The interaction of different working memory mechanisms and sentence processing: A study of the P600

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Abstract

While previous research has shown that working memory capacity (WMC) predicts sentence processing ability, the understanding of the relationship is limited as almost all studies have used the reading span task as their sole measure of WMC. The current study examined how the effects of garden-path sentences and filler-gap dependencies (as indexed by the P600) related to four measures of working memory (reading span, operation span, anti-saccade and *n*-back). P600 effects for garden-path sentences correlated positively with operation span score while effects for object relatives correlated negatively with n-back accuracy. These results indicate that, though both sentence types are associated with increased working memory demands, the resolution of temporary syntactic ambiguity and filler-gap dependencies recruit distinct working memory mechanisms.

Keywords: Garden-Path; Object Relative, Reading Span, *N*-back, P600.

Introduction

Two major sources of difficulty in sentence processing are temporary syntactic ambiguity and syntactic complexity (see sentences 1 and 2, respectively). Sentences containing temporary ambiguities (i.e. garden-path sentences) usually lead to an initial incorrect parse of the syntactic structure which must be reanalyzed when the temporary ambiguity is resolved in order for the sentence to be correctly interpreted. In sentence 1 below, the initial interpretation may be that the patient met the doctor and the nurse but upon arriving at the word "showed" (the disambiguating verb), it is apparent that that interpretation is incorrect and must be revised. A prime example of syntactic complexity is an object relative which represents a filler-gap dependency in which direct or indirect object is displaced from the verb from which it gets its thematic role. In order to resolve the filler-gap dependency, the object ("to whom" in sentence 2 below) must be maintained active until it can be mapped onto the thematic grid of the relevant verb ("showed").

1. The patient met the doctor and the nurse with the white dress showed the chart during the meeting.
2. The patient met the doctor to whom the nurse with the white dress showed the chart during the meeting.[1]

Behavioral research has shown longer reading times and reduced comprehension accuracy for sentences with garden-path sentences (Frazier & Rayner, 1982; Ferreira, Bailey & Ferraro, 2002) and object relatives (Frazier, 1987; King & Just, 1991) compared to simple controls. Research using the noninvasive event-related potential (ERP) technique of recording brain activity has also provided evidence for the increased difficulty of these sentence types. The key potential of interest is the P600, a positive shift which emerges 500 to 800 ms post-stimulus, typically largest over posterior sites. The P600 is generally considered to be an index of syntactic integration difficulty (Kaan et al., 2000). It is elicited by syntactic violations of all types but is also sensitive to syntactic ambiguity and syntactic complexity in well-formed sentences. Garden-path sentences elicit P600 effects relative to non-garden-path sentences (Osterhout, Holcomb & Swinney, 1994; Kaan & Swab, 2003; Gouvea, Phillips, Kazanina & Poeppel, 2010). In addition, several studies have found P600 effects when comparing sentences containing object relative clauses to simple declarative sentences (Kaan, Harris, Gibson & Holcomb, 2000; Gouvea et al. 2010). Gouvea et al. (2010) found that the P600 effect for garden-path sentences is more robust and of longer duration than that of unambiguous object relative structures.

One potential source of the increased difficulty is the increased demand these sentences place on working memory resources. Working memory (WM) is "a multicomponent system responsible for active maintenance of information in the face of ongoing processing and/or distraction" (Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005, p. 770) which facilitates goal directed behavior. Individual differences in working memory capacity (WMC) impact sentence processing ability. A number of studies have found that individuals with high WMC have faster reading times and improved comprehension performance for garden-path sentences (Just & Carpenter, 1992; Friederici, Steinhauer, Mecklinger & Meyer, 1998) and object relative dependencies (Just & Carpenter, 1992; King & Just, 1991) than low WMC participants. The P600 is modulated by WMC as well. ERP studies have shown that individuals with high WMC have greater P600 effects at the disambiguation point of sentences containing temporary ambiguities (Friederici et al., 1998; Vos, Gunter, Schriefers & Friederici et al., 2001; Vos & Friederici, 2003; Bornkessel et al., 2004), indicating increased reanalysis in the high WMC participants. Neither

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[1] It must be acknowledged that this sentence contains an ambiguity with respect to the attachment of the adjunct *during the meeting* but as it occurs after the resolution of the filler gap dependency it should not have any affect on the results.

