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The effects of prosody on sentence comprehension: evidence from a neurotypical control group and seven cases of chronic stroke

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Abstract

Manipulations of both prosody and sentence structure (e.g., canonical versus non-canonical) can affect sentence comprehension. However, few previous studies have examined a possible interaction between prosody and sentence structure and effects on sentence comprehension, despite previous work indicating that prosodic cues assist in sentence comprehension by interacting with some of the same cognitive resources recruited to support comprehension of difficult sentence structures. In Experiment 1, we investigated whether typical sentence prosody and list prosody differentially affect the comprehension of non-canonical sentences compared to canonical sentences in adult control subjects. We found a significant interaction: typical sentence prosody facilitated the comprehension of some but not all canonical and non-canonical sentence structures. In Experiment 2, we examined in seven chronic stroke patients how some cognitive abilities may be related to the effects of prosody on sentence comprehension. Working memory was significantly correlated with comprehension of non-canonical sentences spoken with list prosody, but not with sentence prosody; attentional control did not significantly correlate with performance on sentences with either prosody type. But, single-case Bayesian statistics indicate that impaired attentional control may be related to impaired performance on sentences with sentence prosody but not list prosody, and that impaired working memory may be related to impaired performance on sentences with list prosody, but not sentence prosody. Our results suggest prosody may particularly aid comprehension of some sentence structures, and that impairments of non-canonical sentence comprehension in stroke patients may be modulated by the type of prosody used, based on a patient's relative cognitive abilities.

Keywords

sentence comprehension; prosody; sentence structure; aphasia; cognition

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Introduction

Sentence structure and prosody guide the construction of individual words and phrases into meaningful sentences. However, it remains unclear how prosody may interact with sentence structure to affect comprehension. While the effects of sentence structure and prosody on sentence comprehension have rarely been studied together, it is largely acknowledged that sentence comprehension performance in persons with aphasia (and after left hemisphere stroke more generally, although the research is more limited¹) and controls can be modulated by varying either the prosody or structure of sentences (Caramazza & Zurif, 1976; Lasky, Weidner, & Johnson, 1976; Pashek & Brookshire, 1982; Roncaglia-Denissen, Schmidt-Kassow, & Kotz, 2013; Wilson et al., 2010; Dronkers et al. 2004; Rogalsky et al. 2018).

It is well-established that comprehension performance is typically better (as evidenced by higher accuracies and faster response times) when sentences have a canonical structure (e.g., subject-verb-object in English) compared to a non-canonical structure (e.g., subject-object-verb in English) in both controls and patients with chronic stroke with and without aphasia (Caramazza & Zurif, 1976; Ferreira, 2003; Goodglass & Berko, 1960; Kean, 1977; King & Just, 1991; Dronkers et al. 2004; Rogalsky et al., 2018; Roncaglia-Denissen et al., 2013; Wilson et al., 2010). Much of this work has focused on non-canonical sentences that contain syntactic movement, such as those containing object-relative clauses (Caplan, Michaud, & Hufford, 2013; Dronkers et al., 2004; Rogalsky et al., 2018; Thothathiri, Kimberg, & Schwartz, 2012; Wilson et al., 2010), but this canonical versus non-canonical performance decline is also well-documented in many other non-canonical sentence structures, including passives, object extracted clefts, and center-embedded sentences (Caplan et al., 2013; Dronkers et al., 2004; Ferreira, 2003; Thothathiri et al., 2012).

Performance differences between canonical and non-canonical structures likely reflect an increase in processing load associated with many non-canonical sentence structures (Caplan & Waters, 1999; Gibson, 1998). This performance difference may be at least in part due to increased demands on cognitive processes, including working memory and attentional control (Caplan & Waters, 1999; Haarmann & Kolk, 1991; Zurif, Swinney, Prather, Solomon, & Bushell, 1993). Working memory has been the cognitive measure of focus in most studies of non-canonical sentence comprehension, particularly for sentences containing syntactic movement (Caplan, DeDe, Waters, Michaud, & Tripodis, 2011; Caplan et al., 2013; Caplan & Waters, 2013; Rogalsky, Almeida, Sprouse, & Hickok, 2015; Santi & Grodzinsky, 2007), and is often impaired in individuals with left hemisphere frontal and parietal lobe damage, including individuals with aphasia (Caplan et al., 2013; Caspari, Parkinson, LaPointe, & Katz, 1998; Christensen, Wright, & Ratiu, 2018; Gläscher et al., 2009). However, attention is also often impaired post-stroke, yet no studies to our knowledge

¹Left hemisphere stroke patients, both with and without aphasia, can exhibit sentence comprehension impairments (e.g., Rogalsky et al., 2018). Complex sentence comprehension impairments have been reported in both Broca's and conduction aphasia (Caramazza & Zurif, 1976), but they are not a primary diagnostic criteria for aphasia. Thus, our literature review includes studies of chronic left hemisphere stroke, both with or without resulting aphasia. Similarly we chose to include any participant meeting our inclusion criteria with a chronic left hemisphere stroke. But, traditionally, most studies of sentence comprehension have focused on patients with aphasia, so we have indicated what findings are from aphasia specifically, and which are from stroke patients more broadly.

have investigated the role of attention in non-canonical sentence comprehension. Attention, particularly attentional control, and working memory abilities often correlate in neurotypical adults (Kane, Bleckley, Conway, & Engle, 2001) but are known to dissociate in stroke patients (Peers et al., 2018; Richter, Mödden, Hanken, & Hildebrandt, 2015), likely due to different lesion patterns within the distinct but overlapping brain regions that support attention and working memory (Cabeza, Daselaar, Dolcos, Prince, Budde, & Nyberg, 2004; Gazzaley, & Nobre, 2012; Wallis, Stokes, Cousijn, Woolrich, & Nobre, 2015). Thus, the effects of non-canonical sentence structures on the cognitive resources involved in sentence comprehension remain poorly defined.

Prosody also can affect sentence comprehension. Typical sentence prosody patterns generally yield better sentence comprehension performance than sentences presented with irregular prosodic patterns (Carlson, 2009; Kjelgaard & Speer, 1999; Lehiste, 1973; Roncaglia-Denissen et al., 2013; Speer, Kjelgaard, & Dobroth, 1996). Prosodic cues can perceptually divide sentences into smaller phrases and focus listener attention to critical time points within a sentence. Strategic placement of prosodic boundaries can influence the less preferred meaning of syntactically ambiguous sentence structures (Beach, 1991; Kjelgaard & Speer, 1999; Speer et al., 1996) and pitch inflections can provide cues about new or contrasting information (Dahan, Tanenhaus, & Chambers, 2002; Weber, Braun, & Crocker, 2006; Ito & Speer, 2008). Prosodic cues can also facilitate sentence comprehension by creating temporal expectancy (i.e., rhythmic cueing that generates expectation for the timing of an upcoming stimulus) (Roncaglia-Denissen et al., 2013; Zheng & Pierrehumbert, 2010).

Prosody may also facilitate sentence comprehension by reducing processing loads associated with comprehending complex sentence structures (Kjelgaard & Speer, 1999; Speer et al., 1996; Roncaglia-Denissen et al., 2013). Pitch inflections have been shown to improve sentence comprehension by helping listeners to resolve ambiguities related to pronoun and clause attachment (Lakoff, 1971; Schafer, 1996). Therefore, typical sentence prosody, which contains meaningful pitch inflections and prosodic boundaries, may more generally facilitate sentence comprehension by directing listener attention towards important elements of a sentence (Schafer, 1997). This ability of prosody to segment various sentence structures by directing attention may be particularly important for complex, non-canonical sentence structures. Non-canonical sentences typically have non-linear sentence structures (i.e., subject-object-verb word order in English), which place greater demands on cognitive resources (e.g., working memory and attention) during comprehension as clauses need to be manipulated to deduce agent-patient relationships (Caplan & Waters, 1999; King & Just, 1991; Roncaglia-Denissen et al., 2013). For example, in the sentence, *The boy who the girl is kissing is blue*, it is initially unclear that *the boy is blue* as the noun-phrase *the girl* separates *the boy* from *is blue*. Placing pitch inflections and prosodic boundaries after *boy* and *kissing* aids the listener in segmenting the sentence and successfully attaching *is blue* to *The boy*.

