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Dividing attention influences contextual facilitation and revision during language comprehension

Ryan J. Hubbard[1], **Kara D. Federmeier**[1,2,3]

[1]Beckman Institute for Advanced Science and Technology, University of Illinois Urbana-Champaign, USA

[2]Department of Psychology, University of Illinois Urbana-Champaign, USA

[3]Program in Neuroscience, University of Illinois Urbana-Champaign, USA

Abstract

Although we often seem to successfully comprehend language in the face of distraction, few studies have examined the role of sustained attention in critical components of sentence processing, such as integrating information over a sentence and revising predictions when unexpected information is encountered. The current study investigated the impact of attention on sentence processing using a novel dual-task paradigm. Participants read weakly and strongly constraining sentences with expected or unexpected endings while also tracking the motion of dots in the background, and their EEG was recorded. Under full attention, the amplitude of the N400 component of the ERP, a measure of semantic access, was reduced (facilitated) in a graded fashion by contextual strength and fit. This context-based facilitation was attenuated when attention was divided, suggesting that sustained attention is important for building up message-level representations. In contrast, the post-N400 frontal positivity that has been observed to prediction violations and associated with revision processes was unaffected by dividing attention. However, under divided attention, participants also elicited posteriorly-distributed effects to these violations. Thus, predictive processes seem to be engaged even when attention is divided, but additional resources may then be required to process unexpected information.

Introduction

Humans use their unique language capabilities to take in spoken, signed, or written information rapidly and in a manner that often feels relatively effortless. This effortless comprehension can readily be observed in everyday life, as, for example, when people

Corresponding author: Ryan J. Hubbard, rjhubba2@illinois.edu.
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read articles and messages on their phones amid a barrage of distracting auditory and visual background information. Some models of language processing have posited that word recognition and lexical access are automatic processes – i.e., that they required no attention to perform (Coltheart, Rastle, Perry et al., 2001; LaBerge & Samuels, 1974; Morton, 1969; Seidenberg & McClelland, 1989) – suggesting that understanding a single word may be entirely unimpaired even in the midst of distractions. However, listening to a conversation or reading a sentence requires recruitment of additional mechanisms beyond single word processing, and those more complex mechanisms that are engaged in order to integrate meaning across a sentence and create and update the situational model (Smallwood, 2011) may rely on attentional resources. For instance, comprehenders can use context information to generate predictions about features of likely upcoming words (Federmeier, 2007), yet this predictive processing is thought to require metabolic and cognitive resources (Kuperberg & Jaeger, 2015) and is not always engaged (Wlotko & Federmeier, 2015), suggesting top-down resources must be allocated. Although some studies have investigated how dividing attention influences word processing, very few have examined the role of attention in sentence comprehension, and how the processing mechanisms involved at that level may be affected. This question not only has theoretical importance, but also real-world applications; the same people reading on their phone who appear unaffected by distraction may in fact have impaired comprehension.

Effects of Attention on Word Processing

Behavioral work examining the role of attention in comprehending language has primarily focused on the processing of single words (e.g., lexical decision tasks) or word pairs (e.g., priming paradigms). One subset of this literature specifically examined the relationship between visual word recognition and spatial selective attention using spatial cuing manipulations, in which target words to be read were presented at cued or uncued spatial locations. Some of these studies have supported claims that word processing can be done outside the focus of attention, in showing evidence that the Stroop effect obtains even for target words at uncued locations (Brown, Gore, & Carr, 2002; Brown, Joneleit, Robinson et al., 2002; Lachter, Ruthruff, Lien et al., 2008). Other studies, however, have found marked increases in lexical decision times and reductions in priming for target words at uncued locations (Besner, Risko, & Sklair, 2005; Lachter, Forster, & Ruthruff, 2004; McCann, Folk, & Johnston, 1992; Robidoux & Besner, 2015; Stolz & McCann, 2000), suggesting an impact of selective attention on lexical processing.

Spatial selective attention is but one form of attention, and other studies have examined how lexical processing is affected when a word is presented in an attended location but with reduced attentional resources. An often-used method for examining the attentional mechanisms recruited by a particular cognitive process is the dual-task paradigm, in which participants must perform two tasks concomitantly (Pashler, 1994). Cognitive processes are assumed to share resources when performance (usually response time; RT) is impaired during dual task vs. single task performance (Schneider & Shiffrin, 1977). Many studies examining the role of attention during visual word recognition have used dual-task paradigms, primarily in the form of a lexical decision task along with a distractor task or secondary task (Allen, Ching, Murphy et al., 2002; Becker, 1973; Cleland, Gaskell, Quinlan et al., 2006; Kellas, Ferraro, & Simpson, 1988; Lien, Allen, Ruthruff et al., 2006; McCann, Remington, & Van Selst, 2000; Rabovsky, ÁAlvarez, Hohlfeld et al., 2008). These studies have yielded mixed results. For instance, some aspects of lexical processing, such as word frequency-sensitive processes, may operate automatically (Cleland et al., 2006), and automaticity of lexical processing may increase with age (Lien et al., 2006). Other studies, however, have found that lexical decision and naming latencies for words are increased when attention is divided (McCann et al., 2000; Rabovsky et al., 2008), suggesting that reducing attention can impact some of the processes involved in comprehending language stimuli. However, it remains unclear from these results which stages of processing are impacted, as effects at multiple timepoints could result in the observed behavioral patterns.

Key to understanding what role attention might play in comprehension is gaining a clearer understanding of how processing unfolds differently under different attentional states. Measurements of event-related potentials (ERPs) are a particularly powerful tool for assessing this, as they permit the characterization of processing over time and reveal effects on components linked to specific cognitive and neurophysiological mechanisms (Luck, 2014). For instance, reading a word elicits an N400, a centroparietal negativity peaking around 400 ms, which has been associated with access to semantic memory (Kutas & Federmeier, 2011). The amplitude of the N400 varies with a wide variety of factors that influence how much new semantic information is becoming active when a stimulus is encountered, including orthographic/phonological neighborhood size (Laszlo & Federmeier, 2011), word frequency (Van Petten & Kutas, 1990), repetition (Rugg, 1990), and task goals (Fischer-Baum, Dickson, & Federmeier, 2014); in all cases, N400 amplitudes are smaller when less new information is activated. Correspondingly, the N400 decreases for words following semantic primes (Holcomb, 1993), as well as across words of a congruent sentence (Payne, Lee & Federmeier, 2015; Van Petten & Kutas, 1990), and, at any given point in a sentence, the N400 is graded by how predictable a word is in its context, as measured by cloze probability (Federmeier, Wlotko, De Ochoa-Dewald et al., 2007; Federmeier & Kutas, 1999; Wlotko & Federmeier, 2012). Thus, the N400 reflects a snapshot of semantic processing of a given stimulus, and the amplitude of the N400 can serve as an index of the ease of semantic access, which is increased when a word is primed or is subject to facilitation from accumulating sentence-level context information.

Examining differences in N400 amplitudes elicited by words under conditions of full and divided attention has elucidated how attention specifically impacts semantic access. For example, Luck, Vogel & Shapiro (1996) presented participants with prime-target word pairs that were semantically related or unrelated, and the target word was sometimes presented during an attentional blink, a period in which attentional resources are reduced (Raymond, Shapiro & Arnell, 1992). Target words presented during the attentional blink were notably less likely to be reported, attesting to the impact of reduced attention on processes important for explicit aspects of word processing. However, N400 priming effects onto the target word were equivalent during the attentional blink as during non-blink presentations. Additionally, this preservation of N400 facilitation was also observed when the prime word appeared during the attentional blink (Rolke, Heil, Streb et al., 2001). Finally, preserved N400 priming effects (in the auditory modality) have even been found during some stages of sleep, where little explicit attentional control is expected (Ibáñez, López & Cornejo, 2006). Results like these have been taken to indicate that access to semantic memory may be relatively automatic.

However, other types of attentional manipulations have been found to impact semantic access as indexed by the N400. Zhang & Zhang (2007) combined a priming study with an inhibition of return manipulation, in which cueing a spatial location but delaying stimulus presentation at the cued location leads to attentional inhibition to the cued location (Klein, 2000). Here, N400 facilitation effects were reduced when the second word in the pair was presented at the cued location that was attentionally inhibited, although behavioral priming effects were not reduced. N400 facilitation was also been found to be reduced when prime words were presented at unattended vs. attended locations (McCarthy & Nobre, 1993) or for words that were presented in an unattended color (Czigler & Géczy, 1996). Similarly, N400 priming effects for auditory words were found to be reduced when word pairs were presented while participants attended to a silent movie compared to when they attended only to the word pairs (Relander, Rämä, & Kujala, 2009). Finally, other studies utilizing the attentional blink paradigm have reported reduced or abolished semantic facilitation on the N400 when the target word presented during the blink period was unable to be reported by the participant (Batterink, Karns, Yamada et al., 2010; Pesciarelli, Kutas, Dell'Acqua et al., 2007), suggesting that some aspects of semantic processing may be automatically engaged when attentional resources are limited, but are modulated or terminated under conditions of reduced awareness of stimuli. Taken together, the results of both behavioral and ERP studies thus suggest a complex relationship between attention and word processing, in which the specific type of attentional manipulation and level of participant awareness matters.

Effects of Attention on Sentence Processing

Some aspects of word processing may be relatively automatic, but comprehending a sentence necessarily involves more than just accessing word-related information, as word information must be integrated to form a message-level representation, which, in some cases, can also be used to make predictions about likely upcoming concepts and words. Moreover, incoming information may induce the need for comprehenders to revise their unfolding expectations and/or interpretation. As such, sustaining attention over time may be particularly important for comprehending longer strings of linguistic information, and a shift or lapse in attention at certain points in the sentence could impact the online construction of sentence meaning, leading to greater impacts on sentence processing compared to single word processing.

