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Working memory and sensitivity to prosody in spoken language processing*

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Individual differences in working memory predict qualitative differences in language processing. High span comprehenders are better able to integrate probabilistic information such as plausibility and animacy, the use of which requires the computation of real world knowledge in syntactic parsing (e.g.,[1]). However, it is unclear whether similar individual differences exist in the use of informative prosodic cues. This study examines whether working memory modulates the use of prosodic boundary information in attachment ambiguity resolution. Prosodic boundaries were manipulated in globally ambiguous relative clause sentences. The results show that high span listeners are more likely to be sensitive to the distinction between different types of prosodic boundaries than low span listeners. The findings suggest that like high-level constraints, the use of low-level prosodic information is resource demanding.

Key words : working memory, prosody, parsing, prosodic boundaries

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Introduction

Research on syntactic processing has focused primarily on whether and how different linguistic and non-linguistic constraints influence interpretation of syntactic structure. A growing body of literature has shown that the parsing of syntactic structure can vary across individuals, and some individuals are more affected by those constraints than others (*e.g.,* [1-4]). One source of individual variability in syntactic processing stems from differences in abilities to perform working memory tasks (*e.g.,* [1-8]). People who perform well on these tasks are more likely to employ probabilistic constraints such as plausibility [1][4] or animacy [2] in resolving local syntactic ambiguity than those who do not perform well on these tasks.

One constraint that has not been investigated with respect to ambiguity resolution and memory span is prosodic structure. Prosodic boundaries are perceptual junctures in the speech stream and are correlated with such acoustic cues as pre-boundary word lengthening, changes in pitch, and pauses (see [9], for a review). Consider (1).

(1) *Someone shot the servant of the actress who was on the balcony.*

Sentence (1) is globally ambiguous because the relative clause can be interpreted as modifying either the high noun "servant" (high attachment) or the low noun "actress" (low attachment). A prosodic boundary before an ambiguous constituent creates a bias towards attaching the constituent to an element located higher in the hierarchical structure of the sentence while a prosodic boundary between potential attachment sites promotes attachment to the lower attachment site (*e.g.,* [10][11]). Thus, a prosodic boundary after the high noun (*i.e.,* servant) creates a bias towards low attachment while a prosodic boundary after the low noun (*i.e.,* actress) creates a bias towards high attachment.

However, prosodic boundaries are not interpreted in isolation, but are also interpreted with respect to the global prosodic structure of a sentence [12][13]. Carlson and colleagues [12][13] have argued that listeners evaluate the informativeness of a prosodic boundary by comparing its strength with respect to relevant earlier boundaries in an utterance. Consider the sentence in (2).

(2) *Susie learned* (a) *that Bill telephoned* (b) *after John visited.*

In sentence (2), the adverbial constituent phrase "after John visited" can be associated either with the matrix clause (Susie learned) or with the subordinate clause (Bill telephoned). Carlson et al. (2001)[12] manipulated the strength of a prosodic boundary at (b) relative to a boundary at (a), and found that a boundary was informative about syntax only when it was stronger than a relevant boundary at an earlier position in an utterance. A local prosodic boundary at (b) created a high attachment bias only when it was stronger than a prosodic boundary at (a). However, relative boundary strength is not the only factor that influences syntactic processing. An empirical study by Snedeker and Casserly (2010)[14] has shown that absolute boundary strength as well as relative boundary strength plays a role in syntactic ambiguity resolution. They found that when relative boundary strength was held constant, the frequency of high attachment responses increased as a function of the strength of a prosodic boundary at (b).

The current study investigates the relationship between the use of absolute and relative boundary information and working memory span. This question is of theoretical interest for two reasons. First, prosody has been proposed to be a factor underlying interactions between working memory and attachment preferences in reading [7][15]. An offline study by Swets et al. (2007)[7] has shown that in sentences like (1), high attachment is preferred by individuals with low working memory capacity to a greater extent than those with high working memory capacity. Swets et al. (2007)[7] argue that readers with low working memory capacity were more likely to prefer high attachment because they inserted an implicit prosodic break before the relative clause in reading whereas those with high working memory capacity did not. However, when the complex noun phrase and the relative clause were presented in separate chunks, high span readers preferred high attachment to the same extent to which low span readers did, reducing the working memory and attachment preference interaction. Swets et al.'s findings suggest that comprehenders with different working memory capacities may generate different patterns of implicit prosody. The fact that only the performance of high span comprehenders changed in response to an explicitly manipulated break suggests that high span comprehenders may be more sensitive to prosodic constraints. However, it is not known whether individuals indeed vary in their sensitivity to explicit prosodic information in spoken language. The present paper explores this question by manipulating the presence and strength of prosodic boundaries.