In contrast to sentence prosody, list prosody (i.e., monotone prosody containing a consistent rhythm and a lack of meaningful pitch inflections and prosodic boundaries) may facilitate sentence comprehension by creating temporal expectancy effects that aid the chunking of information within working memory resources (Gilbert, Boucher, & Jemel, 2014). Temporal

expectancy, created through rhythmic cueing prior to a target pseudoword, has been shown to improve speech comprehension in neurotypical adults (Cason & Schön, 2012). However, we propose that temporal expectancy can also be embedded within the speech stimulus itself: the equal emphasis and stress associated with list prosody creates regularly timed intervals which leads to the creation of temporal expectancy effects, which may aid comprehension. Control subjects naturally try to group continuous speech into units/chunks of meaningful information (e.g., syllables, words) (Broadbent, 1975; Cowen, 2001), and perhaps the temporal expectancy effects created by list prosody may help an individual to group information together in such a way as to engage working memory resources, thus facilitating sentence comprehension.

Studies of individuals with aphasia also suggest that sentence comprehension can be affected by prosody. Specifically, individuals with aphasia demonstrate decreased sensitivity to prosodic cues such as rising pitch contours differentiating a question from a statement (Heilman, Bowers, Speedie, & Coslett, 1984; Pell & Baum, 1997; Perkins, Baran, & Gandour, 1996). This decreased sensitivity to prosodic cues suggests that sentence comprehension impairments associated with aphasia may actually stem from a combination of deficits in processing prosody and sentence structure, as prosodic cues may fail to initially guide the listener to a correct interpretation. Prosody can reduce processing demands during sentence comprehension (Kjelgaard & Speer, 1999; Speer et al., 1996; Roncaglia-Denissen et al., 2013), and this reduction in cognitive load may be particularly important for individuals with left hemisphere damage who also have reduced cognitive abilities. If prosodic cues are not attended to and utilized in a typical manner, sentence comprehension, particularly for syntactically complex sentences, may be impaired due to increased processing demands. It should be noted that the right hemisphere also has been implicated in processing linguistic prosody (Kreitewolf, Friederici, & Kriegstein, 2014; Bryan, 1989; Weintraub, Mesulam & Kramer, 1981), including prosodic information such as pauses indicating phrase boundaries that are critical for successful sentence comprehension (Friederici, 2011). Thus, it may be that deficits in sentence comprehension related to linguistic prosody following left hemisphere damage may at least in part be due to a disruption of interactions between right hemisphere prosody resources and syntactic processing brain networks that are generally agreed upon to reside in the left hemisphere (Kreitewolf et al., 2014; Friederici, 2011; Hickok & Poeppel 2007).

Most previous attempts to quantify the interaction of sentence structure and prosody have been limited to syntactically-ambiguous sentences; sentences containing syntactic movement have not to our knowledge been examined in this regard, despite their prevalence in the sentence comprehension literature more broadly. Recent work by Roncaglia-Denissen and colleagues (2013) compared subject-first and object-first sentences spoken with regular and irregular speech rhythms. Their results demonstrate that the addition of irregular speech rhythms decreases comprehension of both syntactically ambiguous subject-first and object-first sentences (Roncaglia-Denissen et al., 2013). Although the rhythmic manipulation did not interact with sentence structure behaviorally² (as measured by reaction time; the

²The lack of a behavioral effect may be due to the regular rhythm condition consisting of one stressed syllable followed by three unstressed syllables; the rhythm was metrically regular, but not normal sentence prosody.

interaction statistics were not reported for accuracy), simultaneous electrophysiological recordings identified an interaction driven by a decreased P600 mean amplitude for rhythmically regular object-first sentences compared to their irregular counterparts, but no differences in amplitude between rhythmically regular and irregular subject-first sentences (Roncaglia-Denissen et al., 2013); suggesting irregular rhythm likely interferes, but does not inhibit successful comprehension. Overall, prosody manipulations appear to bias listeners towards the speaker's preferred interpretation (Lehiste, 1973; Kjelgaard & Speer, 1999; Price, Ostendorf, Shattuck-Hufnagel, & Fong, 1991; Speer et al., 1996), preventing the need for re-analysis, and subsequently facilitating the comprehension of syntactically ambiguous sentence structures.

The present study addresses the need to better understand how prosody may facilitate comprehension as a function of sentence structure. In Experiment 1, we investigate whether typical prosodic cues, compared to list prosody, facilitate the comprehension of non-canonical sentences in control subjects. Four types of sentences, two canonical and two non-canonical adapted from Wilson et al. (2010), were each presented with typical sentence prosody and list prosody (i.e., monotone prosody lacking meaningful pitch inflections and prosodic boundaries). Sentence comprehension was assessed using a sentence-picture matching task (Wilson et al., 2010). Participants were neurotypical young adults, therefore we anticipated accuracy to be above chance in all conditions. However, we expected to find a sentence by prosody interaction for reaction time. We hypothesized that typical sentence prosody would facilitate the comprehension of non-canonical sentences more than canonical sentences, as performance on the non-canonical sentences will presumably benefit from segmentation cues similar to syntactically ambiguous sentences, as seen in previous work. In Experiment 2, we investigated the relationship between some aspects of cognition (working memory and attentional control) and comprehension of non-canonical sentences spoken with typical sentence prosody and list prosody in persons with chronic stroke. We expected preserved attentional control abilities to positively correlate with greater non-canonical sentence comprehension when sentences were spoken with sentence prosody, as sentence prosody presumably facilitates sentence comprehension by drawing the listener's attention to important sentential information (Schafer, 1997). Alternatively, we hypothesized preserved working memory abilities to positively correlate with greater comprehension of non-canonical sentences spoken with list prosody as list prosody may create temporal expectancy effects that may recruit working memory and subsequently aid sentence comprehension (Gilbert, Boucher, & Jemel, 2014).

Experiment 1: Prosody and Non-Canonical Sentence Comprehension

Method

Participants—Thirty-eight participants (34 females) met the following criteria: right-handed, native speaker of American English, 18–30 years of age ($M=21.97$, $sd=2.52$), with no self-reported history of neurological damage or psychiatric disease. Participants were recruited from undergraduate classes and received course extra credit or monetary compensation. Six participants were excluded from the final sample due to standardized working memory scores greater than one standard deviation below the normed mean on the

Wechsler Adult Intelligence Scale-IV Working Memory Index (*WAIS-IV* WMI; $M=100$, $sd=+/-15$). The final sample was comprised of 32 participants (28 females; $M=21.63$ years, $sd=2.35$). Arizona State University's (ASU) Institutional Review Board approved all procedures.

Stimuli—Stimuli were 140 sentences (10 syllables each) representing four sentence structures previously reported in Wilson et al. (2010). Two sentence structures were canonical (C1, C2) and two were non-canonical (NC1, NC2) (see Table 1). All sentences contained two nouns (boy, girl), one of seven verbs (hit, push, kick, kiss, wash, pull, hug), and one of three color adjectives (blue, green, red); thematic role assignment, verb, and adjective use were balanced across all sentence structures. Each sentence structure was spoken with both sentence prosody (i.e., natural prosody) and list prosody (i.e., monotone prosody lacking pitch inflections and meaningful prosodic boundaries), resulting in eight conditions containing 35 sentences each. An additional 28 short sentences (7 syllables), 14 canonical and 14 non-canonical, spoken with both sentence and list prosody, were included as a sort of decoy to interfere with participants' ability to develop strategies for parsing the experimental sentences. These short sentences were not analyzed as they differed from the experimental sentences in terms of sentence length and lexical content (Wilson et al., 2010).

Sentences with sentence prosody were generated by reading each sentence with natural intonation; key words needed to parse the sentence were accentuated using pitch inflections and prosodic boundaries. Pitch inflections and prosodic boundaries have both been shown to capture listeners' attention. Therefore, the sentence prosody manipulation was designed to provide ample cues towards which the listener's attention could be directed. Sentences with list prosody were generated by recording each word separately, and then concatenating the individual words in the order of the sentence with an inter-word interval of 20 milliseconds. The list prosody manipulation was designed to lack the prosodic cues present in the sentence prosody condition. The constant rhythm of the list prosody condition was designed to create temporal expectancy and subsequently potentially facilitate information chunking within working memory resources. All stimuli were digitally recorded by a classically trained female vocalist (author N.B.) in Audacity sound editing software using a 32-bit resolution and 44,100 Hz sampling rate. Loudness was normalized across all stimuli.

