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Age Differences in Memory-Load Interference Effects in Syntactic Processing

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The effects of a memory load on syntactic processing by younger and older adults were examined. Participants were asked to remember a noun phrase (NP) memory load while they read sentences varying in syntactic complexity. Two types of NPs were used as memory loads: proper names or definite descriptions referring to occupations or roles. The NPs used in the sentence and memory load either matched (e.g., all proper names or all occupations), or they mismatched. Participants read complex sentences more slowly than they did simpler sentences; for young adults, this complexity effect was exacerbated when memory interference was generated by matching NPs in the sentence and memory load, whereas for older adults, memory-load interference did not vary with sentence complexity or memory-load matching. These results suggest that a general reduction in older adults' processing capacity was produced by the memory load, whereas the matching memory loads and sentence NPs produced a more specific form of interference that affected young adults' online processing.

RESEARCHERS generally agree that the analysis of complex syntactic structures depends on working-memory capacity (Gordon , Hendrick, & Johnson, 2001; Gordon, Hendrick, & Levine, 2002; Just, Carpenter, & Keller, 1996; Kemtes & Kemper, 1997, 1999; Miyake, Just, & Carpenter, 1994). However, the exact nature of this working-memory capacity is a subject of current debate (Caplan & Waters, 1999a; Daneman & Carpenter, 1980; Gibson, 1998; Just & Carpenter, 1992; Lewis, 1996; Waters & Caplan, 1996a, 1996b). Researchers also generally agree that working memory as measured by digit span and reading span measures the declines that occur with age (cf. Carpenter, Miyake, & Just, 1994 for a review). At issue is whether or not tests of working-memory capacity such as digit span and reading span measure the same working memory that is required for syntactic processing. If they do, then age-related changes in language processing may be attributed to limitations in working-memory capacity that affect syntactic processing.

Just and Carpenter (1992) argue that working memory is composed not only of a storage component but also of a central executive component. This central executive component is responsible for computations such as syntactic parsing in language comprehension. Both of these components draw on the same working-memory capacity; in the case of older adults, this competition contributes to an age-related decline in syntactic processing efficacy (Carpenter et al., 1994). Alternatively, Caplan and Waters (1999a, 1999b) argue that the working-memory resources used for syntactic processing are separate from those used for information storage. This separate-sentence-interpretation resource (SSIR) theory holds that syntactic processing is a highly practiced set of computations that has a specialized resource facility that is independent of other nonsyntactic working-memory tasks. Therefore, the age-related syntactic processing effects observed in previous research cannot be contributed to age-related declines in working memory (Waters & Caplan, 2001). Caplan and Waters argue that most of the research supporting the single-resource memory theory relied on offline comprehension measures, whereas online measures of sentence processing showed no working-memory effects on syntactic processing (Waters & Caplan, 2001).

In the current study, we test the single-resource model with the SSIR model of Caplan and Waters (1999a, 1999b) by using a procedure similar to that of Gordon and colleagues (2002). Experimenters asked participants to remember a memory load while reading syntactically complex object-extracted cleft sentences (as in Example 1) or simpler subject-extracted cleft sentences (as in Example 2). In cleft sentences, a noun phrase (NP) is extracted from its clause and moved to the front of the sentence following an introductory phrase, "It was," which highlights or emphasizes the fronted NP; the remainder of the clause is turned into a relative clause modifying the fronted NP. Either the subject of the clause, for example, "the thief thanked the nurse," may be fronted, producing "It was the thief that thanked the nurse," or the object may be fronted, for example, "It was the nurse that the thief thanked."

Example 1 shows subject-extracted cleft sentences:

> It was Kenneth that thanked Robert after winning the race.
> It was the judge that thanked the nurse after winning the race.

Example 2 shows object-extracted cleft sentences:

> It was Kenneth that Robert thanked after winning the race.
> It was the judge that the nurse thanked after winning the race.