Compared to work on attention and single word processing, fewer studies have investigated the relationship between attention and sentence comprehension. One area of research has examined this relationship with visual masking paradigms, in which each word in a sentence that is read is briefly presented and then followed by a visual mask that reduces awareness of the presented stimulus, or with subliminal presentation, in which sentences are presented at very low contrast, making perception of the sentence difficult. Behavioral results examining response times to probes following such sentences have been mixed, with some studies suggesting preserved multi-word processing without awareness (Armstrong & Dienes, 2014; Sklar, Levy, Goldstein et al., 2012), but others finding that sentence processing was impacted by reduced awareness (Nakamura, Makuuchi, Oga et al., 2018; Rabagliati, Robertson, & Carmel, 2018). When EEG was recorded during sentence masking paradigms, results were more consistent: N400 amplitude differences between congruent and incongruent sentences were reduced or abolished when sentence words were masked (Mongelli, Meijs, van Gaal et al., 2019; Nakamura et al., 2018). Although these studies suggest that processes involved in sentence comprehension require awareness, this differs from a situation in which readers comprehend under full awareness but when their attentional resources are taxed. In one study with a dual task paradigm in which participants were required to respond to a tone with a button press prior to an acceptable or unacceptable sentence target, N400 facilitation for congruent (but low cloze-probability) words was reduced when the tone immediately preceded the target word (Hohlfeld, Martin-Loeches, & Sommer, 2015), suggesting that the availability of attentional resources can affect comprehenders' ability to appreciate the plausibility of an incoming word in the established sentence context. However, attention was only manipulated immediately prior to the target word, a paradigm more similar to single word studies. Few studies have manipulated attention throughout the course of sentence reading to examine its impact on how context-based representations are built over time and how they may be used to make predictions.

Moreover, because the amplitude of the N400 is sensitive to the full range of factors that affect semantic access, basic N400 context effects (e.g., of congruency) do not provide clear evidence about the underlying mechanisms at work, such as whether predictive processing has been engaged. Predictive preactivation can affect semantic access and thus modulate N400 amplitudes. However, the reverse inference does not hold: not all context-based N400 amplitude modulations reflect prediction. For example, in the "related anomaly paradigm" comprehenders encounter anomalous sentence endings that share semantic features with words that might have been predictively preactivated (e.g., "He caught the pass and scored another touchdown. There was nothing he enjoyed more than a good game of *baseball*" where "football" is the expected completion). N400 responses to these related anomalies have been found to be facilitated through predictive mechanisms (e.g., Federmeier & Kutas, 1999), and comprehenders that are less likely to engage prediction, such as older adults and adults with lower literacy, do not show these effects (Federmeier et al., 2002; Ng et al., 2017). Critically, however, these groups still show the basic effect of contextual facilitation (e.g., reduced N400 amplitudes to "football" compared to non-related anomalous endings). Thus, to probe the full range of processes involved in sentence comprehension, including prediction, it is important to examine other aspects of the ERP response to words in sentences.

For example, although N400 amplitudes vary with expectancy, the N400 does not differ between a word that is unexpected because it is in a context with only weak constraint versus a word that is unexpected because a different word was predicted. Instead, such prediction violations, when they are plausible, elicit a post-N400 positivity with a frontally maximal scalp distribution (Brothers, Wlotko, Warnke et al., 2020; DeLong, Quante, & Kutas, 2014; Federmeier et al., 2007; Kuperberg, Brothers, & Wlotko, 2020; Thornhill & Van Petten, 2012)[1]. While the specific mechanism or cognitive process indexed by the frontal positivity remains unclear, it is reliably elicited by prediction violations following a strongly constraining sentence, and thus is likely related to revision or updating processes associated with overcoming an erroneous prediction. Notably, the frontal positivity is not elicited by unexpected endings among older adults (Wlotko, Federmeier & Kutas, 2012) and adults with lower literacy levels (Ng, Payne, Steen et al., 2017) – the same groups that do not show the related anomaly effect discussed above. Thus, measuring the frontal positivity provides an index of whether comprehenders are engaging prediction.

Very few studies have looked at the impact of attention on the frontal positivity. One area of research has examined how processing differs when words in a sentence are read outside of foveal vision – for example, when words are in parafoveal preview (Payne & Federmeier, 2017; Stites, Payne & Federmeier, 2017) or are presented lateralized to the left or right visual field (Wlotko & Federmeier, 2007) – and thus when these words outside of the focus of spatial selective attention. In these studies, words read outside of foveal view produced similar N400 responses as when they were centrally focused; however, the frontal positivity was not elicited by unexpected words outside of foveal vision. Similarly, late posterior ERP responses to syntactic anomalies were also only observed when the unexpected target word was attended to and detected (Batterink & Neville, 2013). One explanation for these results is that attentional resources may be required for these later, revision-related processes to occur, and words outside of foveal vision may receive less attention. If so, post-N400 positivities may be reduced or abolished whenever attentional resources are limited. However, all of the findings thus far involve cases wherein words are outside of spatial selective attention, and there may be a difference in the impact of sustained attention versus attentional resource availability at a selected location.

Few studies have explicitly manipulated sustained attention while participants processed language stimuli. However, one line of research has investigated sustained attention during sentence reading by examining mind wandering, or periods of time in which attentional focus shifts from external task-related information to internal task-unrelated thoughts (Smallwood & Schooler, 2006). In these studies, participants read sentences while their eye-movements were recorded and were instructed to inform the experimenters when they felt that they were “zoning out” (Reichle, Reineberg & Schooler, 2010; Varao-Sousa, Solman, & Kingstone, 2017) or were given probes asking if they were mind wandering (Foulsham, Farley & Kingstone, 2013; Franklin, Broadway, Mrazek et al., 2013). During periods of mind wandering, participants’ reading times were slower and average fixation durations were longer. Additionally, pupil dilations were higher prior to an episode of mind wandering, likely reflecting disengagement from the task (Gilzenrat, Nieuwenhuis, Jepma et al., 2010), and participants were more likely to return and re-read text after mind wandering. These results demonstrate that lapses in sustained attention can influence processing of language information, and this may be as a result of a decoupling of external stimulus processing and internal sentence meaning generation (Smallwood, 2011). However, mind wandering, which is dynamic and self-generated in its nature, potentially differs from sustained attention in the face of external distractions (Smallwood & Schooler, 2015). It

[1]Note that the frontal positivity is distinct from the posterior positivity (often referred to as the P600 or the Late Positive Complex) that is sometimes observed when an implausible or anomalous word is encountered, especially under conditions in which comprehenders need to explicitly judge plausibility (DeLong et al., 2014; Kuperberg et al., 2020). For a review of the difference between these responses, see Van Petten and Luka (2012).

remains unclear whether language comprehension is impaired when attention is persistently divided, and which specific aspects of language comprehension are impacted.

Research on language impairments in clinical populations also suggest a potential role for sustained attention in language comprehension. Children with specific language impairment (SLI) show difficulty with language tasks without associated impairments in hearing or more general neurological damage (Leonard, 2014). Recent evidence suggests that children with SLI also show marked performance impairment on tasks measuring attentional abilities (Helzer, Champlin & Gillam, 1996; Stark & Montgomery, 1995), including sustained attention (Ebert & Kohnert, 2011; Finneran, Francis, Leonard, 2009; Jongman, Roelofs, Scheper et al., 2017). Similarly, adolescents with attention deficit hyperactivity disorder (ADHD), a disorder characterized by dysfunctional attentional systems, also exhibit impaired reading comprehension abilities (Brock & Knapp, 1996). In one study, this deficit in reading comprehension was significantly correlated with an impairment in sustained attention abilities, potentially suggesting shared cognitive resources (Stern & Shalev, 2013). Although these studies highlight the potential link between attention and language comprehension, as well as demonstrate the importance of understanding this link for clinical applications, they are correlational in nature. Thus, a targeted experimental manipulation remains a critical, missing piece to the current understanding of the role of attention in language comprehension.

The Current Study

The aim of the present study was to investigate whether contextual facilitation, prediction, and revision processes, as indexed by the N400 and frontal positivity, are influenced when attentional resources are limited during sentence reading. To test this, a novel dual-task paradigm was implemented in order to allow participants to centrally focus on sentence reading while also engaging their attention in a secondary task. The secondary task involved tracking the direction of moving dots in a random dot kinetogram (RDK), in which there is an array of dots on the screen, the majority of which move in one coherent motion and the others of which move in random motion to create noise (Braddick, 1974; Scase, Braddick & Raymond, 1996). RDKs have been used in several experiments to study visual perception and attention (Andersen & Müller, 2010; Baker & Braddick, 1982; Britten, Shadlen, Newsome et al., 1992; Stirman, Townsend & Smith, 2016), and have even been used in dual-task studies (Motoyoshi, Ishii & Kamachi, 2015). Here, the benefit of the RDK tracking task was that it engaged participants' attention over the entirety of the sentence, allowing for testing of the role of sustained attention in language processing.

To ensure that the RDK would be successful at dividing attention during reading, we first conducted a pilot study in which participants performed a visual oddball task with and without divided attention. In the oddball task, participants responded to low probability target stimuli, which should elicit a large P3b, an ERP component that is linked to stimulus classification (Donchin, 1981; Polich & Kok, 1995) and that is known to be attentionally-dependent. P3b responses are notably reduced in amplitude when attention is divided, as in dual task situations (Isreal, Chesney, Wickens et al., 1980; Wickens, Kramer, Vanasse et al., 1983). The pilot study demonstrated that the RDK task successfully divided attention –

namely, the amplitude of the P300 to target stimuli was reduced during the divided attention oddball task, and reaction times to targets were increased as well (see Supplementary Materials Section 1 for more information). This validated that the RDK tracking task could be used to divide attention during sentence reading. As an additional validation, participants in the sentence reading task also completed an oddball task with and without divided attention to ensure that their P3b amplitudes were reduced in accordance with the pilot results.