Experimental Design—The sentence-picture matching task was presented using E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA) on a 15-inch screen Dell Precision M4800 in a quiet room. Sentences were presented binaurally through headphones at a volume deemed comfortable by the participant. Each participant heard all 140 experimental sentences; half with sentence prosody and half with list prosody. Two sets of sentences were generated, with each set containing either sentence or list prosody for each sentence. Each set contained 140 experimental trials (half with sentence prosody and half with list prosody), 56 short decoy sentence trials (half with sentence prosody and half with list prosody), and 20 rest trials (i.e., four seconds of silence). Each participant completed one set, divided into two blocks. Presentation order was randomized across participants.

Each trial began with the simultaneous presentation of a black fixation cross and an auditory sentence. Following the sentence, a target and foil picture appeared (positioned left and right

respectively with location of the correct picture counterbalanced across trials). Foils were either thematic (i.e., role reversal of agent and patient) or color based (i.e., color assigned to wrong agent/patient) and were counterbalanced across trials. Instructions were to decide which picture matched the target sentence as quickly and accurately as possible. Accuracy and reaction times were recorded via a keyboard button press. After the participant responded, a black fixation cross appeared for one second before initiation of the next trial. Four practice trials preceded the sentence-picture matching task to familiarize participants with the task.

Working memory capacity was assessed using the *WAIS-IV* WMI (Arithmetic and Digit Span subtests) because previous work suggests that off-line sentence comprehension tasks (such as sentence-picture matching) require working memory resources to maintain and manipulate information (Caplan & Waters, 1999).

Data Analysis—Accuracy (correct vs. incorrect) was analyzed using a logistic regression with four levels of sentence structure and two levels of prosody. For reaction time, a 4×2 repeated measures ANOVA with four levels of sentence structure and two levels of prosody was computed. Reaction times associated with incorrect responses and those greater than two standard deviations from each participant's mean and/or those exceeding 8000 milliseconds were excluded from the analyses; this data trimming procedure was determined *a priori* based on it being a standard, well-studied approach in psycholinguistic research (Baayen & Milin, 2010; Lachaud & Renaud, 2011; Ratcliff, 1993). The rationale behind it is that incorrect trials and reaction times abnormally long for a particular participant are removed to help ensure that reaction time statistics are based on trials in which normal sentence processing has occurred. The goal is to capture approximately the middle 85% of the distribution of the reaction time measurements, based on the assumption that we are therefore hopefully capturing the processes of interest, and not other erratic, extraneous factors (e.g., brief distractions, button press mistakes, etc.). This procedure resulted in 16% of the data being removed, consistent with the above recommendation, although it should be noted that the ANOVA results reported below do not change significance if this outlier removal procedure is not used. A Bonferroni correction for multiple comparisons was implemented separately for each omnibus test setting α to 0.0125 ($\alpha = .05/4$).

Results

Accuracy—In line with our hypotheses, participants performed significantly above chance in all experimental conditions (binomial tests for each condition indicate $p < .001$) (Figure 1A). The full logistic model was significant, indicating that at least one of the experimental factors, sentence structure or prosody, reliably predicted correct responses ($\chi^2(7) = 359.53$, $p < .001$). Corresponding with previous work (Wilson et al., 2010), the type of sentence structure significantly predicted participants' comprehension scores ($\chi^2(3) = 351.42$, $p < .001$). A follow up Wald χ^2 analysis indicated that all sentence structures significantly differed from each other at $p < .0125$, Bonferroni corrected. The type of prosody did not significantly contribute to sentence comprehension accuracy ($\chi^2(1) = 0.671$, $p = .413$). The interaction of sentence structure and prosody on accuracy was also not significant ($\chi^2(3) = 2.85$, $p = 0.41$).

Reaction Time—The main effect of sentence structure was significant, $F(3, 93)=89.99$, $p<.0001$, replicating previous work (Wilson et al., 2010). All sentence structures significantly differed from each other at $p<.0125$, Bonferroni corrected (Figure 1B). The main effect of prosody was significant, $F(1, 31)=5.27$, $p=.03$, with participants having longer reaction times for list prosody ($M=1986.44$, $SE= \pm 104.39$) compared to sentence prosody, ($M=1889.22$, $SE= \pm 118.17$). The interaction between sentence structure and prosody was also significant, $F(3, 99)=3.35$, $p=.02$. Simple effects tests reveal sentence prosody improves the comprehension of C2 and NC1 sentence structures compared to list prosody, while C1 and NC2 sentences were not modulated by prosody (Figure 2); these results partially support our hypothesis regarding sentence prosody facilitating the comprehension of non-canonical sentence structures.

Preliminary Discussion

The major finding from Experiment 1 is the significant interaction of sentence structure and prosody affecting reaction time: typical prosodic patterns (i.e., sentence prosody) facilitated the comprehension of certain types of sentence structures (C2 and NC1). Both C2 (e.g., The boy is kissing the girl who is red) and NC1 (e.g., The girl who the boy is kissing is red) contain a modifying clause which can be attached to either the subject or object of the sentence. Typical prosodic cues likely facilitated comprehension of the C2 and NC1 sentences by reducing demands placed on cognitive resources (Schafer, 1997). For example, typical prosodic cues likely directed listener attention to important sentential information and thus aided the correct attachment of the modifying clause to the object (C2) and subject (NC1) of the sentence. This possibility and the relationship between cognition and prosody are explored in Experiment 2, and discussed further in the general discussion.

Experiment 2: The Relationship between Cognition and Prosody

In Experiment 2, we directly examined how cognitive processes may mediate prosody effects on sentence comprehension in seven adults with chronic left hemisphere damage due to stroke.

Method

Participants—Seven chronic stroke patients (3 female) participated in this study (Table 3). All patients experienced a single left-hemisphere cerebral stroke at least 6 months prior to testing, were pre-morbidly right-handed, native speakers of American English, 18+ years of age, with no history of other neurological damage or psychiatric disturbances. ASU's Institutional Review Board approved all procedures.

Stimuli—Stimuli consisted of a subset of the NC1 sentences from Experiment 1. We chose to examine NC1 sentences as patients with Broca's aphasia and conduction aphasia generally demonstrate deficits comprehending non-canonical sentences, but not canonical sentences (Caramazza & Zurif, 1976). Of the two non-canonical sentence structures in Experiment 1, NC1 was chosen because it elicited a higher level of comprehension in control participants (87% accuracy) than the NC2 sentences (69% accuracy).

Experimental Design—Participants completed a modified version of Experiment 1’s sentence-picture matching task, the *WAIS-IV* working memory subtests, and a visual Stroop task. Differences from Experiment 1’s sentence-picture matching task are as follows: (1) each trial began with the simultaneous presentation of an auditory sentence and the target and foil pictures and (2) participants could respond at any point during sentence presentation (this is the same set-up as Wilson et al., 2010). The paradigm consisted of 80 experimental trials (half with sentence prosody and half with list prosody) and 20 rest trials. The short decoy sentences in Experiment 1 were not employed to reduce testing time due to fatigue concerns.

Working memory was assessed using the *WAIS-IV* WMI as in Experiment 1. Attentional control was assessed using a visual Stroop task (MacLeod, 1991). The visual Stroop task consisted of eight words, each presented one at a time, horizontally, in all caps, and presented in the middle of the screen against a grey background. The words were used to generate three conditions: congruent (the color word written in its corresponding colored ink), incongruent (the color word written in a color that differs from what the word reads), and neutral (the neutral words written in any of the four possible colors). Participants were presented with 10 congruent, 12 incongruent, and 16 neutral trials. Response accuracy and reaction time were recorded. The measure of interest for the present study is the difference in reaction time between the incongruent and neutral trials (i.e., the trials that require the most attentional control minus the trials that require the least); values closer to zero reflect less distraction and therefore greater attentional control (MacLeod, 1991).

Data Analysis—Pearson correlations were first used to quantify the relationship between working memory and attentional control, and the comprehension of non-canonical sentences spoken with sentence prosody and list prosody. Then, to facilitate comparisons across tasks, we transformed each patient’s working memory, attentional control, and sentence comprehension accuracies into standard scores (Capitani et al. 1999; Crawford, Garthwaite & Howell, 2009). For working memory, we used the norms provided by the *WAIS-IV* WMI ($M=100$, $sd=15$) to transform the patient scores into z-scores. For attentional control, we used the mean and standard deviation from a group of 41 control subjects performing the same visual Stroop task as part of another study in our laboratory ($M=46.0$, $sd=45.7$) to standardize patient scores. For sentence comprehension accuracy, we used the mean and standard deviation from the control participants in Experiment 1 to transform the patient’s raw scores into z-scores (NC1 sentence prosody: $M=.86$, $sd=.15$; NC1 list prosody: $M=.88$, $sd=.14$).