Bornkessel et al. (2004) nor Friederici et al. (1998) found group differences in the P600 effects for syntactically complex sentences which did not contain temporary ambiguities. This suggests that the resolution of syntactic ambiguity and of filler-gap dependencies differ in terms of working memory demands.

Understanding of the relationship between WMC and different types of syntactic processing is limited by the fact that the vast majority of studies that have examined the connection have used the reading span task (Danemann & Carpenter, 1980) as the sole index of WMC, while many different assessments, which tap different working memory mechanisms, exist (Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005). This makes it impossible to determine if the difference between the working memory demands of two syntactic processes are quantitative or qualitative. Parsing complex but unambiguous syntax may be less costly than reanalysis of garden-path structures, or it could recruit working memory mechanisms not indexed by the reading span task.

The goal of the current study was to determine if working memory mechanisms other than those indexed by reading span are relevant to the online sentence processing as indexed by P600 effect size. To this end, WMC was assessed using four different measures: reading span, operation span, *n*-back and anti-saccade. The reading span is a complex span task which assesses an individual's ability to maintain and process information (i.e. read sentences) under divided attention. Operation span, another complex span task, is very similar except that the processing component is the performance of mathematical operations. These two tasks correlate with each other (Conway et al. 2005) and both have been shown to predict sentence comprehension performance (Turner & Engle, 1989). Also, as mentioned before, reading span has been found to predict P600 effect size for garden-paths (Friederici et al., 1998; Vos et al., 2001, Vos & Friederici, 2003; Bornkessel et al., 2004). *N*-back performance reflects the ability to maintain, monitor and regularly update information. The relationship between *n*-back and sentence processing is unclear and largely untested. Sprouse, Wagers and Phillips (2012) found no evidence of a relationship between *n*-back performance and island effects (i.e. effects of syntactic complexity) on acceptability judgments. Novick and colleagues, however, found that individuals who improve their *n*-back performance via training show reduced garden-path effects in their comprehension accuracy relative to those who do not respond to training (Novick, Hussey, Teubner-Rhodes, Dougherty, Harbison & Bunting, in press). The anti-saccade task tests the ability to suppress a prepotent response. Bilinguals are known to out-perform monolinguals in tasks tapping this skill (Bialystok, 2006, Bialystok, Craik, & Luk, 2008), suggesting a possible connection with language processing. By including a wider range of working memory assessments, the current study aimed to enrich understanding of the cognitive underpinnings of sentence processing.

Methods

Participants

Data was collected from 65 right handed participants. Data from two participants was excluded because it was revealed that they didn't meet the participation criteria. Six participants were excluded due to technical issues with data collection. An additional 6 were excluded due to excessive EEG artifacts. Data from the remaining 51 participants (29 female) between the ages of 18 and 40 (mean age = 21.5, S.D. = 2.33) were included in the analysis. All participants were neurologically normal, native speakers of English. None had had started learning a second language before age 12.

Sentence Stimuli

The sentence stimuli consisted of garden-path, object relative and control sentences (see 3-5 above, respectively. The critical word in each condition was a ditransitive verb ("showed" below). A total of 108 triplets were prepared using 108 different critical verbs such that each sentence in a triplet is identical except for the region at the beginning of the second clause (bolded below). Ninety of the 108 came from Gouvea et al. (2010)'s stimuli set. In the garden-path sentences, the critical verb indicated the need for reanalysis. In the object relative sentences, the critical verb indicated the thematic position of the wh-phrase ("to whom") and, thus, allowed the resolution of the filler-gap dependency. Each list contained 36 sentences in each condition. The presentation of sentences was counterbalanced such that each sentence appeared in one condition per list. In addition, 72 filler sentences (matched for length and complexity) were included. Fifty percent of all sentences were followed by a comprehension question. Questions came either from Gouvea et al. (2010)'s stimuli or were created for the new sentences. The comprehension questions did not specifically target the resolution of the garden-path structure. In total, six lists were created such that each sentence appeared in each condition, with or without a comprehension question, across lists.

3. The patient met the doctor **and** the nurse with the white dress <u>showed</u> the chart during the meeting. (*Garden-Path*)
4. The patient met the doctor **to whom** the nurse with the white dress <u>showed</u> the chart during the meeting. (*Object Relative*)
5. The patient met the doctor **while** the nurse with the white dress <u>showed</u> the chart during the meeting. (*Control*)

Working Memory Tasks

Reading Span Automated Reading-Span (Unsworth, Heitz, Schrock & Engle, 2005) was used in this experiment. Participants were presented with a series of sentences and asked to indicate, via button press, if the sentences make sense. After each sentence they were then presented with a letter that they must remember. At the end of the sequence, they had to recall the letters in the order of presentation. Their score reflects the total number of letters recalled in the correct order.