The second reason for investigating the interaction between prosody and working memory is the fact that prosody differs in important ways from previously studied constraints. Constraints known to interact with working memory capacity, such as plausibility and animacy, all require post-lexical processing, i.e. the use of semantic information to derive the plausibility and meaning of alternative syntactic structures. In contrast, the detection of prosody involves input-driven, bottom-up processes in which the detection of prosodic boundaries is guided by acoustic cues in the speech input. The bottom-up nature of the prosodic signal may make it a less memory-intensive signal to syntactic structure than constraints that require the computation of semantics.

Previous work has shown that low span comprehenders are less successful in using constraints that require using real world information in making syntactic decisions (*e.g,* [1][2][4]). While such high-level constraints are more available to high span comprehenders, prosodic cues may provide greater benefit to low span comprehenders because their grounding in the acoustic signal potentially requires less computation than cues like plausibility or animacy. Thus, prosody might serve as a useful, low-cost scaffolding for low-span listeners who typically have difficulty parsing sentences.

In contrast, as suggested by previous work based on implicit prosody [7][15], high span comprehenders may be more sensitive to prosodic constraints. The use of prosodic information may be resource demanding, being more available to high span comprehenders, like the use of other constraints that require post-lexical processing.

Thus, investigating whether working memory modulates listeners' sensitivity to relative or absolute boundary strength in syntactic processing can provide insight into whether prosody is resource demanding or relatively low cost.

Method

Participants

Fifty-six undergraduate students from the University of Illinois at Urbana-Champaign participated in exchange for course credit. Participants were all native speakers of English. They had normal or corrected-to-normal vision and no reported hearing impairment.

Working Memory capacity test

Participants' working memory capacity was estimated from the mean score of four different working memory measures[1]: reading span, listening span, alphabet span, and

1) The materials used in the listening and reading span tasks were adopted from Stine and Hindman (1994)[16]. The materials used in the alphabet and subtract 2 span tasks were newly constructed following Traxler (2009)[15].

subtract 2 span. This composite measure was employed because using multiple tasks provides higher test-retest reliability and greater classificatory stability than using a single measure [17]. In the reading span test, participants were presented with a set of sentences. Participants were asked to make a true/false judgment after reading each sentence out loud. When all of the sentences on each trial were presented, participants were asked to recall the last word of each sentence. The listening span test was an auditory variant of the reading span test, and participants were asked to listen to each sentence instead of reading the sentences out loud. In the alphabet span test, after reading a set of words aloud, participants were asked to recall them in alphabetical order. In the subtract 2 span test, participants read a set of digits out loud. At the end of each trial, they were asked to perform a recall task in which they subtracted 2 from each digit in order. In all tests, the number of items (*i.e.,* sentences, words, or numbers) on each trial varied from two to eight. There were two trials at each level. If participants successfully recalled all the items on one of the two trials, they moved on to the next level. The score of each test was calculated based on the highest level successfully completed. The number of correctly recalled items at the partially completed level was reflected in the score as a decimal. For example, if the participant successfully recalled all items in one of the two trials at level 3, and only partially completed both trials of level 4, successfully recalling just one item on each trial (*i.e,* 2 out of 8 items), then his/her score was 3.25.

Materials and Procedure

Stimuli were thirty-two instructions to click an object on a computer screen. The instructions contained a complex noun phrase, which was followed by an ambiguous relative clause (*e.g., Click on the candle below the triangle that's in the blue circle*). In order to test the effects of relative and absolute boundary strength, prosodic breaks were manipulated by crossing two different kinds of prosodic boundaries in positions after both critical nouns as shown in (3). As in previous work, prosodic boundaries were either intonational phrase boundaries (IP) or intermediate phrase boundaries (ip). Intonational phrase boundaries create a stronger juncture than intermediate phrase boundaries and are accompanied by more extreme acoustic cues. Intonational phrase boundaries and intermediate phrase boundaries were produced with the L-H% boundary tone and the L- phrase accent in ToBI notation [18], respectively. Pre-boundary words were produced with a presentational pitch accent (H*) when they were followed by an intermediate phrase boundary and with a contrastive pitch accent (L+H*) when they were followed by an intonational phrase boundary.