To further examine the relationship between attentional control and working memory, and comprehension of sentences spoken with each prosody (sentence prosody and list prosody), we quantified impairment on each of these four measures for each patient using single-case Bayesian hypothesis tests (Crawford & Garthwaite, 2010; 2007). This approach allowed us to calculate the probability of whether a given patient’s score was abnormal compared to the control sample for a particular task. A patient was classified as “impaired” on a particular task if this probability was less than .05.

We then used a Bayesian Standardized Difference Test (BSDT) (Crawford, Garthwaite & Ryan, 2011) to further examine the relationship between attentional control and sentence prosody and working memory and list prosody. The BSDT allowed us to identify patients that demonstrated significantly different performance on the sentence and list prosody conditions, and whether this difference was significantly larger ($p < .05$) than the difference observed in the control group in Experiment 1. We then examined the results of the single-case Bayesian hypothesis tests for working memory and attentional control measures (described above, to determine impairment or not) for each patient in relation to the outcome of their BSDT result for sentence versus list prosody. Note, that a stronger test of our hypotheses would be to calculate a BSDT for the difference between working memory and attentional control standard scores for each patient, and then compare those differences to the BSDT for the prosody conditions. However, our control groups for the working memory and attentional control measures are based on different samples (working memory: *WAIS-IV* published norms; attention: $n=41$ controls from another study), and the BSDT, and other similar statistics, require the measures to be taken from the same control group (Crawford & Garthwaite, 2007). Thus, it is not possible to compute BSDTs between the working memory and attentional control measures.

Results

Our hypothesis of a positive correlation between working memory capacity and list prosody performance was supported: working memory capacity significantly correlated with accuracy for NC1 sentences spoken with list prosody ($r(5) = .83$, $p = .02$) but not sentence prosody ($r(5) = .65$, $p = .11$), indicating that as working memory capacity increases, so does comprehension of non-canonical sentences spoken with list prosody. Our hypothesis that attentional control and sentence prosody performance are positively correlated was not supported: the attentional control measure did not correlate with comprehension of sentences spoken with sentence ($r(5) = .43$, $p = .34$) or list prosody ($r(5) = .15$, $p = .75$). However, it is noteworthy that the lack of correlation for sentence prosody is largely driven by one patient (Figure 3 top-right, lowest accuracy data point; Patient 1).

We further characterized the relationship between each cognitive measure and each prosody manipulation in individual patients. To do this, patient's raw scores on all tasks were standardized and Bayesian hypothesis tests (Crawford & Garthwaite, 2010; 2007) and Bayesian Standardized Difference Tests (BSDTs; Crawford, Garthwaite, & Ryan, 2011) were computed (Table 4) to determine which patients demonstrated impairment in each task. We are particularly interested in the patients whose difference in accuracy between the sentence prosody and list prosody conditions significantly differed from what was expected based on the control sample.

The Bayesian hypothesis tests indicate the following (Table 4): Patient 1 and Patient 5 were significantly impaired in the sentence prosody condition ($p < .001$ and $p = .02$, respectively). Patient 2 ($p = .01$) and Patient 5 ($p = .01$) were significantly impaired in the list prosody condition. Patients 2, 5, and 7 were significantly impaired in the working memory measure ($p = .02$, $.006$, and $.005$, respectively). Patients 1, 3, 5, and 7 were significantly impaired on the attentional control measure ($p = .05$, $.03$, $< .001$, and $< .001$, respectively).

The BSDTs identified three patients that had a significantly larger difference in performance on the two prosody conditions compared to what was expected based on the control sample: Patients 1 ($p=.01$), 2 ($p<.001$), and 4 ($p<.001$). Patient 1 exhibited higher comprehension accuracy when sentences were spoken with list prosody compared to sentence prosody. As reported above, Patient 1 was also found to have significant impairments in the sentence prosody and attentional control measures, but was not found to have an impairment in the list prosody condition ($p=.06$) or working memory task ($p=.08$; Figure 4); this supports our hypothesis that unimpaired working memory abilities (paired with impaired attentional control) correspond to better comprehension of sentences spoken with list prosody compared to sentence prosody. Alternatively, Patient 2, who was impaired on working memory ($p=.02$) but unimpaired on attentional control ($p=0.5$), demonstrated better sentence comprehension accuracy when sentences were spoken with sentence prosody compared to list prosody (Figure 4). The performance pattern of Patients 1 and 2 supports our hypothesis that the effect of prosody on sentence comprehension is mediated by the availability of cognitive resources; preserved working memory corresponded with greater comprehension of sentences spoken with list prosody while preserved attentional control corresponded with greater comprehension of sentences spoken with sentence prosody. Patient 4, who performed significantly better on sentences spoken with sentence prosody compared to list prosody, was not found to be impaired in working memory ($p=0.3$) or attentional control ($p=0.1$). Again this aligns with our hypotheses: coinciding with Patient 4's unimpaired working memory and attentional control, Patient 4 was additionally found to be unimpaired on sentence comprehension in both prosody conditions (sentence prosody: $p=0.8$; list prosody: $p=.06$). Thus, Patient 4, with their intact working memory and attentional control abilities, exhibits a similar performance pattern to the neurotypical controls, in that sentence prosody yields higher accuracy compared to list prosody.

The patients not identified by the BSDTs to have a significant difference between performance in the sentence and list prosody conditions will now be descriptively discussed, although interpretation of their findings should be done with caution as these patients were identified due to a null result. Generally, in line with a relationship between the effects of prosody on comprehension and cognitive abilities, Patient 5 was found to be significantly impaired on all four tasks (sentence prosody, list prosody, working memory, attentional control), while Patient 6 was found to be significantly unimpaired on each of these tasks. The performance patterns of Patient 3 and Patient 7 were seemingly unexpected based on our hypotheses, although their lesion location and aphasia severity may provide some insight into why this is the case. Patient 7 was found to be significantly impaired on both the working memory and attentional control tasks, but was unimpaired in both prosody conditions. Patient 3 was found to be impaired in the attentional control task, but not in either prosody condition. Both Patient 7's and Patient 3's lesions were restricted to the left frontal lobe (Patient 7 = large frontal, Patient 3 = small medial frontal). It may be that damage to regions critical for non-canonical sentence comprehension are necessary for cognitive impairments to result in meaningful prosody-related differences in sentence comprehension; multiple recent studies have identified these regions to be located in the anterior and posterior temporal lobes (e.g., Magnúsdóttir et al., 2013; Rogalsky et al., 2018; Pillay et al., 2017), which are intact in these two patients.

General Discussion

The present study investigated how prosody may affect auditory sentence comprehension. Experiment 1 examined how typical sentence prosody affected comprehension of non-canonical versus canonical sentences in control participants compared to list prosody. Our findings replicate previous work: non-canonical sentences compared to canonical sentences elicited longer reaction times and lower accuracy, across prosody type (Ferreira, 2003; King & Just, 1991; Roncaglia-Denissen et al., 2013; Wilson et al., 2010). We also found a main effect of prosody with longer reaction times for list prosody compared to sentence prosody as well as a significant interaction between sentence type and prosody, which has not been previously reported.

Experiment 2 investigated how cognitive abilities may mediate the effects of prosody on sentence comprehension in seven stroke patients. Non-canonical sentence performance was positively correlated with working memory scores for sentences with list prosody, but not correlated for sentences with typical sentence prosody. For attentional control, the pattern was less clear as attentional control did not correlate with sentence or list prosody; but notably, the non-significant correlation between attentional control and sentence prosody was largely driven by one patient. The overall patterns observed at the group level were further supported in two individual patients: Patient 1 with unimpaired working memory but impaired attentional control demonstrated significantly greater comprehension for sentences spoken with list prosody compared to sentence prosody, while Patient 2 with unimpaired attentional control and impaired working memory exhibited the opposite pattern, i.e., significantly better comprehension for sentences spoken with typical sentence prosody. Collectively, Experiment 2's results suggest that chronic stroke patients with preserved working memory abilities may benefit from sentences spoken with a constant prosodic pattern (i.e., list prosody), while chronic stroke participants with preserved attentional control abilities may benefit from sentences spoken with typical sentence prosody cues.