In the main experiment, participants read sentences that varied in constraint and ended with expected or unexpected endings, while attention was either full (no RDK tracking) or divided (concurrent RDK tracking). With full attention, the paradigm was a near-replication of Federmeier et al. (2007); namely, participants read strongly constraining sentences with expected (SCE) and unexpected (SCU) endings, as well as weakly constraining sentences with expected (WCE) and unexpected (WCU) endings. Thus, we expected to replicate the ERP patterns observed in that study. In particular, we expected to observe N400s that were graded with cloze probability -- smallest for expected endings in strongly constraining sentences, intermediate for expected endings in weakly constraining sentences, and largest for unexpected endings, irrespective of constraint. We also expected to observe a post-N400 frontal positivity to unexpected words that violate predictions, especially in strongly constraining contexts. The main question of interest was how these ERP patterns would change under divided attention conditions.

Given the previous electrophysiological and behavioral results with single words suggesting that semantic access can take place even under conditions of diminished attention, it is possible that the N400 pattern will be unchanged. However, building and sustaining a message-level representation from a context is clearly more complex than simply accessing information from a single word and may be more dependent on attention. If these processes are impaired, then N400 facilitation to expected endings should be reduced, both in strongly and in weakly constraining sentences. If prediction is particularly susceptible to diminished attention, then, consistent with patterns observed in groups that have reduced ability to predict, including older adults (Wlotko, Federmeier, & Kutas, 2012) and adults with lower literacy levels (Ng et al., 2017), dividing attention should affect N400 amplitudes to expected endings more in weakly than in strongly constraining sentences. Moreover, we would then also expect the frontal positivity (to unexpected endings in strongly constrained contexts) to be reduced or eliminated when attention is divided. Although separating the direct effects of contextual facilitation on the N400 from those mediated by predictive preactivation is difficult, the combined examination of frontal positivity amplitudes and interactions between contextual constraint and attention condition will allow us to better delineate how dividing attention impacts these two separate processes. In the prior literature, there are strong, consistent patterns, such that the interaction is found in precisely the same conditions wherein other indices of prediction (such as the frontal positivity and related anomaly effects) are also diminished/abolished. Thus, the interaction effect is a much more precise metric of how context is being used and, in particular, whether predictive processing has been impacted.

Results

Oddball Experiment

Behavior—Reaction times to target oddballs during the oddball task are plotted in Figure 1A. Reaction times to targets were significantly increased during the divided attention block compared to the full attention block ($t_{(31)} = 15.97$, $p < 0.01$). Thus, the effect of dividing attention that was found in the pilot experiment was successfully replicated.

ERPs—ERPs at channel MiPa time-locked to the onset of standard and target stimuli during the oddball experiment phases are plotted in Figure 1B. A P3b component in response to target stimuli is clearly observed. A repeated measures ANOVA on P3b amplitudes with factors of stimulus type (standard and target) and attention condition (full and divided) revealed significant main effects of stimulus type ($F_{(1,31)} = 185.5$, $p < 0.01$) and attention condition ($F_{(1;31)} = 31.84$, $p < 0.01$), as well as a significant interaction between stimulus type and attention condition ($F_{(1;31)} = 34.54$, $p < 0.01$). A Bayesian Type II ANOVA agreed with this result, with strong evidence for a main effect of stimulus ($BF_{10} = 1.50 \times 10^{24}$), a main effect of condition ($BF_{10} = 3.35 \text{ x } 10^4$), and an interaction ($BF_{10} = 581.8$). The results of the pilot experiment were replicated: Targets elicited larger P3b amplitudes than standards, and the amplitude of the P3b to targets was reduced when attention was divided by the RDK tracking task. This result validated the use of the RDK tracking task to divide attention during reading.

Reading Experiment

Behavior—Dot tracking error during the oddball task and during the sentence reading task are plotted in Figure 2A. Overall, participants showed good performance at the tracking task, and tracking error did not significantly differ between the two tasks, although it was numerically lower during the sentence reading task ($t_{(31)} = 1.95$, $p = 0.06$). This is likely because the oddball task always preceded the sentence reading task, and thus participants had more training with tracking the dots during the sentence reading task. These results suggest that participants attended to the dot tracking task during the sentence reading, and thus had divided attention during comprehension.

Accuracy for the comprehension questions during the sentence reading phase is plotted in Figure 2B. Comprehension question performance was statistically assessed with a mixed logit model (Jaeger, 2008) predicting accuracy, with a fixed effect of attention (Full or Divided), random intercepts for participants and items, and a random slope for attention on participants. The fixed effect of attention was significant; namely, question accuracy was significantly reduced when attention was divided (*Wald's z* = 10.48, $p < 0.01$), although performance was still above chance (Full attention mean accuracy= 0.81, Divided attention mean accuracy = 0.70). This effect of dividing attention likely reflects a combination of impaired comprehension and impaired memory, as the comprehension questions always focused on sentences not immediately preceding the question. Importantly, however, the behavioral results make clear both that participants were dividing their attention while reading but also that they were still devoting resources to the reading task, so that they were able to comprehend and remember the sentences. Removing from data analysis the few participants that were at chance levels of performance during the divided attention reading (n = 5) did not change the pattern of ERP results, and thus all participants were included for the analysis of ERPs.

ERPs—ERPs to sentence final words were analyzed at two time windows and two channel clusters. N400 amplitudes from 300-500 ms were analyzed at a central cluster of electrodes, while post-N400 frontal positivity amplitudes from 700-1000 ms were analyzed at a frontal cluster of electrodes. A schematic of the EEG channel montage including the two clusters for analysis are presented in Figure 3.

ERPs to sentence endings words during the sentence reading phase without the dual task are plotted in Figure 4. The effect of cloze probability on the amplitude of the N400 was analyzed with specific pairwise comparisons: SCE endings versus both WCE endings and unexpected (combined SCU and WCU) endings, as well as WCE endings versus unexpected endings. N400 amplitudes elicited by SCE endings were significantly more positive in amplitude compared to WCE ($t_{(31)} = 2.97$, $p < 0.01$; $BF_{10} = 7.19$) and unexpected endings ($t_{(31)} = 7.61$, $p < 0.01$; $BF_{10} = 9.37 \times 10^5$), and WCE endings elicited smaller amplitude N400s than unexpected endings ($t_{(31)} = 5.26$, $p < 0.01$; $BF_{10} = 2.06 \times 10^3$). Thus, the expected, graded effect of cloze probability on N400 amplitude (cf Federmeier et al., 2007) was observed when attention was not divided.[2]

Late frontal positivities were also analyzed similarly to the initial localization analysis. Frontal positivites (at the frontal channel cluster) elicited by SCU and WCU endings were compared to positivities elicited by WCE endings. The SCE condition was not used to assess the frontal positivity because this condition is known to elicit a frontally-distributed negativity (Wlotko & Federmeier, 2012). Thus, the WCE provides a baseline of comparison, where neither a positivity or negativity is expected to be elicited.

The comparison of SCU endings to WCE endings revealed a significant difference in frontal positivity amplitude ($t_{(31)} = 2.97$, $p < 0.01$; $BF_{10} = 7.15$), while the comparison of amplitudes from WCU and WCE endings did not significantly differ ($_{t}(_{31}) = 1.80$, $p = 0.08$; $BF_{10} = 0.80$). However, frontal positivities elicited by the two types of unexpected endings also did not differ ($t_{(31)} = 0.97$, $p = 0.34$; $BF_{10} = 0.34$). Thus, while a frontal positivity to SCU endings was observed in comparison to WCE endings, it was not in comparison to WCU endings. It is possible that, on some trials or for some individuals, WCU endings elicited a frontal positivity, leading to a numerical but non-significant difference.

ERPs to sentence endings words during the sentence reading phase while attention was divided are plotted in Figure 5. The previously observed N400 effects appear to be attenuated. As in the full attention condition, the effect of cloze probability on the N400 was analyzed. SCE endings elicited significantly more positive N400s than unexpected endings ($t_{(31}) = 3.53$, $p < 0.01$; $BF_{10} = 25.24$). In contrast, both the comparison of SCE and WCE endings ($t_{(31)} = 1.93$, $p = 0.06$; $BFi_{10} = 1.03$) and the comparison of WCE and

[2]Post-hoc comparison of SCU and WCU endings revealed a significant difference in N400 amplitude (t(31) = 2.15, p = 0.04), with SCU endings eliciting more negative N400s. However, the Bayes Factor provided only weak evidence for this effect ($BF_{10} = 1.40$).

unexpected endings ($t_{(31)}$ = 1.96, p = 0.06; BF_{10} = 1.00) trended toward significance, with weak evidence from Bayes Factors against the null hypothesis. Thus, evidence of facilitation based on N400 amplitudes was found for strong constraint sentences, but limited evidence of facilitation was found for weak constraint sentences. Frontal positivities also showed a different pattern of results under divided attention conditions compared to full attention. SCU endings elicited significantly larger frontal positivity amplitudes than WCE endings ($t_{(31)}$ = 3.30, p < 0.01; BF_{10} = 14.87), as well as WCU endings ($t_{(31)}$ = 3.15, p < 0.01; BF_{10} = 10.60), while WCU endings did not significantly differ in amplitude compared to WCE endings ($t_{(31)}$ = 0.12, p = 0.91; BF_{10} = 0.19). Thus, the frontal positivity to unexpected endings was preserved for strongly constraining sentences when attention was divided, while the limited evidence of frontal positivity in the WCU condition seen during full attention was not observed when attention was divided.