We used descriptions of human occupations or roles (e.g., the banker) or proper names (e.g., John) as the subject and object of the sentences. We compared two memory-load conditions. The memory load consisted of three NPs; these were either three human occupations or roles, such as thief, banker, and pilot, or three proper nouns, such as James, Peter, and Paul. Gordon and colleagues (2002) demonstrated that memory loads that matched the type of NP used in the sentence impaired sentence comprehension, and that this effect was greater for the more complex object-extracted clefts than for the simpler subject-extracted clefts. Both the capacity-constrained model of Just and Carpenter (1992) and the SSIR model of Caplan and Waters (1999a) predict online reading-time differences between complex object-extracted clefts and the simpler sentences. However, the SSIR model postulates that sentence processing taps language-specific processing resources that are independent of general memory resources required to retain the memory load, whereas the capacity-constrained model holds that both sentence processing and general memory processes draw on a common, limited-capacity resource. The findings of Gordon and colleagues favor the capacity-constrained model, because the matching memory loads impaired online sentence processing, indicating that the syntactic processes required for the analysis of complex structures rely on working-memory resources that are also used for nonsyntactic processes such as retaining the memory load. If this is so, then older adults with more limited working-memory resources should be prone to more interference during sentence comprehension than are young adults.

We undertook the present study to compare the sentence processing by young and older adults by using the memory-load interference paradigm of Gordon and colleagues (2002). We predicted an Age Group × Sentence Complexity × Memory Load interaction such that older adults would have more difficulty processing the sentences than would young adults and that the age differences would be exacerbated for the more complex object-extracted clefts, particularly when we imposed a matching memory load. (Gordon and colleagues reported a nonsignificant interaction between the sentence complexity manipulation and the match between the type of NP used in the memory load and the sentence for the critical reading-time measure.) We examined both online processing of the sentences by using reading-time measures and offline sentence comprehension. Our procedures differed from those of Gordon and colleagues in three regards: First, we matched both types of memory loads for syllable length and word frequency to control for possible confounds in memorability. Second, we analyzed reading times only for those trials in which the participants were able to answer a probe question about the sentence correctly and able to recall the memory load. Third, we added a no-load condition consisting of strings of XXXXs to provide a baseline against which to compare the interference effects of both types of memory loads.

METHODS

Participants

Thirty-one young adults, 19 to 30 years of age, and 30 older adults, 66 to 84 years of age, participated. We recruited the young adults by signs and other solicitations on campus and paid them \$10 for participating. We recruited the older adults from a registry of previous research participants; all were living at home alone or with family. We paid the participants a modest honorarium; for the older adults, this honorarium also included compensation for their travel to an off-campus research site to participate in this research. We had older adults initially screened for possible dementia by use of the Short Portable Cognitive Status Questionnaire (Pfeiffer, 1975); the exclusion criterion was failing four or more questions. We also excluded data from participants who performed poorly on the sentence-processing task in the no-load condition from further analysis. To ensure participants were reading the sentences for comprehension, we required a criterion of 7 out of 10 correct for inclusion. We excluded 11 young adults and 10 older adults from the analysis as a result of this criterion.

Experimenters gave the remaining 20 young adults (M = 22.6, SD = 3.1) and 20 older adults (M = 72.2, SD = 5.8) a battery of cognitive tests designed to assess individual and age group differences in verbal ability, working memory, inhibition, and processing speed. The young adults had completed approximately the same number of years of formal education as the older group had ($M_Y = 14.8$ years, $SD = 1.9$ years; $M_O = 14.2$ years, $SD = 2.5$), $F(1, 39) = 0.412$, $p = .524$. The older adults scored higher on the Shipley (1940) vocabulary test ($M_O = 35.5$ of 40 correct, $SD = 3.6$) than young adults did ($M_Y = 30.5$, $SD = 6.7$), $F(1, 39) = 6.115$, $p = .017$. The young adults scored higher on the Wechsler (1958) Digits Forward and Digits Backward tests ($M_Y = 9.7$, $SD = 2.5$ and $M_Y = 7.9$, $SD = 2.5$), respectively, than the older adults did ($M_O = 8.2$, $SD = 2.6$ and $M_O = 6.4$, $SD = 2.4$ respectively), $F(1, 39) = 9.680$, $p = .004$ and $F(1, 39) = 3.268$, $p = .079$, respectively. The young adults had higher scores on the Daneman and Carpenter (1980) Reading Span test ($M_Y = 4.4$, $SD = 0.62$; $M_O = 3.1$, $SD = 0.54$), $F(1, 39) = 11.080$, $p = .002$.