Operation Span Automated Operation-Span (Unsworth et al., 2005) was used in this experiment. Operation span is identical to reading span as described above except instead of making sense judgments on sentences, participants had to solve math problems involving multiple operations.

***N*-Back** In the *n*-back task, participants were presented with a sequence of single letters and asked to judge if the current letter is the same as the one that occurred *n* places back in the sequence. For example, in a 4-back task, the third "X" in the following sequence would be a target: X U P X X U U. Lures, which appeared one space before a target (*n*-1; the second "X") or one space after a target (*n*+1; the third "U") were also included. Participants in the current experiment performed 2-back and 4-back. Accuracy for four item types (target, non-target, *n*-1 lure and *n*+1 lure) were averaged across *n* level (2-back and 4-back).

Anti-Saccade In the anti-saccade task, participants performed a letter monitoring task. They were first presented with a flashing cue that appears on either the left or right side of the computer screen. The cue was followed by a letter. The letter was either on the same side of the screen as the cue (pro-saccade) or on the opposite side (anti-saccade). Participants had to suppress the impulse to shift their gaze to the cue in order to maximize performance. Accuracy for anti-saccade trials was included in the analysis.

EEG Recording

Electroencephalographic (EEG) data was acquired using the Electrical Geodesics Inc. (EGI) NetStation 128-channel system. The HyrdoCel Geodesic Sensor Net is an elastic structure containing Ag/AgCl electrodes, individually housed underneath a sponge pedestal, which is soaked in a saline solution (KCl) and placed carefully over the participant's head. The signal was high-pass filtered online at 0.1 Hz, low-pass filtered at 100 Hz, and notch filtered at 60 Hz. The EEG signal was sampled at 250 Hz. Impedances were kept below 50 KΩ where possible and otherwise under 100 KΩ. Prior to averaging, drift, eye blinks and other movement artifacts were corrected via either the EP Toolkit for MatLab (Dien, 2010). EEG were recorded using CZ as a reference and later re-referenced to the global mean.

Procedure

After signing a consent form and background questionnaire, the experimenter applied the sensor net. Participants were seated in a sound attenuated booth using a chin rest in order to reduce movement artifacts. EEG data was collected during the sentence processing task. Sentences appeared word-by-word in a rectangular box in the center of a high resolution computer screen. The rectangular box appeared continuously on the monitor. Each word was presented for 300 ms, followed by a blank of 200 ms. The final word of the sentence was presented with a period sign and was followed by a 5.5 second rest period. 50% of the test sentences were followed by comprehension questions. The questions were presented in their entirety above the rectangular frame for 2500 ms, followed by a rest period of 3500 ms. Key presses with the right and left index fingers (counterbalanced across subjects) were used to for yes and no responses to the questions. Within the session, the stimuli were broken into 6 runs consisting of 27 sentences and lasting approximately 8 minutes each. The EEG session, including electrode application and removal, lasted approximately 1.5 hours. After electrode removal, participants performed the four working memory assessments (also in a sound attenuated booth). The order of the four working memory tasks was counterbalanced across participants. Completion of the working memory tasks took no more than one hour and, thus, the entire session lasted approximately 2.5 hours.

Data Analysis

Upon completion of pre-processing, ERPs were computed for each individual in each experimental condition for a 1500 ms interval time-locked to the presentation of the critical verb ("showed" above) relative to a 200 ms pre-stimulus baseline. The following time windows were considered in the analysis: 500-700 and 700-900. The analyses were performed on midline, dorsal and ventral electrodes. The midline electrodes were divided into anterior (FPZ, FZ, FCZ, CZ) and posterior (CPZ, PZ, POZ, OZ) sections. The dorsal electrodes were grouped by anterior-posterior (AP) location and hemisphere: Left anterior (FP1, AF3, F3, 20, FC3, C3), right anterior (FP2, AF4, F4, 118, FC4, C3), left posterior (CP3, 53, P3, P1, 59, PO7) and right posterior (CP4, 86, P4, P2, 91, PO8). The ventral electrodes were similarly grouped: Left anterior (F7, FT7, FC5, T10, 40), right anterior (F8, FT8, FC6, T11, 109), left posterior (T3, TP7, CP5, 50, P5, T5, P9) and right posterior (T4, TP8, CP6, 101, P6, T6, P10).