Visualization of ERP waveforms when attention was divided suggested a posterior positivity elicited by SCU sentence endings (along with the frontal positivity). Post-hoc exploratory analyses were conducted to analyze this effect. Mean amplitudes from 700-1000 ms at the central-posterior channel cluster were extracted from each of the sentence ending conditions and compared statistically with *t*-tests. Resultant *p*-values were corrected for multiple comparisons using the false discovery rate (Benjamini & Hochberg, 1995); the adjusted *p*-values are reported. SCU sentence endings elicited larger posterior positivities than WCE endings ($t_{(31)}$ = 3.43, p < 0.01; BF_{10} = 20.29) and WCU endings ($t_{(31)}$ = 4.28, p < 0.01; BF_{10} = 161.69), whereas WCE and WCU endings did not differ in their posterior positivity amplitude ($t_{(31)}$ = 0.19, p = 0.85; BF_{10} = 0.19). Thus, SCU endings elicited an additional posterior positivity, but only when attention was divided. Additional analyses examining differences between the frontal and posterior positivities across individual trials are reported in Supplementary Materials Section 3.

To better test the effect of dividing attention on specific ERP components, analyses were done comparing condition differences under full vs. divided attention, in part to determine if dividing attention had differential effects across constraint. First, N400 effects were analyzed for the expectancy effect (difference between expected and unexpected endings) at each level of constraint. Note that statistically testing amplitude differences in this way also controlled for differences in low level visual information between the full and divided attention condition due to the background RDK in the divided attention task. Effect amplitudes were submitted to a repeated measures ANOVA, as well as a Bayesian ANOVA, with factors of constraint (Strong and Weak) and attention (Full and Divided). The ANOVA revealed main effects of attention ($F_{(1,31)}$ = 7.14, p = 0.01) and constraint ($F_{(1,31)}$ = 8.36, p < 0.01), but no significant interaction ($F_{(1,31)}$ = 0.35, p = 0.56). The Bayesian ANOVA was in agreement, as evidence was found for main effects of constraint (BF_{10} = 9.76) and attention (BF_{10} = 21.33), but no evidence for an interaction (BF_{10} = 0.29). Thus, the N400 expectancy effect was larger under strong constraint (replicating a large body of literature), and dividing attention reduced context-based facilitation on the N400. However, there was no evidence that attention differentially impacted readers' ability to use contexts of different strength to facilitate word processing.

Next, the effect of dividing attention on the late frontal positivity was tested in a similar manner. The frontal positivity effect to SCU endings and WCU endings (again using WCE as the comparison condition) was extracted for both the full attention block and divided attention block. These amplitude differences were then submitted to a repeated measures ANOVA and a Bayesian ANOVA. The ANOVA revealed only a significant main effect of constraint ($F_{(1,31)} = 9.33$, $p < 0.01$); no significant main effect of attention ($F_{(1,31)} = 0.56$, $p = 0.46$) or interaction ($F_{(1,31)} = 1.62$, $p = 0.21$) was found. Similarly, the Bayesian ANOVA found evidence for a main effect of constraint ($BF_{10} = 3.29$), but no evidence of a main effect of attention ($BF_{10} = 0.58$) or an interaction ($BF_{10} = 0.43$). Thus, dividing attention had no influence on SCU endings eliciting a frontal positivity. Boxplots summarizing the amplitude differences for conditions of interest between full and divided attention are presented in Figure 6.

Discussion

The aim of the current study was to investigate the role of sustained attention during sentence comprehension. Previous behavioral and electrophysiological investigations have primarily focused on attention's role in single word processing. Sentence reading taps into additional mechanisms, including contextual integration, predictive processing, and later revision. Many of these processes, such as prediction, have been posited to be resource-demanding (Kuperberg & Jaeger, 2015), yet experimental evidence attesting to the role of attention in these mechanisms is relatively scarce. In order to better understand the link between sustained attention and sentence comprehension, a novel paradigm was developed for the study, in which participants concurrently tracked the movement of dots in an RDK display while reading sentences that varied in contextual constraint, completed with expected or unexpected endings. The efficacy of the RDK tracking task at dividing attention was validated in both a separate pilot study (see Supplementary Materials Section 1), as well as in the current experiment; namely, dividing attention with the RDK task successfully reduced P3 ERP amplitudes to targets during an oddball task, as well as reduced comprehension question accuracy during the reading task. Thus, the application of this paradigm allowed for the assessment of what specific neurocognitive mechanisms of comprehension were influenced by a reduction of attentional resources.

Our language materials provided comparisons for examining core processes of sentence comprehension -- namely, contextual integration, prediction, and revision. Basic aspects of contextual facilitation could be assessed by measuring the strength of cloze probability effects on the amplitude of the N400. Indeed, when participants read sentences without an additional task, N400 amplitudes elicited by sentence endings were graded by cloze probability, with strongly constrained expected endings eliciting the smallest N400s and unexpected endings the largest, replicating prior work (Federmeier et al., 2007). However, when attention was divided, this contextual facilitation effect was reduced: N400 amplitudes to expected endings were more negative than when attention was not divided, to the degree that N400s to expected endings of weak constraint sentences did not reliably differ from N400s to unexpected endings. Consistent with our findings, Hohlfeld et al. (2015) found that N400 effects distinguishing plausible from implausible endings of weakly constraining sentences were reduced when an attentional disruption occurred immediately prior to the target word of a sentence. Thus, appreciation of word congruency seems to be affected both by a punctate attentional disruption and by more continuous distraction across the sentence. Our results are additionally in line with previous visual masking studies, in which masking each word of a sentence reduced N400 congruency effects (Mongelli et al., 2019; Nakamura et al., 2018). We have expanded on these previous results by including sentences that vary in their cloze probability, allowing us to assess the impact of attentional resources on comprehenders' ability to build a message-level representation from accruing context. Note that there do appear to be cases where contextual facilitation of N400 amplitudes does not seem to require much attentional resources, as robust N400 effects are observed for words presented in parafoveal view (Payne & Federmeier, 2017; Stites et al., 2017). However, this is the first study to test the impact of dividing attention on the formation of context-based representations themselves, across a range of cloze probability/sentential constraint, allowing us to assess the impact of attentional resources on comprehenders' ability to build a message-level representation from accruing context. We show that N400 effects are diminished for expected endings of both weakly and strongly constraining contexts, supporting the idea that the message-level representation being formed from the sentences is impoverished. Thus, while some aspects of semantic access may be automatic, leading to no effects of attention on single word access, our results provide novel evidence that sustained visual attention does play a role in mechanisms of integration and situation model building during sentence comprehension.

Separating the contributions of prediction over and above direct facilitation from the context information can be difficult; for instance, in young adults, both the build-up of a discourse model from the integration of words across the sentence (Hald, Steenbeek-Planting & Hagoort, 2007; Van Berkum, Hagoort & Brown, 1999) and processing benefits from predictive preactivation of word features (Brothers, Swaab & Traxler, 2015; Federmeier & Kutas, 1999; Nieuwland, Barr, Bartolozzi et al., 2020) can engender facilitated processing of a target word, leading to reduced amplitude of the N400. However, studies using these same materials have consistently shown that in groups or under conditions in which predictive processing tends to be reduced/eliminated – e.g., in older adults (Wlotko, Federmeier, & Kutas, 2012), in adults with lower literacy (Ng et al., 2017), and with processing biased to the right hemisphere (Wlotko & Federmeier, 2007) – N400 facilitation is disproportionately reduced for expected items in weakly constraining contexts, suggesting that prediction is especially useful for augmenting context-based facilitation when the context information is itself less constraining. Here, we found that dividing attention did not differentially impact N400 amplitudes to expected endings based on the constraint of the sentence -- both were similarly reduced relative to their levels under non-distracted conditions. Thus, although dividing attention reduced context-based facilitation in general, it did not create a pattern in the time window of the N400 suggesting the eradication of predictive processing effects.

The perhaps surprising idea that predictive processing is not especially impacted by dividing attention was additionally supported by our findings on the post-N400 frontal positivity. The frontal positivity has been linked to revision and/or updating processes initiated by plausible prediction violations in sentence or phrasal contexts, when a stimulus that is unexpected but still fits with the context-based model is encountered (see discussion in Brothers et al., 2020). In the context of passive reading, the frontal positivity is typically observed to unexpected endings of strongly constraining sentences (Federmeier et al., 2007; Payne & Federmeier, 2017); when there are additional memory demands, the effect may extend to unexpected endings of weakly constraining contexts as well (Hubbard, Rommers, Jacobs et al., 2019). Like other effects linked to predictive processing, the frontal positivity is reduced or eliminated in older adult samples (Federmeier, Kutas, & Schul, 2010; Wlotko, Federmeier, & Kutas, 2012). Here, we replicated the positivity to strongly constrained unexpected words when young adults were reading under full attention (with a possible tendency for effects to extend into weakly constraining contexts as well, perhaps due to the addition of memory demands in the present study; cf, Hubbard et al., 2019). Strikingly, when attention was divided there was no impact on the size of the positivity[3]. Thus, we found no indication that predictive processing was diminished by dividing attention during sentence reading, nor that revision or updating processes recruited to deal with prediction violations were affected by reduced attentional resources.

Note that other work investigating prediction during language comprehension does suggest that attention could still influence predictive processing. For instance, one study instructing participants to actively predict the final word of a sentence reported larger N400 facilitation effects to expected sentence endings, as well as larger frontal positivities to unexpected endings, compared to passive reading (Brothers, Swaab & Traxler, 2017), suggesting readers can allocate attentional resources through top-down control to predictive processing. Similarly, other research has demonstrated that individuals with greater working memory capacity made more predictive eye movements in a visual word paradigm (Huettig & Janse, 2016), and predictive eye movements were reduced when participants performed a concurrent working memory task (Ito, Corley & Pickering, 2018), suggesting prediction can be influenced by availability of cognitive resources. A possible explanation to reconcile our results with the previous research is that individuals can allocate resources toward predictive processing through executive control, leading to greater engagement of prediction processes, but, under conditions of divided attention, predictive mechanisms are still engaged. This gives rise to the notion that prediction during language is ballistic or “all-or-none” and is engaged or disengaged based on the demands of the task and top-down resources allocated. In line with this idea, when the presentation rate of words in a sentence was increased, prediction effects on the N400 were not observed, suggesting individuals did not engage prediction when information presentation was rushed (Wlotko & Federmeier, 2015). Engagement and success of prediction may be variable across trials, and top-down resource allocation towards prediction may not “enhance” or “sharpen” prediction as much as engage it more often, reducing variability. Indeed, other work measuring ERPs to the same sentences, but where the pacing of presentation was controlled by the participant, reported frontal positivity differences only for faster pace reading (Payne & Federmeier, 2017). In sum, certain task demands may lead to disengagement of prediction, and top-down control may lead to greater engagement of prediction, but a reduction in sustained attention or contextual facilitation does not affect mechanisms of prediction.