We formed a composite working-memory score by conducting a confirmatory factor analysis with a single latent working-memory factor (Loehlin, 1998). Young adults had a higher composite working-memory score than did older adults, $F(1, 39) = 10.676$, $p = .002$. The young adults also scored higher on the Wechsler (1958) Digit Symbol test, ($M_Y = 35.88$, $SD = 6.2$; $M_O = 25.2$, $SD = 4.7$), $F(1, 39) = 54.953$, $p < .001$. We also had given participants a Stroop test. The Stroop test required participants to name the color of blocks of Xs printed in colored inks or to name the color of color words printed in contrasting colored inks (e.g., RED printed in blue ink). Experimenters gave each participant 45 s to complete the tasks; the participant's score is the number of colors correctly named in the 45-s time period. On this task, the young adults named the colors of the words more rapidly than the older adults did ($M_Y = 64.1$, $SD = 11.4$ years; $M_O = 40.3$, $SD = 11.3$), $F(1, 39) = 70.473$, $p < .001$; they also named the colors of the Xs more rapidly ($M_Y = 88.3$, $SD = 11.3$ years; $M_O = 70.5$, $SD = 13.5$), $F(1, 39) = 27.368$, $p < .001$. We created a relative difference score by subtracting scores for the color Xs condition from scores for the color word condition and dividing by the scores for the color Xs condition; young adults also had smaller difference scores than older adults did, $F(1, 39) = 19.258$, $p < .001$, indicating greater inhibition of the competing responses. We set an alpha level of $\alpha = 0.05$ for these and all subsequent t and F tests.

Materials

We constructed the stimuli to follow the materials used in a study by Gordon and colleagues (2002). Our experimental sentences consisted of 120 cleft sentences, 24 of which we modified from Appendix 2 of another study by Gordon and colleagues (2001). We created 12 conditions (see Figure 1) by crossing syntactic complexity (subject-extracted vs object-extracted cleft sentences), type of NP used in the sentence (descriptions or names), and the type of NPs used in the memory load (matching type of NP used in the sentence, mismatching, or none). We used two types of NPs: familiar descriptions of human occupations or roles (e.g., the thief, the nurse) or familiar proper names. The memory load consisted of three NPs, either three descriptions or three proper names, or a sequence of three blocks of Xs. We intended the no-load condition to provide a baseline for the comparison of the effects of the matching versus mismatching memory loads. All NPs were of medium frequency (15–50 occurrences/million words; Kucera & Frances, 1967). We matched the sets of proper names and descriptions for character and syllable length and frequency of occurrence. The sentences used either descriptions or proper names as both the sentence subject and the sentence object. When proper names were used, all three memory-load items and the sentence subject and object matched for gender. We wrote a true–false statement for each sentence; it required the participant to verify the syntactic–semantic relationship between the two NPs and the verb of each sentence, that is, who did what to whom. One-half of the statements were true and one-half were false. In addition to the experimental items, we also constructed filler sentences. The fillers were simple subject-verb-object sentences containing no clefts.

Design and Procedure

We created 12 lists by counterbalancing sentence complexity (subject-extracted clefts vs object-extracted clefts) with sentence NP type (descriptions vs proper names) and memory load (matched sentence NP type, mismatched, none) across lists. Ten different examples of each combination of cleft type, sentence NP type, and memory load occurred in each list. Individual sentences and NP proper names and descriptions were not repeated within a list. We blocked the items into an initial warm-up block of 24 filler items followed by two experimental blocks each containing 60 experimental items (5 from each condition) and 60 filler items. The items within a block were presented in a different random order for each participant.

The trial event sequence is shown in Figure 1. Using E-prime software (Schneider, Eschman, & Zuccolotto, 2002), we had participants presented first with a memory-load set: the words were all in capital letters, centered on a computer monitor. An experimenter instructed the participants to read the three memory-load items aloud twice, saying “Xs” if no memory load was presented, and to remember the memory load. Following this, the participants read a single sentence, which was presented one word at a time in the center of the screen by the use of self-paced reading-time methodology. They were instructed to read the sentences at a natural pace, not to hurry but not to linger longer than necessary before pressing the space bar to see the next word. Immediately after the participants read the last word of the sentence, a true–false comprehension statement was presented; the participants responded by pressing the “z” key for true and the “/” key for false. After the comprehension statement, the participants were prompted to recall the three memory-load items aloud, repeating the proper names or descriptions or saying “Xs.” Each participant’s response was recorded and later scored for accuracy of recall.