Experiment 1's sentence by prosody interaction resulted from typical prosodic cues facilitating the comprehension of certain sentence structures (C2 and NC1). Prosody likely facilitated the comprehension of these sentence structures, but not the others, due to differences in the demands each sentence type places on cognitive resources. For example, in order to successfully parse NC1 sentences (e.g., The girl who the boy is pulling is red), participants must maintain and manipulate sentential information to correctly assign the clause *is red* to the subject *girl*, likely relying on cognitive resources, such as working memory (Caplan & Waters, 1999). Therefore, typical prosodic cues may be facilitating sentence comprehension by reducing demands placed on cognitive resources by directing listener attention to important sentential information (Schafer, 1997). The C1 and NC2 sentences do not exhibit a prosody effect, and yield the highest and lowest performance, respectively. The C1 sentences do not improve with sentence versus list prosody due to a ceiling effect. The NC2 sentences may be so difficult that cognitive resources are saturated even with prosodic cues.

While future studies are needed to identify the specific mechanism(s) by which sentence prosody is facilitating sentence comprehension, one possible mechanism by which this

reduction in cognitive demands facilitates sentence comprehension of the NC1 sentences may be related to syntactic movement: perhaps the prosodic cues aid in the reactivation of the moved constituent at the appropriate point (Bever & McElree, 1988; Corbett & Chang, 1983). However, comprehension of our C2 sentences were also facilitated by prosody and they did not contain syntactic movement, so it may be that prosody also contributes to clause attachment, with or without syntactic movement.

Across both prosody types, our results from Experiment 1 extend previous work by identifying processing differences within both the canonical and non-canonical sentence structures with C1 and NC1 being easier to comprehend than C2 and NC2, respectively. We postulate that the C2 sentence structure (e.g., The boy is pulling the girl who is red) may be more difficult to comprehend than the C1 sentence structure (e.g., The girl who is red is pulling the boy) as the clause *who is red* can be attached to either the object or the subject while in the C1 sentence structure the clause *who is red* can only be attached to the subject of the sentence. Within the non-canonical sentence conditions, NC2 (e.g., The boy who the girl is pulled by is red) is likely more difficult to comprehend than NC1 (e.g., The girl who the boy is pulling is red) as it contains a passive clause while NC1 is spoken in the active tense; there are numerous studies in stroke patients and controls indicating that passive clauses elicit more errors and slower reaction times than active clauses (Brookshire & Nicholas, 1980; Dronkers, Wilkins, Van Valin Jr, Redfern, & Jaeger, 2004; Ferreira, 2003; Rogalsky et al., 2018; Thothathiri, Kimberg, & Schwartz, 2012; Wilson et al., 2010). The comprehension differences observed between C1 and C2, and NC1 and NC2, respectively, indicate that even within each sentence category (i.e., canonical, non-canonical), differences exist in terms of processing demands, as partially seen in previous work (Wilson et al., 2010). Collectively, these findings underscore the importance of investigating multiple sentence types within each category of “canonical” and “non-canonical” in future studies of sentence comprehension.

In the control subjects in Experiment 1, prosody may be facilitating the comprehension of some non-canonical sentence structures by reducing demands on cognitive resources (Kjelgaard & Speer, 1999; Speer et al., 1996; Roncaglia-Denissen et al., 2013). For example, prosody may serve as a placeholder in working memory while other linguistic analyses occur (i.e., syntactic and semantic) (Schafer, 1997). Once these linguistic analyses are complete, the information is reintegrated into working memory and the presence of an *a priori* mental representation of prosodic cues facilitates comprehension (Cohen, Douaire, & Elsabbagh, 2001; Kjelgaard & Speer, 1999; Speer et al., 1996; Frazier, Carlson, & Clifton, 2006). This possible link between prosody and cognitive resources may explain the discrepancy between the accuracy and reaction time results in Experiment 1. While main effects of sentence structure, prosody, and their interaction were observed in our reaction time data, only a main effect of sentence structure was identified in the accuracy data. This discrepancy supports the notion that irregular prosodic patterns tax sentence comprehension resources but correct responses are still eventually chosen despite increased processing time.

In Experiment 2, we turned to investigating the relationship between prosody and cognitive abilities in the comprehension of non-canonical sentences. While prosody facilitated comprehension of some sentence structures in neurotypical adults in Experiment 1,

questions remain regarding the effectiveness of prosodic cueing in individuals with aphasia. Notably, patients with aphasia, including Broca's aphasia, can have deficits in processing both complex sentence structures (Caramazza & Zurif, 1976) and prosody (Heilman et al., 1984; Pell & Baum, 1997; Perkins et al., 1996). Despite the presence of prosody deficits in aphasia, previous research suggests that patients with aphasia benefit from prosodic cueing: patients with aphasia demonstrate increased comprehension accuracy when sentences (Lasky et al., 1976) and paragraphs (Pashek & Brookshire, 1982) were presented with a reduced speech rate and exaggerated linguistic stress. Importantly, exaggerated linguistic stress increased sentence comprehension independent of speech rate (Lasky et al., 1976; Pashek & Brookshire, 1982).

The previously established relationship between exaggerated linguistic stress and sentence comprehension suggests that a similar relationship may exist between our sentence prosody manipulation and sentence comprehension in persons with aphasia and chronic stroke. Our sentence prosody condition contained pitch inflections and prosodic boundaries to accentuate important sentential information. After a stroke, the strategic placement of pitch inflections and prosodic boundaries in the sentence prosody conditions may result in increased sentence comprehension as the prosodic cues can be used by unimpaired attentional control resources to direct the patient's attention to important sentential information (e.g., Patient 2).

Alternatively, our list prosody manipulation may facilitate sentence comprehension in aphasia through temporal expectancy. Previous research indicates that temporal expectancy can be created through rhythmic cueing prior to the stimulus, which subsequently improves speech comprehension (Cason & Schön, 2012). Temporal expectancy may also be embedded within the speech stimulus itself: the list prosody manipulation contained equal emphasis and stress on each word, creating regular intervals. Temporal expectancy may facilitate comprehension in patients with aphasia by helping them to chunk words/phrases into smaller, more manageable units, that can be maintained by unimpaired working memory resources, particularly when attentional control is diminished and thus typical prosodic information cannot be utilized as attentional cues (e.g., Patient 1).

List prosody, compared to sentence prosody, may also be facilitating sentence comprehension in select persons with aphasia due to its longer duration. Previous studies demonstrate that syntactic knowledge is preserved in persons with aphasia (Linebarger et al., 1983; Wulfeck, 1988), and that sentence comprehension impairments in aphasia actually stem, at least partially, from timing deficits (Patil, Hanne, Burchert, Bleser, & Vasishth, 2015; Mätzig, Vasishth, Engelmann, Caplan, & Burchert, 2018). Specifically, persons with aphasia demonstrate difficulty appropriately timing the simultaneous activation of language processes (e.g., lexical, semantic, and syntactic information, etc.) needed for correct sentence parsing and a mismatch in the timing of activation across these various language processes may result in a breakdown in syntactic comprehension (Love, Swinney, Walenski, & Zurif, 2008). The slower duration of list prosody may therefore be mitigating these timing inconsistencies across language processes, thus improving comprehension. Importantly, timing deficits in persons with aphasia have been linked to auditory working memory deficits (Zipse, Worek, Guarino, & Shattuck-Hugnagel, 2014), further suggesting that

relatively preserved working memory is necessary for benefiting from list prosody. But, future work is needed to better understand the specific elements of prosody (e.g., pitch, syllable/word duration, loudness, rhythm, stress, timing) that are critical to modulating sentence comprehension in persons with aphasia, particularly as a function of cognitive abilities.

As we consider the findings from Experiment 1, the restricted age and gender demographics of our sample may impact the generalizability of our results. It has been well documented that older adults are on average slower to respond in sentence comprehension tasks, however their comprehension accuracy remains high and comparable to younger adults (Wingfield, Peele, & Grossman, 2003; Tun, Benichov, & Wingfield, 2010; Yoon, Campanelli, Goral, Marton, Eichorn, & Obler, 2015). Males and females have been shown to have comparable auditory comprehension abilities (Rossiter Jr., 1972), but nonetheless should be investigated further because there are known sex differences related to the brain regions recruited for language processing (Baxter et al., 2003; Shaywitz et al., 1995).