[3]The numerical tendency for a frontal positivity effect to the weakly constrained unexpected words under full attention was not observed under divided attention.

Although the frontal positivity was preserved when attention was divided, a difference did emerge in the later time window: namely, a post-hoc analysis revealed that unexpected endings of strong constraint sentences also elicited a posterior positivity. This has not been observed before, as frontal positivities are generally elicited by unexpected but plausible words, whereas posterior responses are elicited by unexpected words that are **not** plausible and hence cannot be easily integrated into the situation model, leading to alternative revision processes (Kuperberg et al., 2020; Van Petten & Luka, 2012). _One explanation for this finding could be that the observed effect is simply the same frontal positivity with a different topography; however, this seems unlikely. We performed additional analyses to rule out the possibility that we measured the same ERP that had simply spread further across the scalp (see Supplementary Materials Section 3). Thus, it seems more likely that, when attention was divided, unexpected words elicited both frontal and posterior positivities, although it remains unclear the extent to which these signals were generated on separate trials, or in some instances were generated concomitantly. We hypothesize that when attentional resources are limited, the brain may require more effort for reanalysis and integration of the unexpected information, leading to engagement of both mechanisms.

Previous work has shown that distracting attention can reduce the amplitude of the posterior positivity (P600) response (Hohlfeld et al., 2015). However, it is important to note that in such cases, task demands (in this case, making acceptability judgments) encouraged the elicitation of the P600 in the non-distracted condition (Schacht, Sommer,Shmuilovich et al., 2014). Under those conditions, the availability of attentional resources seems to affect the magnitude of the response. With passive reading, as in the present experiment, posterior positivity effects are unlikely, especially to unexpected words that are not semantically anomalous. Thus, reduced attention during sentence processing seems to bring out a new kind of response. Given the finding of impaired semantic integration as indexed by the N400, one explanation of these findings is that the constructed situation model had low fidelity, leading to errors in determining the necessary revision process to engage (e.g., in uncertainty about whether the ending is or is not plausible). This creates an interesting view of the relationship between prediction and the constructed context: Prediction may be engaged even when attentional resources are low, but if the context used to generate predictions is of poor quality, then more mismatches and a greater difficulty integrating the mismatch into the contextual representation will occur.

Broadly speaking, our results enter into a literature with mixed results, with some studies suggesting lexical access or semantic priming affects may be automatic, but others finding that dividing attention impacts word processing. Indeed, results within our own study are somewhat mixed; it seems that some higher-level language processing mechanisms involved in comprehending sentences depend on attentional resources, while other mechanisms may be independent of attention. However, another factor to consider is the type of attentional manipulation used in the experiment. Importantly, there are multiple subsystems of attention that may differentially be involved in language processing, leading to differences in results depending on which subsystem is being targeted by a particular manipulation. Posner and Petersen's influential theory (Petersen & Posner, 2012; Posner & Petersen, 1990) defines the attentional system as a set of subsystems involved in alerting (detecting stimuli and maintaining vigilance), orienting (shifting focus to attend to specific stimuli), and executive control (selecting or inhibiting information based on task demands or goals). The current study specifically focused on the role of sustaining attention or maintaining vigilance during sentence reading. Many previous studies on single word comprehension have focused more on orienting, or shifting attention to focus on stimuli, for instance by cueing the spatial location of where a word stimulus would appear (Cristescu & Nobre, 2008; McCarthy & Nobre, 1993). Orienting may lead to momentary focusing of attentional resources to enhance sensory processing, unlike sustained attention, which is involved in maintaining optimal vigilance during a task (Petersen & Posner, 2012). Indeed, studies examining orienting to auditory stimuli suggest that attentional orienting and stimulus predictability have opposing effects on early sensory ERP components, with attentional orienting increasing and predictability decreasing the amplitude of the N1 component (Lange, 2013). These results suggest that attentional orienting can potentially divert cognitive resources from predictive semantic processing towards sensory processing, leading to reduced effects of predictability, whereas our results indicate that taxing sustained attention did not appear to induce a substantial trade-off or change in processing, but rather a reduction in the ability to use contextual information to form a discourse model.

This difference in attentional sub-systems can also be observed when examining the late frontal positivity effect. As previously described, frontal positivities were not observed to unexpected words presented in the parafovea (Payne & Federmeier, 2017; Stites, Payne & Federmeier, 2017) or lateralized to the left or right visual field (Wlotko & Federmeier, 2007). However, in all of these cases the target word was outside of the focus of central attention, unlike the current experiment, wherein all stimuli were centrally presented, but attention was divided with a dual-task design. Thus, the processes indexed by the frontal positivity seem to require that stimuli be in the focus of attention but are robust to decreases in attentional resources within that area of focus. As a set, then, the previous results in conjunction with the results of the current study suggest that the separate subsystems of the attentional system are involved in different language comprehension processes. Basic semantic access and priming of that access by a word or context can seemingly operate automatically, and central focus or attentional orienting may not be required. However, building a message-level representation of a context does rely on sustained attention, as dividing attention reduces (but does not eliminate) sentence-based facilitation effects on the N400. On the other hand, central focus or attentional orienting may be required to initiate revision processes entailed by prediction violations, as indexed by the late frontal positivity, but changing levels of sustained attention do not appear to notably affect those processes.

The current results suggest that dividing sustained attention impairs integrative mechanisms during language comprehension, but predictive processing may be spared and continue to be engaged. In some ways, this aligns with recent research that suggests that words that are predicted and then encountered are not processed as deeply or to the same degree as unpredicted information (Hubbard et al., 2019; Rommers & Federmeier, 2018). Thus, the brain appears to allocate attentional resources towards predictive processing in order to reduce demands on sensory processing. Given that language input generally arrives rapidly and continuously, it may be beneficial for the brain to prioritize speed of processing over depth of encoding and accuracy. One way to do so would be to pre-activate features of upcoming information and shift towards a "verification mode" of processing, in which stimuli that match the predicted input are not processed further and are simply used as a cue to generate the next set of predictions (Van Berkum, 2010). Thus, even when attentional resources are limited and the situation model used to generate predictions is poorer, the brain may prioritize engaging prediction mechanisms in order to "keep up" with language input. These results open the door for future studies to further investigate how separate attentional subsystems interact with comprehenders' top down control to permit them to understand, as well as predict, language stimuli.

Methods and Materials

Participants

32 right-handed individuals participated in the experiment in exchange for cash. All participants reported normal or corrected-to-normal vision, were native English speakers, and had no history of any neurological or psychiatric disorder. Mean age was 23 years (range 18-35 years), and 21 of the participants were female. The study was approved by the Institutional Review Board at UIUC, and all participants provided written informed consent and were debriefed following participation.

Materials

The stimuli used in the reading blocks were originally developed for a previous language comprehension ERP study (Federmeier et al., 2007) and consisted of 280 sentences that varied in contextual constraint, as measured by cloze probability. Half of the sentences were strongly constraining (cloze probability of the most expected completion > 0.67), while the other half were weakly constraining (cloze < 0.42). Each of the sentences was paired with its highest cloze probability (expected) ending, as well as an unexpected but plausible ending. Thus, there were four sentence types: strong constraint sentences with expected endings (SCE), strong constraint sentences with unexpected endings (SCU), weak constraint sentences with expected endings (WCE), and weak constraint sentences with unexpected endings (WCU). The four sentence types were evenly divided into two lists, such that each participant read all the sentence contexts exactly once, half with expected and half with unexpected endings, and, across participants, every sentence was read the same number of times with an expected and unexpected ending. These two lists were then further divided into full attention and divided attention blocks, also counterbalanced across participants. This resulted in each participant reading 35 sentences of each type (SCE, SCU, WCE, and WCU) with full attention, and 35 sentences of each type with divided attention. Sentence frames were globally matched in length across constraint and the length of sentences was also matched across conditions within each list (average = 10 words). Unexpected items were the same words across constraint conditions, and expected endings were matched across constraint for lexical properties (word length, word frequency; see Federmeier et al. (2007) for more details). Lexical properties were also matched across conditions within each list. Examples of the sentences are presented in Table 1.

In Federmeier et al. (2007), subjects read passively for comprehension. However, to ensure that participants could not neglect the reading task during the divided attention blocks, in the present study we asked participants to respond to comprehension questions (presented several sentences after the initial presentation of the sentence; see Procedure for more detail). Therefore, 40 simple yes/no questions comprehension questions were created (20 for the full attention block, 20 for the divided attention block). For instance, for the experimental sentence “Father carved the turkey with a knife” the corresponding comprehension question was “Did Father carve the turkey?” The order of presentation of the questions was counterbalanced across participants to match the four stimulus lists. The sentences that the questions focused on varied in their contextual constraint, such that participants could not predict which sentence would be asked about. These questions served as attention checks to keep participants focused on the task, and also gave a metric of the effectiveness of dividing attention on comprehension.

The stimulus used to divide attention was an RDK, created in PsychoPy following Scase, Braddick & Raymond (1996). The RDK was made up of 500 dots, each 3 pixels in size and white in color. Each dot had a lifespan of 5 frames, meaning that after 5 frames the dot disappeared and was replaced by another dot at a different location. The dots moved across the screen at a speed of 0.004 pixels per frame. 60% of the dots moved in the same direction (the signal dots), whereas the other 40% of the dots moved in a random direction (the noise dots).