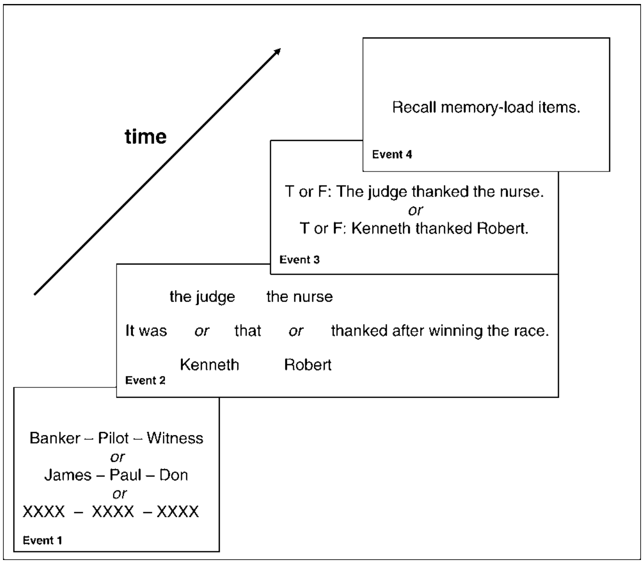

Figure 1. Schematic illustration of trial event sequence. Participants read the memory-load items aloud twice (Event 1), read the sentence one word at a time at their own pace (Event 2), responded to a true–false comprehension statement (Event 3), and finally recalled the memory-load items (Event 4).

RESULTS

We first present the results of the comprehension probes, and then we present the memory-load recall findings and then the online processing results. We performed the primary analysis of all dependent measures with a 2 (age group) × 2 (sentence complexity: subject-extracted clefts, object-extracted clefts) × 2 (sentence NP: descriptions, names) × 3 (memory load: matching sentence NP type, mismatching, none) analysis of variance. We report findings from both an analysis with subjects as random, $F1$, and an analysis with items as random, $F2$. In the final section we present a series of regression analyses examining how individual differences in age, vocabulary, working memory, and inhibition affect comprehension, online processing, and memory-load recall.

Comprehension

We analyzed the proportion of incorrect answers to probe questions. The main effect of age was significant, $F1(1, 38) = 4.549$, $p = .047$, $\eta^2 = .209$; $F2(1, 119) = 1.1770$, $p = .187$, $\eta^2 = .018$. Older adults answered fewer probe questions correctly than young adults (see Figure 2). Both young and older adults made more errors on questions about object-extracted clefts than on those about subject-extracted clefts, $F1(1, 38) = 35.174$, $p < .001$, $\eta^2 = .474$, $F2(1, 119) = 3.546$, $p = .063$, $\eta^2 = .462$. No other effects were significant in either the $F1$ or $F2$ analysis.

Recall

We analyzed the proportion of errors for recall of the memory loads. The main effect of age group was significant, $F1(1, 38) = 10.382$, $p < .001$, $\eta^2 = .417$; $F2(1, 119) = 2.704$,