(3) a. (ip, ip): *Click on the candle* ip *below the triangle* ip *that's in the blue circle.*
b. (IP, ip): *Click on the candle* IP *below the triangle* ip *that's in the blue circle.*
c. (ip, IP): *Click on the candle* ip *below the triangle* IP *that's in the blue circle.*
d. (IP, IP): *Click on the candle* IP *below the triangle* IP *that's in the blue circle.*

Stimuli were cross-spliced to control for unintended acoustic differences across conditions. First, the initial words in the sentence (*i.e., Click on the*) were cross-spliced across items so that they were identical across conditions. To ensure that there were no acoustic differences between conditions that had the same type of early boundary, the high noun and the words leading up to the onset of the low noun (*i.e., candle below the*) were cross-spliced so that this acoustic region matched across conditions with the same early boundary ((3a) and (3c), (3b) and (3d)). For the same reason, the low noun and the following words (*i.e., triangle that's in the blue circle*) were cross-spliced so that this acoustic region matched across conditions with the same late boundary ((3a) and (3b), (3c) and (3d)). This process ensured that for each experimental item, the critical nouns were identical across conditions if they were followed by the same type of prosodic boundary.

Of course, one concern is that this sound manipulation will yield sentences that sound unnatural. To address this, after the experiment, participants were asked to fill out a post-sentence questionnaire asking if there was anything strange about the auditory or visual stimuli in the experiment. None of the participants noticed that the stimuli were cross-spliced.

As shown in Table 1, the mean durations of the pre-boundary words and the post-boundary pauses were longer when they were followed by intonational phrase boundaries than by intermediate phrase boundaries (pre-boundary lengthening: high noun (HN), $t(31)=25.7$, $p<.001$; low noun (LN), $t(31)=24.9$, $p<.001$; pause: after HN: $t(31)=56.5$, $p<.001$; after LN: $t(31)=56.4$, $p<.001$).

Table 1. Mean durations of pre-boundary words and post-boundary pauses (in ms)

	High Noun	Pause after HN	Low Noun	Pause after LN
ip	461 (11.7)	34 (2.4)	472 (10.6)	33 (1.4)
IP	624 (10.7)	215 (2.2)	646 (14.1)	215 (2.6)

Note. Standard errors are presented in parentheses.

Table 2. Mean F0 values at L- and H% (in Hertz)

	High Noun		Low Noun	
	L-	H%	L-	H%
ip	184 (2.8)		163 (2.7)	
IP	167 (2.7)	207 (2.0)	156 (2.3)	202 (1.8)

Note. Standard errors are presented in parentheses.

Table 2 presents the mean values of the low f0 target (L-) and of the high f0 target (H%) at the end of the critical nouns. The mean f0 minimum of intonational phrase boundaries was reliably lower than that of intermediate phrase boundaries (HN, $t(31)=4.6$, $p<.001$; LN, $t(31)=2.3$, $p<.05$).

On each trial, participants listened to a target sentence. As soon as it ended, they were presented with a visual scene that included 4 pairs of the pictures of the object and the shape as in Figure 1. The participants' task was to click on the picture of the object that matched their interpretation of the target sentence.

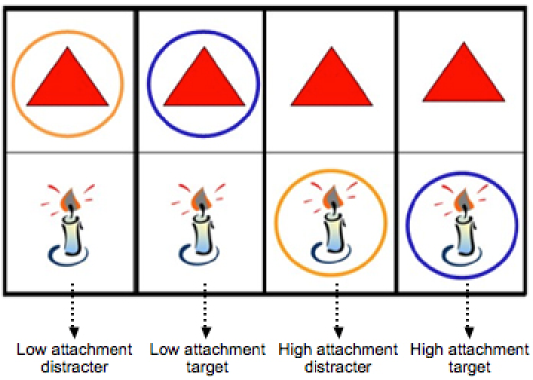

Figure 1. Example visual scene.

In Figure 1, the high attachment target is the picture of the candle that is in the blue circle while the low attachment target is the picture of the candle that is paired with the triangle in the blue circle. The Informative Boundary Hypothesis predicts more high attachment responses when a prosodic boundary before the relative clause is stronger than an earlier prosodic boundary. Thus, more high attachment responses are expected in condition (3c) than in (3b) while conditions (3a) and (3d) should lie somewhere in between.

Eight lists were constructed by rotating critical items through 4 prosodic boundary conditions and 2 types of locative prepositions (below and above). Each list contained 96 distracter trials in addition to 32 critical trials. Distracter trials included instructions that required participants to determine the spatial relationship between objects and shapes to find a correct target. The complexity of the distracter instructions varied across trials (*e.g., Click on the alarm clock [that's] above the gray triangle, Click on the harp [that's] next to the arrow in the gray circle*). The critical and distracter sentences were presented in a randomized order. Before the main experiment, participants completed the four working memory capacity tests described above.