The direction of the signal dots changed +/− 7 degrees on every frame, and also abruptly shifted +/− 90-180 degrees at random intervals. The RDK extended the entirety of the screen, except for the box in the center where the other stimuli (words or oddball standards and targets) were presented.Finally, the stimuli used in the oddball experiment during the pilot study and validation check were an “O” for the standard stimulus and an “X” for the target stimulus. The letters were presented in blue font over a white box at the center of the screen.

Procedure

After informed consent and EEG setup, participants were comfortably seated approximately 100 cm from a CRT monitor in a dark, quiet room. Participants first completed a block of the oddball task, without any dividing of attention. They were given an Xbox controller and were told to press the A button as quickly as possible when an “X” appeared on the screen, and to make no response when an “O” appeared on the screen. A total of 160 stimuli, comprised of 120 standards and 40 targets (a 25% target rate), were presented. Presentation order was pseudo-random, such that every series of 4 stimuli had a target in it. On each trial, a stimulus appeared in the center of the screen for 100 ms and then disappeared for 900 ms. Trials were separated by a random ISI between 300 and 600 ms.

The first block of sentence reading followed completion of the oddball task, in which participants read the first half (140 sentences) of the stimuli. Participants were instructed to read and pay attention to the sentences, as they would be asked comprehension questions about them. Each sentence was presented word-by-word in the center of the screen, with each word appearing for 200 ms and disappearing for an interval of 300 ms. Sentences were separated by an interstimulus interval of a random duration between 1500 and 2000 ms. Every 7 sentences, a comprehension question about one of the previously read sentences would appear. Participants were instructed to respond “Yes” or “No” with two different buttons on the controller. The comprehension question never pertained to the 7th sentence in the series so that participants could not learn the timing of the questions and would have to attend to all sentences in the series. Note that, during the full attention reading block, no dots were presented in the background – these only appeared during the divided attention block.

After the first block, participants were told they would have to perform these tasks again while also tracking the movement of dots in the background. They were instructed to push the joystick on the controller in the same direction that the majority of the dots were moving. They were given a brief training period so that they could practice moving the joystick along with the RDK without any other task. The experimenter made sure that each participant was able to detect the motion of the signal dots as well as use the joystick to track the motion. Following the training session, participants performed another oddball block, in which they were presented with another 160 stimuli, comprised of 120 standards and 40 targets, along with the RDK. Reaction times (RTs) to target stimuli were recorded, as well as the number of targets missed and false alarms to standards. Additionally, the participant’s tracking accuracy on the RDK task was recorded. During the 1 second interval of the trial, on each frame, the absolute difference between the angle of the joystick and the angle of the signal dot motion was recorded. The average across time was recorded for each trial. This allowed for a measure of performance on the RDK tracking task.

Finally, participants then completed a second block of sentence reading in which they concurrently read sentences and tracked RDK motion with the joystick. In this second block, participants read the second half of the sentence stimuli (140 sentences). The procedure was exactly like the first block, except for the addition of the RDK. Participants did not have to track the RDK during the comprehension questions, and were told they could use the question answering period as a short break. Answering the comprehension started the next series of sentences. As in the oddball task, the tracking error on the RDK task was measured during sentence reading.

The block order was the same for all participants, with the full attention condition preceding the divided attention condition, in order to ensure that the full attention condition was uncontaminated by other experimental manipulations or task demands. Previous work has demonstrated that task order can impact the processing engaged during passive reading; for instance, in an experiment in which participants read sentences at a standard rate or a faster rate, reading a faster rate first led to diminished effects of context on the N400 during the standard rate block (Wlotko & Federmeier, 2015). We suspected that the divided attention block preceding the full attention block would influence the degree to which participants engage in the same reading mechanisms, leading to difficulty in interpreting the results; thus, the full attention block was presented first. However, this led to the possibility that the observed differences between attention conditions could be due to participant fatigue. We conducted an analysis to rule out this explanation, which is detailed in Supplementary Materials Section 4.

EEG Recording and Pre-Processing

EEG data were recorded from 26 Ag/AgCl electrodes embedded into a flexible elastic cap and distributed over the scalp in an equidistant arrangement. Additional facial electrodes were attached for monitoring of electro-oculogram (EOG) artifacts, including one adjacent to the outer canthus of each eye and one below the lower eyelid of the left eye. Electrode impedances were kept below 10 kΩ, Signals were amplified by a Brain Vision amplifier with a 16-bit A/D converter, an input impedance of 10 MΩ, an online bandpass filter of 0.016–250 Hz, and a sampling rate of 1 kHz. The left mastoid electrode was used as a reference for on-line recording; offline, the average of the left and right mastoid electrodes was used as a reference.

Following data collection and offline re-referencing, each raw EEG time series was passed through a 0.2–20 Hz Butterworth filter with a 24 dB/oct roll-off. Filter parameters were chosen a priori to remove low frequency drifts and high frequency noise without causing artifacts in ERP analyses (Tanner, Morgan-Short, & Luck, 2015). The time series was then segmented into epochs ranging from −200 to 1000 ms relative to the onset of each oddball stimulus, and the 200 ms pre-stimulus window was used to baseline correct the post-stimulus data. Epoched data were then submitted to AMICA, an ICA algorithm that decomposes the signal into independent components (Palmer, Kreutz-Delgado, & Makeig, 2012). Each component time-course was correlated with a bipolar vertical EOG channel (the lower eye channel minus the channel above the left eye), as well as a bipolar horizontal EOG channel (the subtraction of the two outer canthus channels). Components with high correlations and topographies indicative of eye-related activity were removed, and the data were reconstructed from the remaining components. For 22/32 participants, a single eyeblink component was removed. For the other 10 subjects, 1 to 2 additional components were removed; this was primarily a second eyeblink component with the same topography as the first, only with reversed polarity. Horizontal eye movements are more difficult to isolate with ICA, and thus a more conservative approach was taken: for all 32 participants, only 1 horizontal eye movement component was removed, and any trials with remaining horizontal eye movement artifact were rejected. Lastly, the EOG-cleaned data was scanned for large voltage deflections (>80 μV), and manually scanned by eye to remove any epochs with remaining artifacts. Overall, an average of 5% of trials was removed across subjects, and each condition had at least 20 trials within each participant.

Trials were averaged to create ERPs, and channel clusters and time windows were chosen based on previous studies to examine the P3b, N400 and frontal positivity. Previous studies have shown that the P3b typically peaks over central-posterior electrodes between 250-500 ms (Polich, 2007). Therefore, to analyze P3b amplitudes during the oddball task a channel cluster of 8 central-posterior electrodes was created, and mean amplitudes from 250-500 ms at the channel cluster were extracted. The N400 peaks between 300-500 ms over central-posterior channels (Federmeier et al., 2007), and so mean amplitudes in this time window at the same 8-channel cluster were used to analyze N400 amplitudes during the reading task. The precise distribution of the late frontal positivity is less well-established; it has sometimes been reported as bilateral (e.g., Federmeier et al., 2007) and sometimes left-lateralized (DeLong et al., 2014). Thus, an initial, condition-blind analysis was performed to characterize the effect and choose analysis parameters (more details in Supplementary Materials Section 2). Channel clusters are presented in Figure 3.

Differences in ERP amplitudes were statistically tested either with repeated-measures ANOVAs, or with planned pairwise comparisons when testing specific hypotheses about ERP effects. Bayesian hypothesis testing was also performed to make better statistical inferences from the data (Rouder, Speckman, Sun et al., 2009). Bayes Factors provide estimates of the odds of the alternative hypothesis (the effect of interest) over the null hypothesis (no difference between conditions), and thus can provide a more nuanced understanding of the magnitude of effects (Jarosz & Wiley, 2014). Bayes Factors are reported in terms of odds in favor of the alternative hypothesis (e.g., $BF_{10} = 5$ would be 5:1 odds). Grand average ERPs were created by averaging across ERP waveforms. For visualization purposes only, these grand averages were filtered with an additional 10 Hz low-pass filter.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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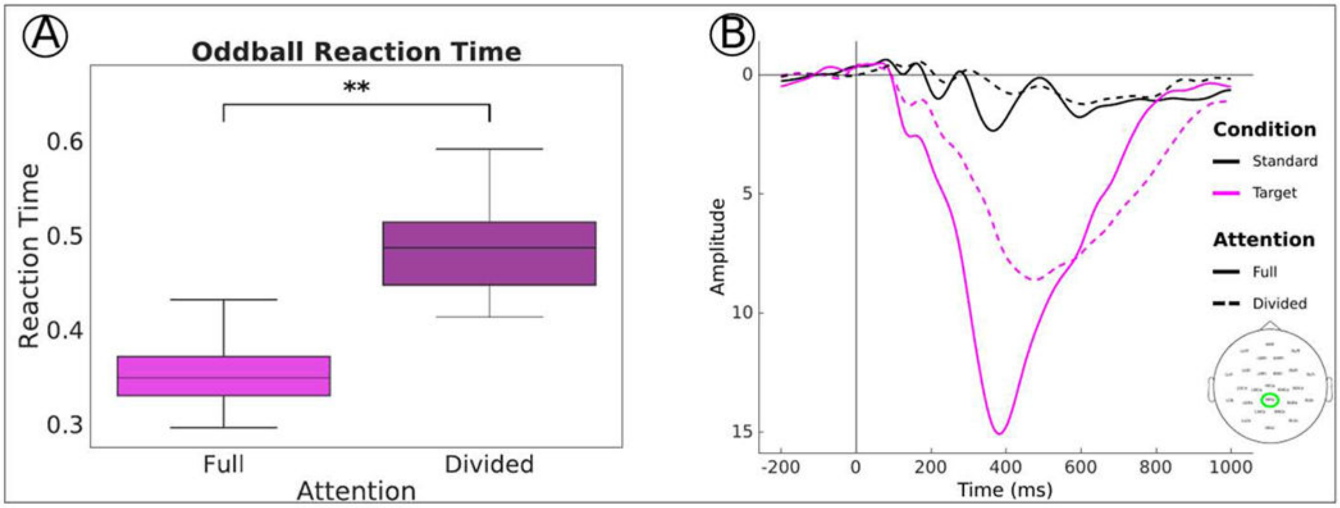

Figure 1.