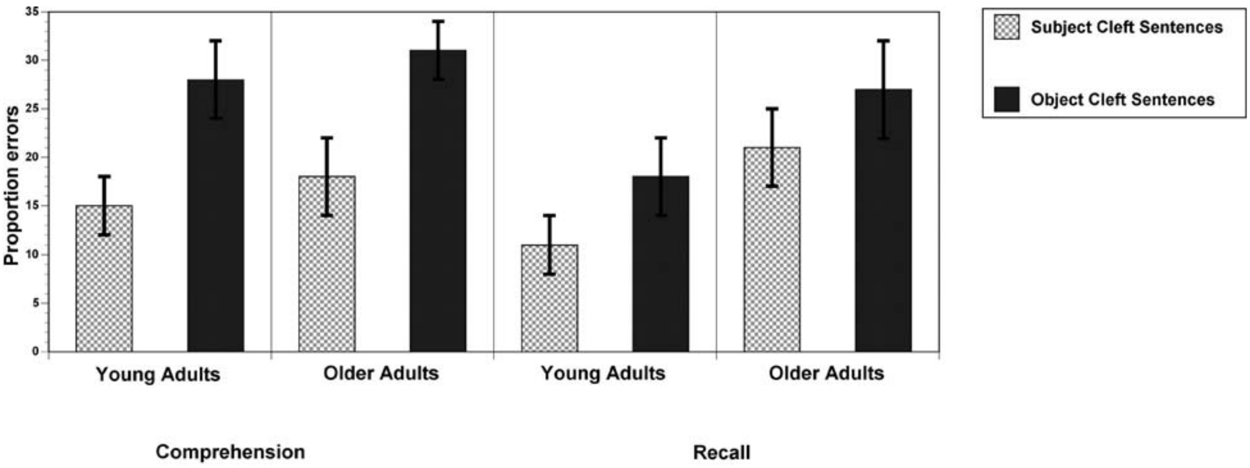

Figure 2. Mean error rates (with standard deviations) for comprehension probes and for recall of the memory loads for subject- and object-extracted cleft sentences.

$p = .025$, $\eta^2 = .353$. Older adults had significantly worse recall of the memory loads than did young adults (see Figure 2). Recall by both groups was worse following object-extracted cleft sentences than following subject-extracted cleft-sentences, $F1(1, 38) = 11.199$, $p = .002$, $\eta^2 = .196$; $F2(1, 119) = 2.612$, $p = .109$, $\eta^2 = .027$. The recall data supports both the comprehension data in showing that object-extracted clef sentences impose higher processing demands than subject-extracted cleft sentences, impairing recall of the memory-load NPs.

Online Processing

We analyzed reading times only for those trials in which the participants correctly answered the comprehension probe and correctly recalled the memory load. We found that sentence comprehension and recall of the memory loads were highly correlated across conditions, $r(39) \geq .85$; therefore, the number of valid trials included in the reading-time analysis varied with condition, parallel to the comprehension and recall results. There were more valid trials for young adults ($M = 7.8$ per condition) than for older adults ($M = 6.3$ per condition) and more for subject-extracted cleft sentences ($M = 7.3$ per condition) than for object-extracted cleft sentences ($M = 5.8$ per condition). Because the reading times were highly positively skewed, we used log-transformed reading times in all analyses. We averaged word-by-word reading times within three critical regions. Region 1 included the sentence initial cleft and was the same for both subject-extracted and object-extracted cleft sentences; Region 2 included a NP and verb and the word order varied between the two types of sentences; Region 3 included the sentence final prepositional phrase and was the same for both types of sentences.

Region 1.—Included in this region were the first clause of the sentence and the relative pronoun (i.e., "It was NP that . . ."). Region 1 was constant across cleft types. There was a significant main effect of age group; young adults had faster reading times than did older adults ($M_y = 393.7$, $SD = 10.9$ ms; $M_o = 686.4$, $SD = 15.1$ ms), $F1(1, 38) = 37.889$, $p < .001$, $\eta^2 = .452$; $F2(1, 119) = 32.849$, $p < .001$, $\eta^2 = .444$. We found no other significant effects or interactions for Region 1 in either the $F1$ or $F2$ analysis.

Region 2.—This region was the critical region for the cleft manipulation. It contained the same words, NP and verb, for the two cleft types, with a difference in word order. The word order for subject-extracted cleft sentences was verb–NP, whereas the word order for object-extracted cleft sentences was NP–verb. We found a main effect of age group such that young adults had faster reading times than older adults ($M_y = 411.3$, $SD = 31.1$ ms; $M_o = 682.0$, $SD = 49.4$ ms), $F1(1, 38) = 25.123$, $p < .001$, $\eta^2 = .853$; $F2(1, 119) = 25.258$, $p < .001$, $\eta^2 = .887$. The main effect of sentence complexity was significant, $F1(1, 38) = 24.454$, $p < .001$, $\eta^2 = .385$; $F2(1, 119) = 13.260$, $p < .001$, $\eta^2 = .385$. As we expected, for both young and older adults, reading times were longer for object-extracted clefts than for subject-extracted clefts.