For Experiment 2, the heterogeneity of our sample may impact our power to detect statistically significant findings. Similarly, our Pearson correlations should be interpreted with caution as our small sample size may limit the generalizability of the correlation results. To help address these issues within the confines of the present study, we employed single-case statistical tests (Crawford & Garthwaite, 2010; 2007) to determine impairment by comparing each individual patient to the performance of neurotypical controls in each task. We also used single-case methods (BSDT; Crawford et al., 2011) to determine if each patient's relative performance on the sentence prosody and list prosody comprehension tasks is significantly different than what is expected based on the performance of the control group from Experiment 1. The BSDT allowed us to identify three patients for whom the difference between comprehension with the two prosodies was significantly greater than the control group from Experiment 1. Then, for each of the three patients, we compared their impaired/unimpaired status on the working memory and attentional control measures to determine if their performance patterns aligned with our hypotheses regarding list prosody engaging intact working memory resources, and sentence prosody facilitating intact attentional control resources. The three patients' performance patterns across the sentence comprehension and cognitive tasks supported our hypotheses. But, we could not determine if each patient's difference in performance between the working memory and attentional control measures was significantly different than that of the control group (i.e., we could not calculate the same single-case difference score statistic we used to test the difference between the two prosody conditions), which would have been a stronger test of our hypotheses. Using the BSDT to determine performance differences between working memory and attentional control was not possible since the BSDT requires the same control sample for the two tests being compared; our working memory control data was based on published norms of the *WAIS-IV*, while the attentional control measure was collected in 41 neurotypical controls from another study in our laboratory. Therefore, future work is needed to further explore this relationship in a larger sample of stroke patients and one well-matched control group that complete all of the cognitive measures of interest. Nonetheless, Experiment 2's correlations and single-case approaches suggest that the role of prosody in

facilitating the engagement of specific intact cognitive resources to improve sentence comprehension is worthy of future study in stroke patients.

In conclusion, the present study investigated how prosodic cues facilitate sentence comprehension. Our results in control subjects indicate that typical prosodic cues facilitate the comprehension of at least some canonical and non-canonical sentences. In seven chronic stroke patients, our results suggest a relationship between unimpaired cognitive resources and effects of prosody on comprehension of non-canonical sentences. Our findings provide insight into some of the possible mechanisms contributing to the sentence comprehension deficits observed in aphasia and how linguistic prosody may be manipulated to aid comprehension post-stroke.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- Baayen RH, & Milin P (2010). Analyzing reaction times. *International Journal of Psychological Research*, 3(2), 12–28.
- Baddeley A (2010). Working memory. *Current Biology*, 20(4), R136–R140. [PubMed: 20178752]
- Baxter LC, Saykin AJ, Flashman LA, Johnson SC, Guerin SJ, Babcock DR, & Wishart HA (2003). Sex differences in semantic language processing: a functional MRI study. *Brain and Language*, 84(2), 264–272. [PubMed: 12590915]
- Beach CM (1991). The interpretation of prosodic patterns at points of syntactic structure ambiguity: Evidence for cue trading relations. *Journal of Memory and Language*, 30(6), 644–663.
- Bever TG, & McElree B (1988). Empty categories access their antecedents during comprehension. *Linguistic Inquiry*, 19(1), 35–43.
- Broadbent DE (1975). The magic number seven after fifteen years. *Studies in long term memory*, 3–18.
- Brookshire RH, & Nicholas LE (1980). Verification of active and passive sentences by aphasic and nonaphasic subjects. *Journal of Speech, Language, and Hearing Research*, 23(4), 878–893.
- Bryan KL (1989). Language prosody and the right hemisphere. *Aphasiology*, 3(4), 285–299.
- Cabeza R, Daselaar SM, Dolcos F, Prince SE, Budde M, & Nyberg L (2004). Task-independent and Task-specific Age Effects on Brain Activity during Working Memory, Visual Attention and Episodic Retrieval. *Cerebral Cortex*, 14(4), 364–375. [PubMed: 15028641]
- Capitani E, Laiacona M, Barbarotto R, & Cossa FM (1999). How Can We Evaluate Interference in Attentional Tests? A Study Based on Bi-Variate Non-Parametric Tolerance Limits. *Journal of Clinical and Experimental Neuropsychology*, 21(2), 216–228. [PubMed: 10425518]
- Caplan D, DeDe G, Waters G, Michaud J, & Tripodis Y (2011). Effects of age, speed of processing, and working memory on comprehension of sentences with relative clauses. *Psychology and Aging*, 26(2), 439–450. [PubMed: 21480714]
- Caplan D, Michaud J, & Hufford R (2013). Short-term memory, working memory, and syntactic comprehension in aphasia. *Cognitive Neuropsychology*, 30(2), 77–109. [PubMed: 23865692]
- Caplan D, & Waters G (2013). Memory mechanisms supporting syntactic comprehension. *Psychonomic Bulletin & Review*, 20(2), 243–268. [PubMed: 23319178]

- Caplan D, & Waters GS (1999). Verbal working memory and sentence comprehension. *Behavioral and Brain Sciences*, 22(01), 77–94. [PubMed: 11301522]
- Caramazza A, and Zurif EB (1976). Dissociation of algorithmic and heuristic processes in language comprehension: evidence from aphasia. *Brain Lang.* 3, 572–582. [PubMed: 974731]
- Carlson K (2009). How prosody influences sentence comprehension. *Language and Linguistics Compass*, 3(5), 1188–1200.
- Cason N, & Schön D (2012). Rhythmic priming enhances the phonological processing of speech. *Neuropsychologia*, 50(11), 2652–2658. [PubMed: 22828660]
- Caspari I, Parkinson SR, LaPointe LL, & Katz RC (1998). Working Memory and Aphasia. *Brain and Cognition*, 37(2), 205–223. [PubMed: 9665743]
- Christensen SC, Wright HH, & Ratiu I (2018). Working memory in aphasia: Peeling the onion. *Journal of Neurolinguistics*.
- Cohen H, Douaire J, & Elsabbagh M (2001). The role of prosody in discourse processing. *Brain and cognition*, 46(1–2), 73–82. [PubMed: 11527368]
- Corbett AT, & Chang FR (1983). Pronoun disambiguation: Accessing potential antecedents. *Memory & Cognition*, 11(3), 283–294. [PubMed: 6621344]
- Cowan N (2001). The magic number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, 24, 87–185. [PubMed: 11515286]
- Cowan N, Elliott EM, Saults JS, Morey CC, Mattox S, Hismjatullina A, & Conway AR (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, 51(1), 42–100. [PubMed: 16039935]
- Crawford JR & Garthwaite PH (2007). Comparison of a single case to a control or normative sample in neuropsychology: Development of a Bayesian approach. *Cognitive Neuropsychology*, 24(4), 343–372. [PubMed: 18416496]
- Crawford JR, Garthwaite PH, & Howell DC (2009). On comparing a single case with a control sample: An alternative perspective. *Neuropsychologia*, 47(13), 2690–2695. [PubMed: 19383506]
- Crawford JR, Garthwaite PH, & Porter S (2010). Point and interval estimates of effect sizes for the case-controls design in neuropsychology: Rationale, methods, implementations, and proposed reporting standards. *Cognitive Neuropsychology*, 27(3), 245–260. [PubMed: 20936548]
- Crawford JR, Garthwaite PH, and Ryan K (2011). Comparing a single case to a control sample: Testing for neuropsychological deficits and dissociations in the presence of covariates. *Cortex*, 47(10), 1166–1178. [PubMed: 21458788]
- Dahan D, Tanenhaus MK, & Chambers CG (2002). Accent and reference resolution in spoken-language comprehension. *Journal of Memory and Language*, 47(2), 292–314.
- Danly M, & Shapiro B (1982). Speech prosody in Broca's aphasia. *Brain and Language*, 16(2), 171–190. [PubMed: 7116126]
- Dronkers NF, Wilkins DP, Van Valin RD Jr, Redfern BB, & Jaeger JJ (2004). Lesion analysis of the brain areas involved in language comprehension. *Cognition*, 92(1–2), 145–177. [PubMed: 15037129]
- Ferreira F (2003). The misinterpretation of noncanonical sentences. *Cognitive Psychology*, 47(2), 164–203. [PubMed: 12948517]
- Frazier L, Carlson K, & Clifton C (2006). Prosodic phrasing is central to language comprehension. *Trends in cognitive sciences*, 10(6), 244–249. [PubMed: 16651019]
- Friederici AD (2011). The brain basis of language processing: from structure to function. *Physiological Reviews*, 91(4), 1357–1392. [PubMed: 22013214]
- Gazzaley A, & Nobre AC (2012). Top-down modulation: Bridging selective attention and working memory. *Trends in Cognitive Sciences*, 16(2), 129–135. [PubMed: 22209601]
- Gläscher J, Tranel D, Paul LK, Rudrauf D, Rorden C, Hornaday A, ... Adolphs R (2009). Lesion Mapping of Cognitive Abilities Linked to Intelligence. *Neuron*, 61(5), 681–691. [PubMed: 19285465]
- Gibson E (1998). Linguistic complexity: Locality of syntactic dependencies. *Cognition*, 68(1), 1–76. [PubMed: 9775516]