The effects of the garden-path/object relatives compared to controls on brain activity were assessed in the dorsal and ventral regions with three way ANOVAs (sentence type x AP x hemisphere) and in the midline electrodes with a two-way ANOVA (sentence type x AP). In addition, the mean amplitude in posterior midline electrodes in the 700-900 ms time window was used in the correlational analyses of the working memory assessment and behavioral data.

Scores and accuracy data from the four working memory assessments were used in the correlational analysis. First, the correlations between the working memory measures were assessed. Second, the correlations between the WM measures and garden-path/object relative effects in the comprehension accuracy and P600 data were assessed. The sentence type effects were calculated for the comprehension data by subtracting accuracy for control sentences from that of garden-path/object relatives. Likewise, for the ERP data, the mean amplitude at over posterior midline electrodes during the 700-900 ms time window for the control sentences was subtracted from that of garden-path/object relative sentences.

Results

Behavioral Data

Accuracy was lower for garden-path (79.2%, S.D. 17.1) and object relative (80.6%, S.D. 19.0) sentences than for controls (84.3%, 15.3). There was an effect of sentence type for the garden-path/control comparison ($F(1,50) = 4.03$, $p = .050$) but not for the analysis of object relatives ($p > .2$).

ERP Data

In the 700-900 ms time window, garden-path sentences elicited increased positivity compared to controls. At midline regions, there was a significant interaction of type and AP ($F(1,50) = 6.08$, $p < .05$) such that garden-paths are more positive than controls at posterior sites. Simple comparisons showed a marginal effect in posterior sites ($F(1,50) = 3.61$, $p = .06$). Over dorsal regions, there was a main effect of sentence type ($F(1,50) = 5.39$, $p < .05$) and an interaction of sentence type and AP ($F(1,50) = 5.24$, $p < .05$. Simple comparisons showed a significant effect of type at posterior electrodes ($F(1,50) = 10.4$, $p < .005$) such that garden-paths elicited greater positivity. There was also an interaction of sentence type and AP over ventral sites ($F(1,50) = 4.28$, $p < .05$). Simple comparisons revealed no significant effects. For the object relatives, there was a main effect of sentence type ($F(1,50) = 4.12$, $p < .05$) such that object relatives were more positive.

Correlations

The correlational analysis of the working memory assessments showed significant correlations between operation span and reading span ($r = .353$, $p < .05$), operation span and anti-saccade accuracy ($r = .334$. $p < .05$), and anti-saccade and *n*-back target accuracy ($r = .349$, $p < .05$).

Analysis of the accuracy effects showed a correlation between garden-path effects and reading span ($r = -.294$, $p < .05$). There was also a significant correlation between object relative effects and accuracy for *n*+1 lures in the *n*-back task ($r = .317$, $p < .05$). A similar pattern was seen in the P600 data. The P600 effect for garden-path sentences correlated positively with operation span score ($r = .381$, $p < .01$) and marginally with reading span score ($r = .266$, $p = .06$). The P600 effect for object relatives correlated negatively with *n*-back accuracy for *n*-1 lures ($r = -.352$, $p < .05$) and *n*+l lures ($r = -.332$, $p < .05$).

Discussion

The effects of sentence type (both P600 and accuracy) are consistent with previous findings. The effects for garden-path sentences were significant and typical in terms of distribution and time course. With respect to object relatives, Gouvea et al. (2010) got no significant effects for object relatives versus controls while the current study found a main effect of sentence type (with no interactions with topographical factors). This difference is likely due to power as the current study had 50 participants while Gouvea et al. (2010) had twenty. Accuracy for garden-path sentences was significantly lower than controls, as in previous studies (Frazier & Rayner, 1982; Ferreira, Bailey & Ferraro 2002) but there was no effect for object relatives. Gouvea et al. (2010) with almost the same materials got no effects of sentence type whatsoever in the accuracy data. Though the garden-path effects differ from Gouvea et al. (2010) in this respect, they are consistent with previous studies. The cross-correlations between the working memory measures (specifically the lack of correlation between the complex span tasks and *n*-back) were also consistent with established findings (Kane, Conway, Miura & Colflesh, 2007; Unsworth, Schrock & Engle, 2004). The two complex span tasks (reading span and operation span) did correlate significantly with each other which was also expected based on previous findings (Conway et al. 2005). The correlational analyses between the WM and sentence processing effects were, therefore, run on data showing standard effects and not anomalous in any way.