The memory-load main effect was significant, $F1(2, 37) = 9.591$, $p = .004$, $\eta^2 = .822$ and $F2(2, 118) = 12.346$, $p = .129$, $\eta^2 = .288$, as was the Age Group × Sentence Complexity × Memory Load interaction, $F1(2, 38) = 7.745$, $p = .008$, $\eta^2 = .216$ and $F2(2, 118) = 3.399$, $p = .072$, $\eta^2 = .439$. We decomposed this interaction to examine the Sentence Complexity × Memory Load NP interaction separately for each age group. For young adults, there were significant main effects of both sentence complexity and memory load, $F1(1, 19) = 9.567$, $p = .006$, $\eta^2 = .335$ and $F2(1, 119) = 9.628$, $p = .003$, $\eta^2 = .170$; $F1(2, 19) = 8.803$, $p = .008$, $\eta^2 = .317$ and $F2(2, 118) = 1.832$, $p = .183$, $\eta^2 = .038$, respectively. There was also a significant Sentence Complexity × Sentence NP interaction, $F1(2, 19) = 6.8133$, $p = .017$, $\eta^2 = .264$; $F2(2, 118) = 2.155$, $p = .149$, $\eta^2 = .045$. Young adults took longer to read object-extracted cleft sentences than subject-extracted cleft sentences; this effect of syntactic complexity was exacerbated when the type of NP used in the memory load matched that used in the object-extracted cleft sentence (see Figure 3).

Object-extracted cleft sentences required an additional 76 ms ($SD = 31$) to process than subject-extracted cleft sentences when the NPs in sentence and memory load matched, an additional 62 ms ($SD = 22$) when the NPs did not match, and an additional 37 ms ($SD = 21$) when there was no memory load. The object – subject difference was greater in the matched condition than in the mismatched condition, $t(19) = 4.142$,

$p = .001$, and greater in the mismatched condition than in the no-load condition, $t(19) = 3.954$, $p = .001$. In contrast, the main effect of sentence complexity was significant for older adults' Region 2 reading times, $F(1, 19) = 15.197$, $p = .001$, $\eta^2 = .432$; $F2(1, 119) = 6.386$, $p = .015$, $\eta^2 = .120$. Older adults required an additional 65 ms ($SD = 31$) to read Region 2 of object-extracted cleft sentences than Region 2 of subject-extracted cleft sentences (see Figure 3), regardless of memory load. In addition, the main effect of memory load was significant, $F(2, 18) = 15.197$, $p = .001$, $\eta^2 = .432$; $F2(2, 118) = 6.386$, $p = .015$, $\eta^2 = .120$. Both types of memory-load NPs impaired older adults' Region 2 reading times, increasing reading times by 39 ms ($SD = 26$), compared with the no-load condition, $t(19) = 8.587$, $p < .001$, and memory-load interference was similar for both subject-extracted and object-extracted cleft sentences, both $t(19) < 1.0$, $p < .50$.

Region 3.—We included the remainder of the sentence in this region; it was constant across all conditions. We found a main effect of age such that young adults had faster reading times than older adults, $F(1, 38) = 23.789$, $p < .001$, $\eta^2 = .352$; $F2(1, 119) = 6.386$, $p = .015$, $\eta^2 = .120$. We observed no other significant main effects or interactions in this region.

Regressions

We conducted a series of regression analyses to examine how individual differences in vocabulary, working memory, and inhibition affected comprehension, online processing, and recall of the memory loads. The predictor variables were the participants' age, score on the vocabulary test, working-memory composite latent factor score, Digit Symbol test score, and Stroop test difference score. We considered the Digit Symbol score to be a measure of processing speed (Salthouse, 1992), and we considered the Stroop difference score to be a measure of inhibitory function (Dempster, 1992). Dependent variables were the comprehension scores for the object-extracted cleft sentences, Region 2 reading times (after we first controlled for reading times for the subject-extracted cleft sentences), and memory-load recall scores. We averaged all scores over sentence NP type manipulation. We entered all predictor variables simultaneously. None of the predictors was significant in the analysis of the condition in which no memory load was presented or in the conditions in which the memory-load NP type did not match the type of NP used in the sentence. However, in the interference condition, when the memory-load NP matched the type of NP used in the sentence, the working-memory composite score accounted for 9% of the variance in comprehension of object-extracted cleft sentences, $R = .306$, $F(4,36) = 1.515$, $p = .24$; 23% of the variance in the Region 2 reading time, $R = .483$, $F(4,36) = 4.469$, $p = .008$; and 28% of the variance in memory-load recall, $R = .526$, $F(4,36) = 7.427$, $p < .001$. Adding other predictors did not improve the fit of the regression models. These results support the interpretation that immediate syntactic processing of complex constructions is constrained by working-memory capacity as measured by span scores.