Results of the Oddball experiment. A) Behavioral results. Reaction times (ms) to respond to target stimuli are plotted on the y axis. Dividing attention led to increased reaction times. B) ERP results. ERPs to standard and target stimuli are plotted at a central-parietal electrode. A clear P300 is observed to targets, and the amplitude is reduced when attention is divided.

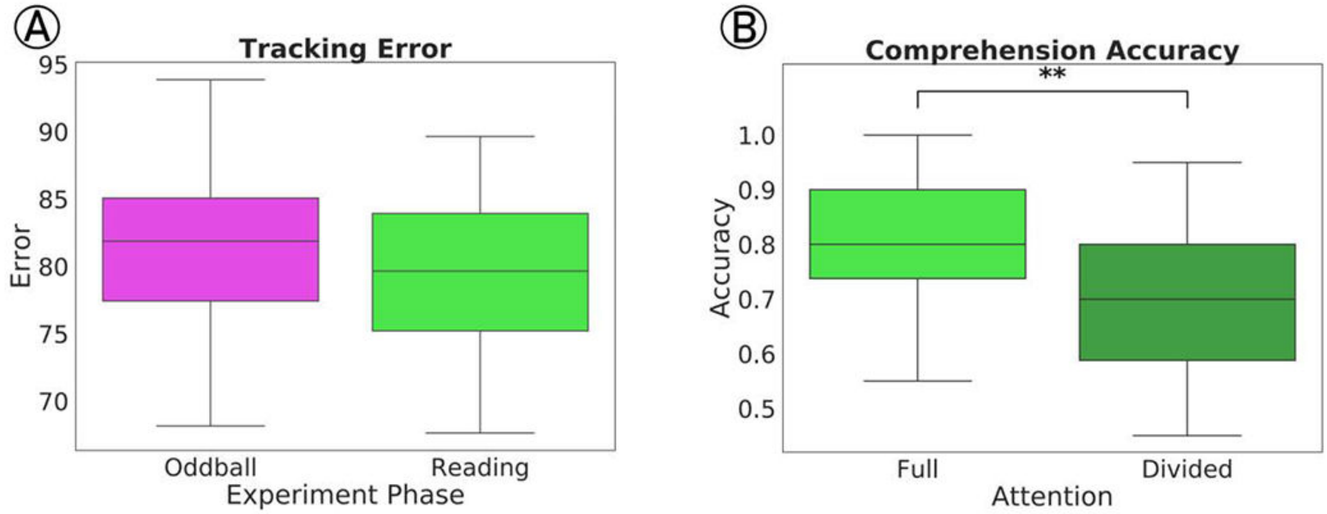

Figure 2.

Behavioral results. A) Dot tracking error during the oddball and reading tasks. Error metric reflects the difference in angle between the direction of dots and the direction of the joystick. B) Comprehension question accuracy during the reading task. Dividing attention significantly reduced accuracy.

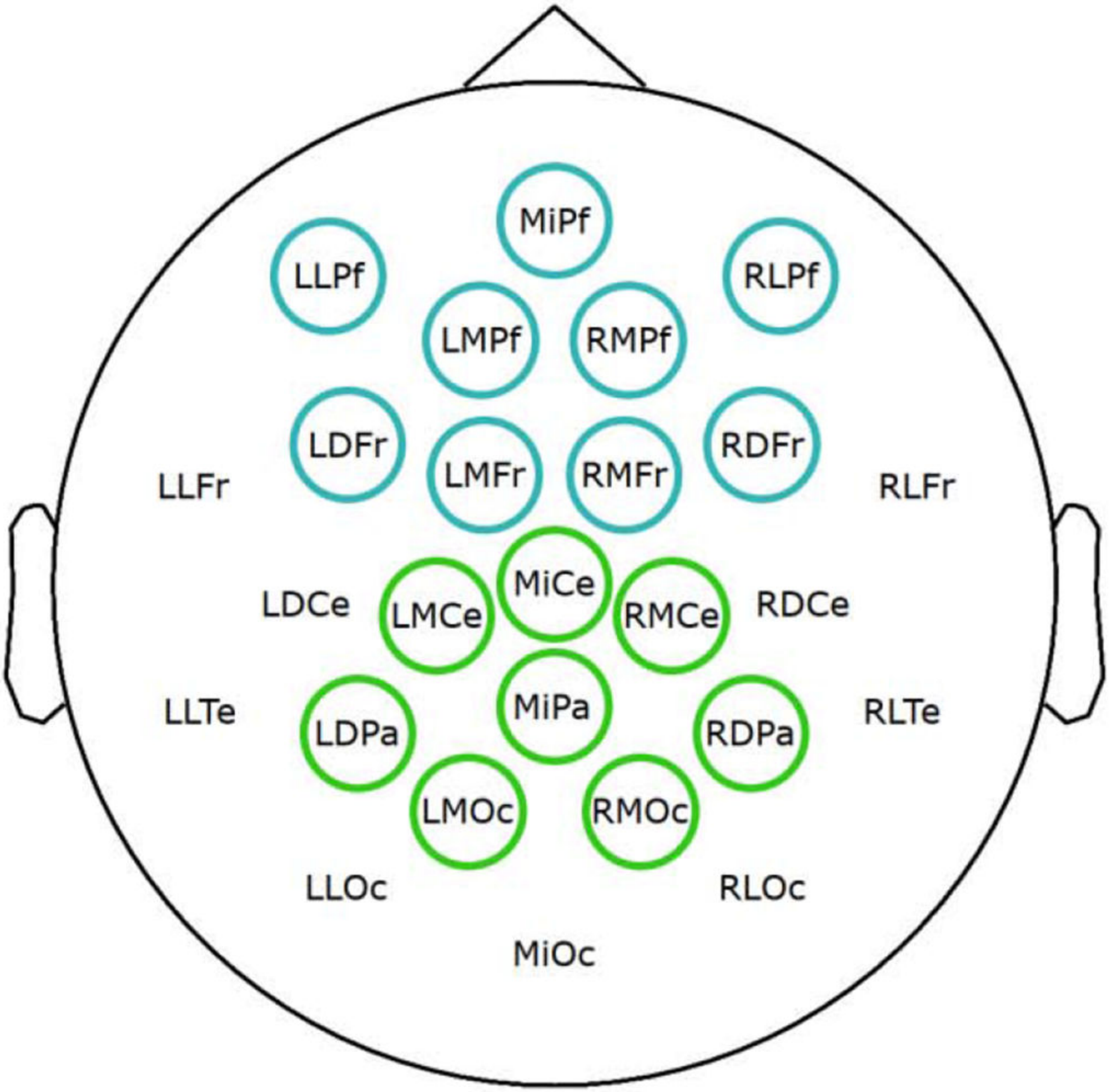

Figure 3.

Channel layout and channel clusters used for ERP analysis. Central cluster for N400 analyses is in green, frontal cluster for late positivity analyses in blue.

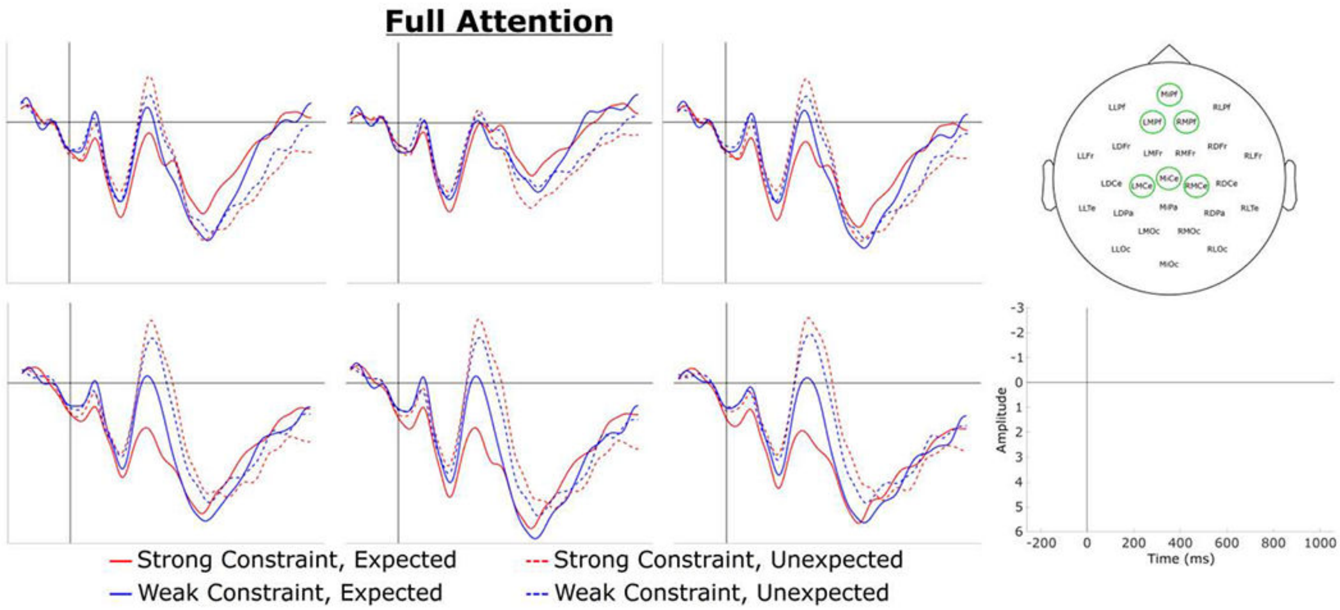

Figure 4.