The key finding of the correlational analysis is that, while performance on the complex span tasks (reading span and operation span) does predict garden-path effects, it is *n*-back accuracy that predicts the effect for object relatives. This is seen in both P600 data and accuracy. Though this is a novel finding, both assessments are intuitively related to their respective sentence types.

In garden-path sentences, individuals must maintain the linear sequence of words active in memory while reanalyzing the syntactic structure. The resolution of a garden-path does, therefore, require dividing attention between storage and sentence processing as does the reading span task. The correlation with operation span was positive for the P600 effect, indicating greater effects for individuals with higher operation span. The marginal correlation with reading span was also positive. These findings are consistent with the Early Commitment Model (Friederici et al., 1998) which argues that high span individuals, when faced with a syntactic ambiguity, commit early to one structure and proceed accordingly rather than entertaining multiple possibilities. The consequence, in the case of a garden-path, is that they then must execute the costly reanalysis process (Friederici et al., 1998). Reading span score correlated with the garden-path effect on comprehension accuracy, similarly predicting greater effects for high span participants. Taken together, these results affirm complex span performance as a predictor online and offline garden-path effects.

In the object relative sentences, the relative pronoun must be maintained active and eventually matched to the appropriate thematic position. This involves assessing each new word in the sentence sequence to determine if it is the relevant predicate. In this way, the process resembles *n*-back in which each new letter must be checked against the letter that is *n* places back in the sequence. The correlation was negative for the P600 effect suggesting that increased *n*-back accuracy is associated with either (1) reduced sensitivity to structural relationships or (2) increased efficiency in that processing such that complex syntactic structure is less disruptive. The positive correlation between the comprehension accuracy effects accuracy for *n*+1 (indicating reduced effects of syntactic complexity among individuals with high *n*+1 lure accuracy) does not enable a distinction between the two accounts, as both would predict reduced differences between object relative and control sentences. While this is a question for future research, the finding remains that working memory mechanisms reflected in n-back are recruited during the resolution of filler-gap dependencies.

The lack of a relationship between n-back accuracy and garden-path effects is somewhat surprising given the findings of Novick et al. (in press). This could be due to methodological differences (for example, Novick et al. used self-paced reading). It could also indicate, in addition to increasing n-back accuracy as a result of training, participants gained some strategic skills that facilitated task performance.

In contrast to the n-back and complex span tasks, anti-saccade also showed no relationship with the online and offline sentence type effects. Mendelsohn (2002) also failed to find a relationship between anti-saccade and garden-path effects but he did succeed in with a verbal sorting task that also measured the ability to inhibit automatic responses. It is possible that anti-saccade is a poor predictor of language performance.

The finding that separate working memory measures correlate with P600 effects for the two sentence types leads to the speculation that the late positive components elicited by these two processes may be categorically distinct. The notion of distinct late positive components is not new (see Kutas, van Petten, & Kluender 2006 for review) but findings have been mixed. Friederici, Hahne and Saddy (2002) found differences in time course and topographical distribution in the P600s effects of grammaticality and syntactic complexity. Kaan and Swaab (2003), however, found no difference in P600 effects of grammaticality and dispreferred structure. The current results, that late positivities elicited by the resolution of temporary syntactic ambiguity and syntactic complexity are underpinned by distinct working memory mechanisms provides a fresh perspective on this question. In addition to the correlational effects, the two effects did show topographical differences such that the garden-path sentences elicited a late positivity with a posterior distribution while that of the object relatives was not limited to posterior sites. While this difference is slight, due to the relatively coarse topographical analyses it is not possible “to rule out the possibility that the P600 is the consequence of a disparate set of processes that happen to elicit topographically similar responses” (Gouvea et al. 2010, p. 177). While the proposal is speculative at this time, consideration of the relationship of working memory mechanisms to these components in future research will likely provide valuable insights.

In conclusion, the results of the current study suggest a more complex relationship between working memory mechanisms and online sentence processing than has previously been considered, such that different working memory mechanisms support the resolution of different types of difficult structures. Furthermore, the findings provide evidence for functionally distinct late positive ERP components. Future research on the interaction of working memory and language must include a variety of working memory assessments in order to increase understanding of the cognitive underpinnings of sentence processing.

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