Although the sentences were ambiguous, overall preferences for low attachment were expected given that it is more frequent than high attachment in English [19][20].

Results

On 2% of trials (31 out of 1792), participants incorrectly selected distracter pictures (*e.g.,* the candle in the orange circle). Those trials were excluded from the analysis.

Table 3 displays the proportion of high attachment responses for each condition. There were overall strong low attachment preferences.

Table 3. Proportion of high attachment of the relative clause by condition

(ip, ip)	(IP, ip)	(ip, IP)	(IP, IP)
.18	.17	.25	.25

Participants' choice of high attachment responses was analyzed using a mixed logit model [21]. In order to examine whether working memory capacity had an impact on the extent to which listeners use prosody in syntactic ambiguity resolution, the model included working memory capacity, early boundary and late boundary as fixed effects, and random intercepts for participants and items as random effects. Working memory capacity was treated as a continuous variable representing the average of the scores from the four working memory tests and it was mean centered. Categorical variables were coded using mean-centered contrast coding. None of the random slopes significantly improved the model. Table 4 presents the results from a mixed logit model analysis.

Table 4. Parameter estimates of the mixed logit model (N =1761; log-likelihood = -746.0)

Predictor	Coefficient	SE	Wald *Z*	*p*
(Intercept)	-1.88	0.22	-8.7	<.001
Early Boundary	0.01	0.14	0.1	>.1
Late Boundary	**0.64**	**0.14**	***4.6***	***<.001***
WM	-0.52	0.35	-1.5	>.1
Early Boundary x Late Boundary	0.11	0.28	0.4	>.1
Early Boundary x WM	-0.14	0.22	-0.6	>.1
Late Boundary x WM	**0.80**	**0.23**	***3.5***	***<.001***
Early Boundary x Late Boundary x WM	0.10	0.45	0.2	>.1

Inconsistent with the prediction of the Informative Boundary Hypothesis, the data provide no evidence that listeners used relative boundary strength in syntactic decisions: There was no main effect of the early boundary, nor was there a reliable interaction between the early boundary and late boundary. This is further discussed in the Discussion. There was a reliable effect of the absolute strength of the late boundary as illustrated in Table 4: Participants selected the high attachment target more frequently when the late boundary was an intonational phrase boundary than when it was an intermediate phrase boundary (.25 vs. .18).

Listeners with low working memory capacity showed an overall greater preference for high attachment than those with high working memory capacity, but this difference was not reliable. The interaction between late boundary and working memory capacity was reliable, suggesting that listeners' sensitivity to the absolute strength of the late boundary (ip vs. IP) varied with working memory capacity. The interaction between the early boundary and working memory capacity was not reliable, nor was the 3-way interaction.

To further illustrate the interaction between the listener's sensitivity to absolute boundary strength and working memory capacity, participants were classified into three different capacity groups of approximately equal size (Low: 19 participants (mean WM: 3.7), Medium: 18 participants (mean WM: 4.3), High: 19 participants (mean WM: 5.0)). Figure 2 displays the effect of the absolute boundary strength of the late boundary for each capacity group. (Note that these groups were created simply for the purpose of illustration. Working memory capacity was treated as a continuous variable in the model reported above.)

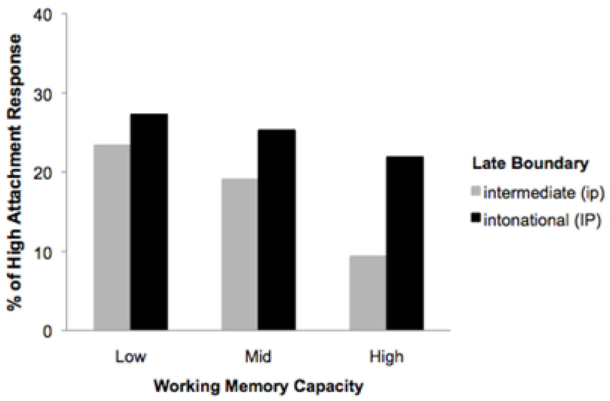

Figure 2. Effects of late boundaries for listeners with different working memory capacities.

Figure 2 illustrates that the reliable interaction between the listener's sensitivity to absolute boundary strength and working memory capacity was driven by high span listeners. They were more sensitive to absolute boundary strength than low span listeners.