DISCUSSION

The results of this study support a single-resource model of working memory. They parallel the finding by Gordon and colleagues (2002) that syntactic processes do rely on working-memory resources that are also used for other nonsyntactic processes: First, object-extracted cleft sentences were more difficult to comprehend than subject-extracted cleft sentences in that readers allocate additional processing time to Region 2 of object-extracted cleft sentences, compared with subject-extracted clefts, in order to correctly map the subject and verb relations. Second, errors on the comprehension probes and the memory-load recall test increased whenever complex object-extracted cleft sentences were read. Third, a working-memory composite latent factor score, derived from the span measures, predicted 23% of the variance in Region 2 reading times for the complex object-extracted cleft sentences.

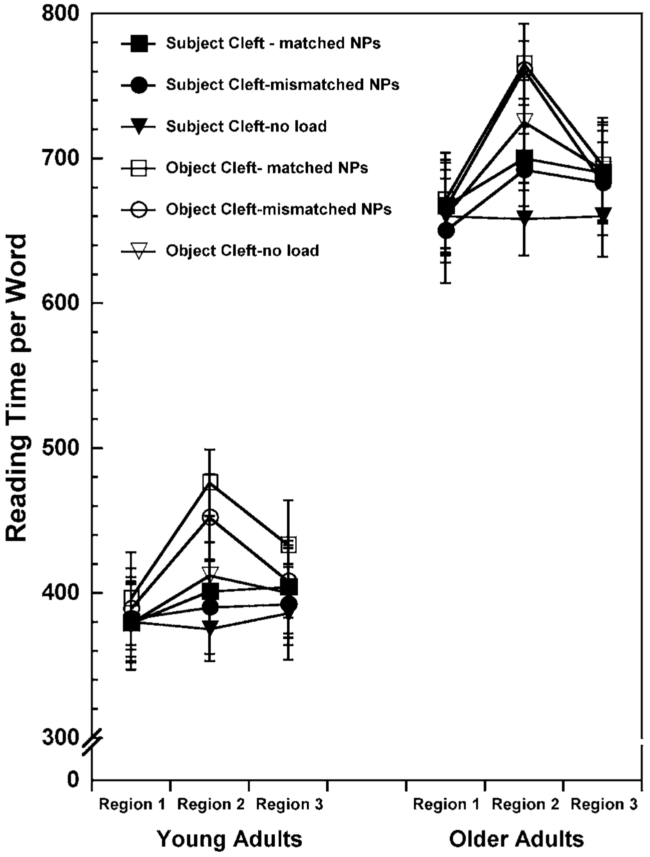

Figure 3. Mean reading time (milliseconds per word) for the three sentence regions (with standard errors) for young and older adults for subject- and object-extracted cleft sentences as a function of memory-load NP.

An additional finding was that older adults with more limited working-memory resources exhibited a pattern of online reading times across conditions that was different from that of young adults. Overall, readers allocated additional processing time to Region 2 of the object-extracted cleft sentences compared with Region 2 of the subject-extracted clefts. This complexity effect was exacerbated for young adults when the type of NP used in the memory load matched that used in the object-extracted cleft sentence. This pattern suggests that the young adults experienced two forms of memory interference. One form was due to the reduction in working-memory resources from the imposed memory load, and a second, more specific form of interference was due to the confusability of the NPs used in the memory load and those used in the sentences. The effect of the memory load on older adults' reading times for Region 2 was constant, regardless of whether the memory-load NP matched or mismatched the type used in the sentence. This suggests that the older adults experienced only a general reduction in online processing caused by the burden placed on working memory by the memory-load task and did not experience additional memory interference from the confusability of the NPs.

These results pose problems for the Caplan and Waters (1999a, 1999b) SSIR theory. According to this theory, a memory load should not effect syntactic processing nor differentially effect syntactic processing by young and older adults. Our findings suggest that working-memory capacity, memory interference, and language processing are closely intertwined. As a consequence, increasing the complexity of a sentence, decreasing working-memory capacity by imposing a memory load, or decreasing memory capacity as happens in normal aging will increase the difficulty of online language processing as well as impair comprehension and recall.

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