- Gilbert AC, Boucher VJ, & Jemel B (2014). Perceptual chunking and its effect on memory in speech processing: ERP and behavioral evidence. *Frontiers in Psychology*, 5.
- Goodglass H, & Jerrold J (1960). Agrammatism and inflectional morphology in English. *Journal of Speech & Hearing Research*, 3, 257–267. [PubMed: 13851047]
- Haarmann HJ, & Kolk HH (1991). Syntactic priming in Broca's aphasics: Evidence for slow activation. *Aphasiology*, 5(3), 247–263.
- Haarmann HJ, Just MA, & Carpenter PA (1997). Aphasic sentence comprehension as a resource deficit: A computational approach. *Brain and language*, 59(1), 76–120. [PubMed: 9262852]
- Heilman KM, Bowers D, Speedie L, & Coslett HB (1984). Comprehension of affective and nonaffective prosody. *Neurology*, 34(7), 917–917. [PubMed: 6539867]
- Hickok G, & Poeppel D (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, 8(5), 393. [PubMed: 17431404]
- Ito K, & Speer SR (2008). Anticipatory effects of intonation: Eye movements during instructed visual search. *Journal of memory and language*, 58(2), 541–573. [PubMed: 19190719]
- Just MA, & Carpenter PA (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological review*, 99(1), 122. [PubMed: 1546114]
- Kane MJ, Bleckley MK, Conway ARA, & Engle RW (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, 130(2), 169–183. [PubMed: 11409097]
- Kean ML (1977). The linguistic interpretation of aphasic syndromes: Agrammatism in Broca's aphasia, an example. *Cognition*, 5(1), 9–46.
- King J, & Just MA (1991). Individual differences in syntactic processing: The role of working memory. *Journal of memory and language*, 30(5), 580–602.
- Kjelgaard MM, & Speer SR (1999). Prosodic facilitation and interference in the resolution of temporary syntactic closure ambiguity. *Journal of Memory and Language*, 40(2), 153–194.
- Kreitewolf J, Friederici AD, & von Kriegstein K (2014). Hemispheric lateralization of linguistic prosody recognition in comparison to speech and speaker recognition. *Neuroimage*, 102, 332–344. [PubMed: 25087482]
- Lasky EZ, Weidner WE, & Johnson JP (1976). Influence of linguistic complexity, rate of presentation, and interphrase pause time on auditory-verbal comprehension of adult aphasic patients. *Brain and Language*, 3(3), 386–395. [PubMed: 949592]
- Lachaud CM, & Renaud O (2011). A tutorial for analyzing human reaction times: How to filter data, manage missing values, and choose a statistical model. *Applied Psycholinguistics*, 32(2), 389–416.
- Lehiste I (1973). Phonetic disambiguation of syntactic ambiguity. *The Journal of the Acoustical Society of America*, 53(1), 380–380.
- Linebarger MC, Schwartz MF, & Saffran EM (1983). Sensitivity to grammatical structure in so-called agrammatic aphasics. *Cognition*, 13(3), 361–392. [PubMed: 6683142]
- Love T, Swinney D, Walenski M, & Zurif E (2008). How left inferior frontal cortex participates in syntactic processing: Evidence from aphasia. *Brain and Language*, 107(3), 203–219. [PubMed: 18158179]
- MacLeod CM (1991). Half a century of research on the Stroop effect: an integrative review. *Psychological Bulletin*, 109(2), 163. [PubMed: 2034749]
- Magnusdottir S, Fillmore P, den Ouden DB, Hjaltason H, Rorden C, Kjartansson O, ... Fridriksson J (2013). Damage to left anterior temporal cortex predicts impairment of complex syntactic processing: A lesion-symptom mapping study: ATL Damage Impairs Complex Syntax Processing. *Human Brain Mapping*, 34(10), 2715–2723. [PubMed: 22522937]
- Mätzig P, Vasishth S, Engelmann F, Caplan D, & Burchert F (2018). A computational investigation of sources of variability in sentence comprehension difficulty in aphasia. *Topics in Cognitive Science*, 10(1), 161–174. [PubMed: 29356427]
- Mellon L, Brewer L, Hall P, Horgan F, Williams D, & Hickey A (2015). Cognitive impairment six months after ischaemic stroke: a profile from the ASPIRE-S study. *BMC Neurology*, 15(1), 31. [PubMed: 25879880]

- Pashek GV, & Brookshire RH (1982). Effects of rate of speech and linguistic stress on auditory paragraph comprehension of aphasic individuals. *Journal of Speech, Language, and Hearing Research*, 25(3), 377–383.
- Patil U, Hanne S, Burchert F, De Bleser R, & Vasishth S (2016). A computational evaluation of sentence processing deficits in aphasia. *Cognitive Science*, 40(1), 5–50. [PubMed: 26016698]
- Peers PV, Astle DE, Duncan J, Murphy FC, Hampshire A, Das T, & Manly T (2018). Dissociable effects of attention vs working memory training on cognitive performance and everyday functioning following fronto-parietal strokes. *Neuropsychological Rehabilitation*, 1–23.
- Pell MD, & Baum SR (1997). Unilateral brain damage, prosodic comprehension deficits, and the acoustic cues to prosody. *Brain and Language*, 57(2), 195–214. [PubMed: 9126413]
- Perkins JM, Baran JA, & Gandour J (1996). Hemispheric specialization in processing intonation contours. *Aphasiology*, 10(4), 343–362.
- Pillay SB, Binder JR, Humphries C, Gross WL, & Book DS (2017). Lesion localization of speech comprehension deficits in chronic aphasia. *Neurology*, 88(10), 970–975. [PubMed: 28179469]
- Price PJ, Ostendorf M, Shattuck-Hufnagel S, & Fong C (1991). The use of prosody in syntactic disambiguation. *The Journal of the Acoustical Society of America*, 90(6), 2956–2970. [PubMed: 1787237]
- Ratcliff R (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin*, 114(3), 510. [PubMed: 8272468]
- Richter KM, Mödden C, Hanken K, & Hildebrandt H (2015). Recovery after brain damage: Is there any indication for generalization between different cognitive functions? *Journal of Clinical and Experimental Neuropsychology*, 37(6), 571–580. [PubMed: 26059257]
- Rogalsky C, Almeida D, Sprouse J, & Hickok G (2015). Sentence processing selectivity in Broca's area: evident for structure but not syntactic movement. *Language, Cognition and Neuroscience*, 30(10), 1326–1338.
- Rogalsky C, LaCroix AN, Chen KH, Anderson SW, Damasio H, Love T, & Hickok G (2018). The neurobiology of agrammatic sentence comprehension: a lesion study. *Journal of Cognitive Neuroscience*, 30(2), 234–255. [PubMed: 29064339]
- Roncaglia-Denissen MP, Schmidt-Kassow M, & Kotz SA (2013). Speech rhythm facilitates syntactic ambiguity resolution: ERP evidence. *PloS one*, 8(2), e56000. [PubMed: 23409109]
- Rossiter CM Jr. (1972). Sex of the speaker, sex of the listener, and listening comprehension. *The Journal of Communication*, 22(1), 64–69.
- Santi A, & Grodzinsky Y (2007). Working memory and syntax interact in Broca's area. *NeuroImage*, 37(1), 8–17 [PubMed: 17560794]
- Schafer AJ (1997). Prosodic parsing: The role of prosody in sentence comprehension (Doctoral dissertation, University of Massachusetts Amherst).
- Shaywitz BA, Shaywitz SE, Pugh KR, Constable RT, Skudlarski P, Fulbright RK, ... & Gore JC (1995). Sex differences in the functional organization of the brain for language. *Nature*, 373(6515), 607. [PubMed: 7854416]
- Speer SR, Kjelgaard MM, & Dobroth KM (1996). The influence of prosodic structure on the resolution of temporary syntactic closure ambiguities. *Journal of psycholinguistic research*, 25(2), 249–271. [PubMed: 8667298]
- Thothathiri M, Kimberg DY, & Schwartz MF (2012). The neural basis of reversible sentence comprehension: evidence from voxel-based lesion symptom mapping in aphasia. *Journal of Cognitive Neuroscience*, 24(1), 212–222. [PubMed: 21861679]
- Tun PA, Benichov J, & Wingfield A (2010). Response latencies in auditory sentence comprehension: effects of linguistic versus perceptual challenge. *Psychology and Aging*, 25(3), 730. [PubMed: 20853977]
- Wallis G, Stokes M, Cousijn H, Woolrich M, & Nobre AC (2015). Frontoparietal and Cingulo-opercular Networks Play Dissociable Roles in Control of Working Memory. *Journal of Cognitive Neuroscience*, 27(10), 2019–2034. [PubMed: 26042457]
- Weber A, Braun B, & Crocker MW (2006). Finding referents in time: Eye-tracking evidence for the role of contrastive accents. *Language and Speech*, 49(3), 367–392. [PubMed: 17225671]