Discussion

The present study tested whether working memory capacity modulates the use of relative boundary strength and absolute boundary strength in syntactic processing. The results showed that high working memory capacity predicted listeners' sensitivity to the absolute strength of the late boundary. While low span listeners' attachment responses did not vary with the strength of the late boundary, high span listeners chose more high attachment responses when the late boundary was an intonational phrase boundary than when it was an intermediate phrase boundary. Given that Swets et al. (2007)[7] did not manipulate the strength of a break in their reading task, it is not possible to make a direct comparison between that study and the present one. However, the finding that high span listeners are more sensitive to explicitly manipulated prosodic details than low span listeners is consistent with Swets et al.'s findings. Crucially, the interaction between working memory capacity and the sensitivity to absolute boundary strength suggests that the detailed use of low-level prosodic information is resource-demanding in the same way that high level constraints are.

There are two possible explanations for why low span listeners are less sensitive to the absolute strength of the late boundary. One possibility is that low span listeners are less sensitive to the distinction between different types of late boundaries because they lack sufficient resources for maintaining detailed representations of prosody during the parsing process. Another possibility is that working memory capacity modulates the ways in which listeners process the acoustic information itself. Low span listeners may not have sufficient resources to process fine-grained, low-level acoustic cues, which may reduce the fidelity of the acoustic signal.

The results showed no evidence for the use of relative boundary strength, primarily because of the absence of an effect of the early boundary. The lack of the effect of the early boundary might have been due to a floor effect: there was a strong low attachment preference in the current data. This speculation is supported by data from Clifton et al. (2002)[13]. Clifton et al. examined interactions between early and late boundaries by investigating several different syntactic structures. The authors manipulated the strength of the early boundary (no boundary, intermediate phrase boundary, and intonational phrase boundary) while the strength of the late boundary was constant across conditions. In general they found that effects of the late boundary were modulated by the strength and presence of an early boundary: the stronger the early boundary, the smaller the effect of the late boundary on disambiguation. However, for relative clause attachment ambiguities in which there was an overall low attachment preference, they found a marginal difference between intermediate and intonational phrase boundaries at the early position. Thus, it is possible that listeners' sensitivity to prosodic boundary information might interact with default syntactic preferences.

One possible concern with these results is that the task may have relied too heavily on working memory, thereby exaggerating the link between working memory and prosody use. In the task, participants first heard the instructions, and were then presented with the display. It is possible that participants maintained a phonological representation of the sentence in memory and only interpreted the sentence once the display was made available, lending an advantage to participants with higher working memory. This seems to be unlikely. The memory literature suggests that listeners are relatively good at extracting gist information and relatively poor at remembering surface level details of a sentence [22-26]. This would suggest that it would be easier for participants to interpret sentences as they hear them rather than maintain the phonological properties of the sentence in memory. Furthermore, participants made incorrect selections on only 2% of trials, which suggests that the task was not particularly difficult. These errors, though few, were evenly distributed across the working memory span groups (high span: 8 trials, medium span: 13 trials, low span: 10 trials). Thus, it seems unlikely that the interaction between working memory capacity and the sensitivity to absolute boundary strength was driven by a memory component in the task. Future work using online methodologies may be required to definitively answer this question.

Finally, there is a great deal of debate in the literature about what performance on working memory tasks actually measures. It has been argued that working memory differences are mediated by other measures such as processing speed, phonological fluency, linguistic experience, and inhibitory control (e.g., [2][27-30]). The exact nature of the mechanisms that are engaged in working memory tasks will need to be determined in future work. Whatever the ultimate mechanism, the data here suggest that individuals who do well on working memory tasks make use of more detailed representations of prosodic information in syntactic ambiguity resolution.

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〈요 약〉

언어 처리에서 운율 제약 활용과 작업 기억의 관계

이 은 경

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본 연구에서는 구문 처리에서 운율 정보 활용이 작업 기억 용량의 영향을 받는지를 검증하였다. 구체적으로 작업 기억 용량이 운율 경계의 강도와 위치에 따른 관계절 부착 중의성 해소 방식 차이를 예측하는지를 알아보았다. 실험 결과, 작업 기억 폭이 큰 청자들의 중의성 해소 방식이 작업 기억 폭이 작은 청자들에 비해 운율 경계 강도의 영향을 더 받는 것으로 나타났다. 이는 다른 상위 수준 제약과 마찬가지로 운율 제약의 활용도 작업 기억과 같은 인지적 자원을 필요로 함을 시사한다.

주제어 : 작업 기억, 운율, 구문 분석, 운율 경계