
The horse that kicked the cow broke the gate to the fence.
The painter that insulted the soldier wrote the letter to the paper.
The fireman that stopped the plumber heard the shout in the basement.
The banker that attacked the girl left the office quickly that afternoon.
The doctor that phoned the artist watched the movie in the theater.
The dancer that shoved the baker painted the sign before the show.
The monkey that followed the frog left the tree in a hurry.
The bear that scared the lion climbed the mountain to the top.

CVP sentences

The cat chased the rabbit and enjoyed the hunt in the yard.
The teacher taught the students and stopped the lesson in a week.
The coach helped the swimmer and cleaned the edge of the pool.
The bride blamed the groom and left the church in a hurry.
The woman paid the farmer and brought the fruit to the store.
The driver left the teenager and drove the car to his house.
The sailor liked the poet and caught the fly with his net.
The owl warned the animals and left the tree in the storm.
The pilot bribed the clown and flew the kite in the air.
The owner paid the worker and examined the roof on his house.
The chicken saw the fox and ran quickly up the steep hill.
The nurse upset the patient and kept him awake until the morning.

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