- Weintraub S, Mesulam MM, & Kramer L (1981). Disturbances in prosody: A right-hemisphere contribution to language. *Archives of Neurology*, 38(12), 742–744. [PubMed: 7316838]
- Wilson SM, Dronkers NF, Ogar JM, Jang J, Growdon ME, Agosta F, ... & Gorno-Tempini ML (2010). Neural correlates of syntactic processing in the nonfluent variant of primary progressive aphasia. *The Journal of Neuroscience*, 30(50), 16845–16854. [PubMed: 21159955]
- Wingfield A, Peelle JE, & Grossman M (2003). Speech rate and syntactic complexity as multiplicative factors in speech comprehension by young and older adults. *Aging, Neuropsychology, and Cognition*, 10(4), 310–322.
- Wulfeck BB (1988). Grammaticality judgments and sentence comprehension in agrammatic aphasia. *Journal of Speech, Language, and Hearing Research*, 31(1), 72–81.
- Yoon J, Campanelli L, Goral M, Marton K, Eichorn N, & Obler LK (2015). The effect of plausibility on sentence comprehension among older adults and its relation to cognitive functions. *Experimental Aging Research*, 41(3), 272–302. [PubMed: 25978447]
- Zheng X, & Pierrehumbert JB (2010). The effects of prosodic prominence and serial position on duration perception a. *The Journal of the Acoustical Society of America*, 128(2), 851–859. [PubMed: 20707454]
- Zipse L, Worek A, Guarino AJ, & Shattuck-Hufnagel S (2014). Tapped out: do people with aphasia have rhythm processing deficits?. *Journal of Speech, Language, and Hearing Research*, 57(6), 2234–2245.
- Zurif E, Swinney D, Prather P, Solomon J, & Bushell C (1993). An on-line analysis of syntactic processing in Broca's and Wernicke's aphasia. *Brain and language*, 45(3), 448–464. [PubMed: 8269334]

Figure 1.

(A) Mean accuracies (proportion correct) and (B) reaction times (milliseconds) of control subjects for sentence structure collapsed across prosody. Error bars show SEM. The dashed line separates the two canonical sentence types from the two non-canonical sentence types. All conditions significantly differ from each other at $p < .0125$, Bonferroni corrected.

Figure 2.

Graph depicting the interaction of the effects of sentence structure and prosody on reaction time (milliseconds) across the four sentence types, in control subjects. Error bars show SEM.

Figure 3.

Scatterplots for working memory (left column) and attentional control (right column) with comprehension of non-canonical sentences (NC1) with sentence prosody (top row) and list prosody (bottom row) in chronic stroke patients.

Figure 4.

(A) Working memory performance, (B) Attentional control performance, and (C) NC1 sentence comprehension in two chronic stroke patients. For working memory, sentence prosody, and list prosody, negative z-scores reflect worse performance than the control sample. For attentional control, positive z-scores reflect worse performance compared to the control sample.

Table 1.

Sentence stimuli.

Sentence Structure*	Example	Syntactic Parsing	Sentence Prosody Duration	List Prosody Duration
C1	The boy who is red is kissing the girl.	Subject-verb-object word order. Active modifying clause can only be attached to the subject.	3.81–4.35 seconds ($M=4.07$, $sd=.13$)	4.52–4.79 seconds ($M=4.68$, $sd=.08$).
C2	The boy is kissing the girl who is red.	Subject-verb-object word order. Active modifying clause can be attached to either the subject or object; correct parsing leads to attachment of modifying clause to the object.	3.81–4.35 seconds ($M=4.07$, $sd=.13$)	4.52–4.79 seconds ($M=4.68$, $sd=.08$).
NC1	The girl who the boy is kissing is red.	Subject-object-verb word order. Active modifying clause can be attached to either the subject or object; correct parsing leads to attachment of modifying clause to the subject.	3.88–4.73 seconds ($M=4.29$, $sd=.15$)	4.53–4.80 seconds ($M=4.72$, $sd=.07$).
NC2	The boy who the girl is kissed by is red.	Subject-object-verb word order. Passive modifying clause can be attached to either the subject or object; correct parsing leads to attachment of modifying clause to the subject.	3.88–4.73 seconds ($M=4.29$, $sd=.15$)	4.53–4.80 seconds ($M=4.72$, $sd=.07$).
Short Canonical	The boy is kissing the girl.	Subject-verb-object word order with no modifying clause.	2.54–2.95 seconds ($M=2.71$, $sd=.12$)	2.81–3.19 seconds ($M=2.97$, $sd=.12$).
Short Non-Canonical	The boy is kissed by the girl	Subject-object-verb word order with no modifying clause.	2.67–2.98 seconds ($M=2.86$, $sd=.08$)	3.06–3.42 seconds ($M=3.27$, $sd=.12$).

* C1 and C2 correspond to the two types of sentences within Wilson et al.'s (2010) "long easy" sentences. NC1 and NC2 correspond to Wilson et al.'s (2010) "long medium" and "long hard" sentences, respectively. The short canonical and short non-canonical sentences correspond to Wilson et al.'s (2010) short active and short passive conditions.

Table 2.

Simple effects for reaction time for each sentence structure compared across prosody.

Contrast	<i>t</i>	df	<i>p</i>
C1 List Prosody > C1 Sentence Prosody	0.52	31	.61
C2 List Prosody > C2 Sentence Prosody	3.61	31	.001 *
NC1 List Prosody > NC1 Sentence Prosody	2.81	31	.009 *
NC2 List Prosody > NC2 Sentence Prosody	0.14	31	.89

* Statistically significant, Bonferroni corrected at $p < .0125$

Table 3.

Stroke patient demographics.

	Gender	Age	Years Post Stroke	BDAE Aphasia Severity Score	Aphasia Diagnosis	Lesion Location*
Patient 1	Female	75	15	3	Broca's	FTP
Patient 2	Male	36	11	3	Broca's	FTP
Patient 3	Male	78	1	5	none	medial F
Patient 4	Female	46	7	4	Broca's	F
Patient 5	Male	58	9	1	Broca's	FTPO
Patient 6	Male	78	5	5	none	LH**
Patient 7	Female	41	10 mos.	3	Broca's	F

* LH = left hemisphere; F = frontal; T = temporal; P = parietal; O = occipital

** Clinical evaluation indicates LH damage; however, patient has a pacemaker incompatible with MRI.

Table 4.

Standard scores (i.e., point estimates of effect sizes) from the single-case Bayesian hypothesis tests and Bayesian Standardized Difference Tests (BSDT); the p -value corresponding to each Bayesian test is reported in parentheses. Please refer to the Supplemental Materials for additional reporting of these results, including control group statistics, as well as patient raw scores, t -values, and credible intervals.

	Working Memory	Attentional Control	Accuracy: sentence prosody	Accuracy: list prosody	Difference between sentence & list prosody
Patient 1	-1.7 (.09)	2.0 (.05)	-3.7 (<.001)	-1.9 (.06)	-2.8 (.02)
Patient 2	-2.3 (.02)	-0.7 (.5)	-0.4 (.7)	-2.7 (.01)	3.8 (<.001)
Patient 3	0.7 (.5)	2.2 (.03)	0.3 (.8)	0.8 (.40)	-1.0 (.3)
Patient 4	-1.1 (.3)	1.6 (.10)	0.3 (.8)	-1.9 (.06)	3.7 (<.001)
Patient 5	-2.8 (.006)	9.1 (<.001)	-2.4 (.02)	-2.7 (.01)	0.5 (.6)
Patient 6	1.9 (.06)	0.8 (.4)	0.9 (.4)	0.9 (.4)	0.1 (.9)
Patient 7	-2.5 (.01)	6.2 (<.001)	-1.1 (.30)	-0.6 (0.6)	-0.8 (.4)

* Bold font indicates a significant impairment (or difference) compared to neurotypical controls, $p < .05$.

*** For working memory, sentence prosody, and list prosody, negative z-scores reflect worse performance than the norming sample. For attentional control, positive z-scores reflect worse performance than the norming sample.