ERPs to sentence endings, full attention condition, at 6 electrode sites (3 frontal and 3 central, shown in the head diagram in the top right). Negative is plotted up (see axis in the bottom right). The N400 can be observed from 300-500 at central sites, and the late frontal positivity can be observed from 700-1000 ms at frontal sites.

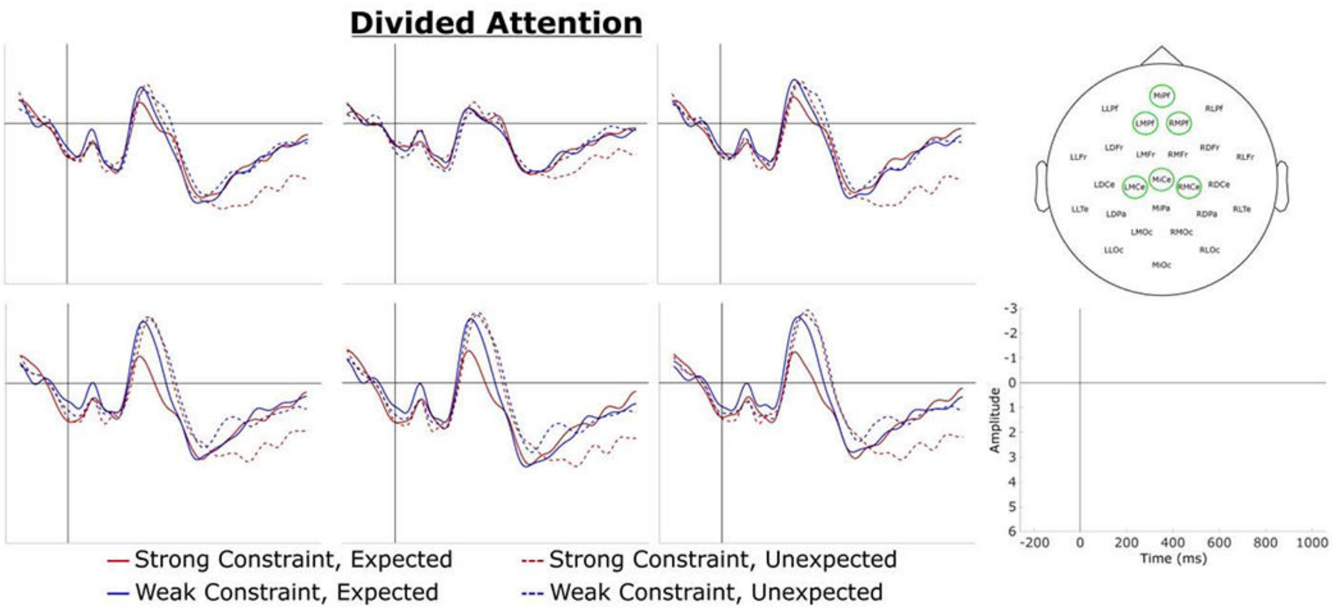

Figure 5.

ERPs to sentence endings, divided attention condition, at the same 6 electrode sites as in Figure 4 (shown in the head diagram in the top right). Negative is plotted up (see axis in the bottom right). The N400 effect from 300-500 is reduced in magnitude, but the late frontal positivity from 700-1000 is preserved.

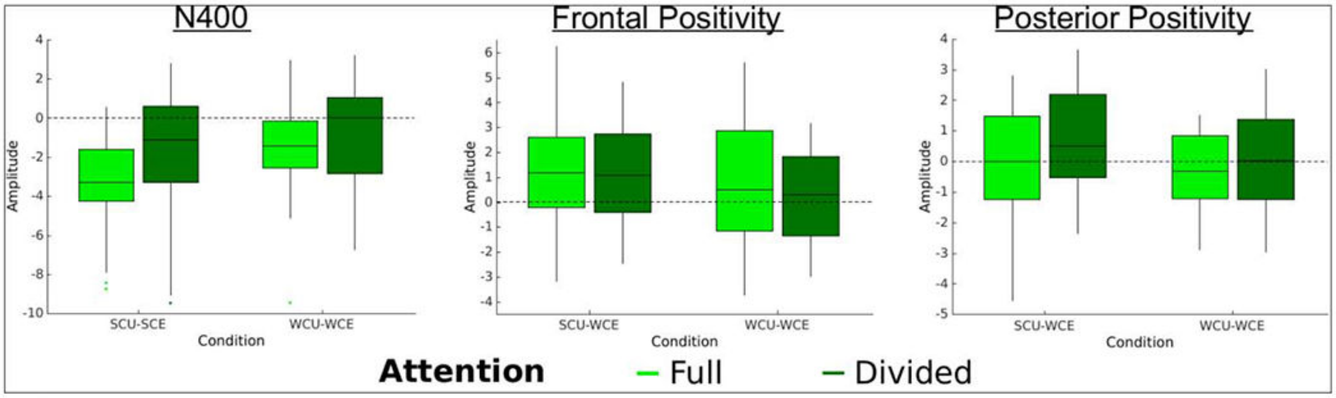

Figure 6.

Boxplots summarizing ERP amplitude differences between constraint conditions for the three components of interest (N400, frontal positivity, and posterior positivity). Full attention is shown in bright green, and divided attention is plotted in dark green.

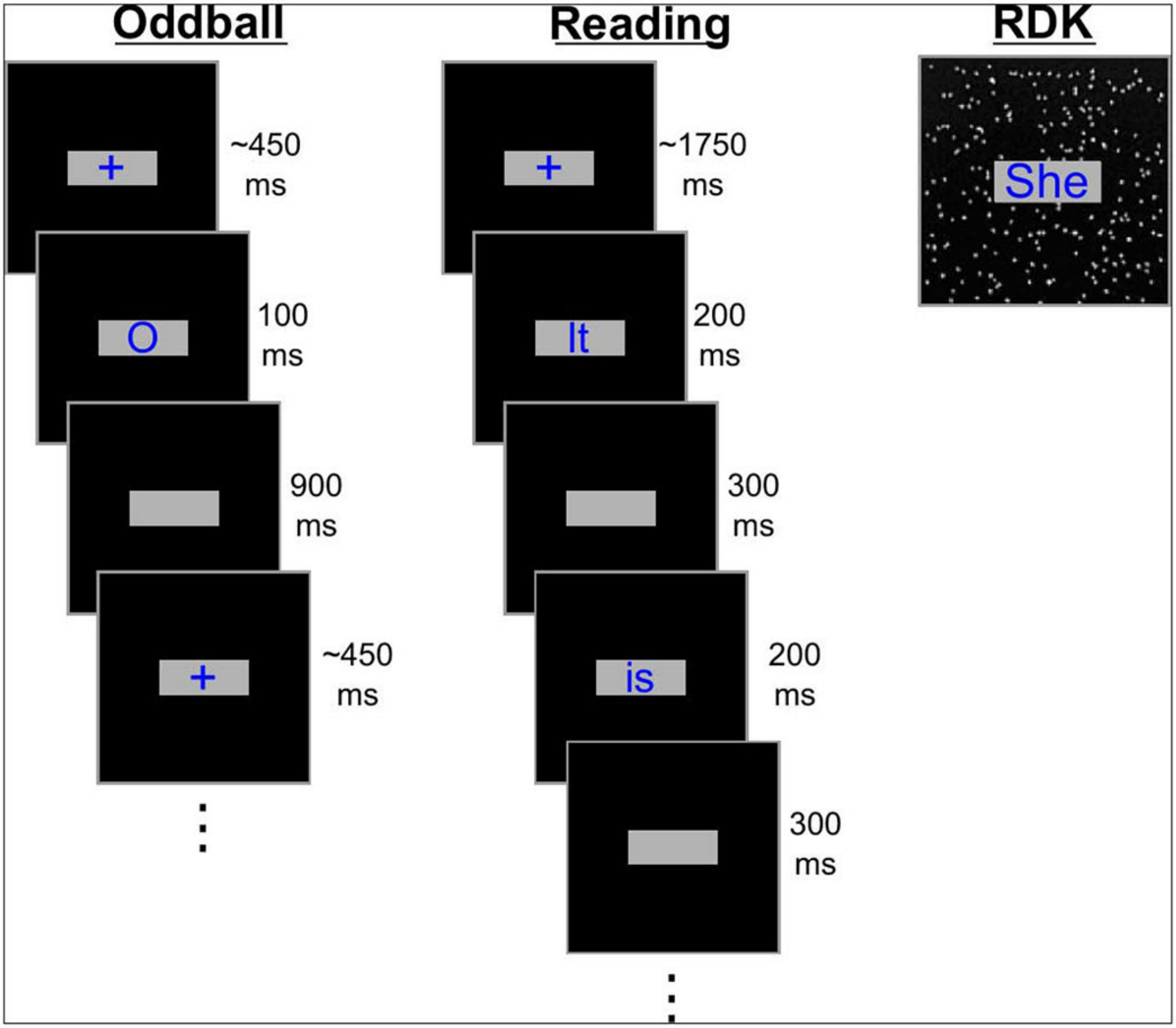

Figure 7.
Experimental paradigm. In the oddball task, the participant pressed a button when a target (X) was presented. This was followed by sentence reading, where sentences were presented word by word in an RSVP. This procedure was then repeated, but attention was divided by the RDK dot tracking task.

Table 1.

Examples of sentence stimuli. SC = strong constraint, WC = weak constraint.

Constraint	Sentence Frame	Expected	Unexpected
SC	She was docked one hour's pay for coming to work	late	unprepared
WC	The long test left the class	tired	unprepared
SC	Shuffle the cards before you	deal	forget
WC	It was difficult to decide which bills to pay and which to	ignore	forget