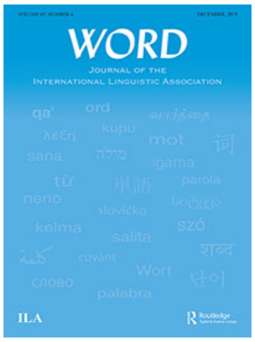

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Individual Differences in Reading Speed are Linked to Variability in the Processing of Lexical and Contextual Information: Evidence from Single-trial Event-related Brain Potentials

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In the current paper, we examined the effects of lexical (e.g. word frequency, orthographic neighborhood density) and contextual (e.g. word predictability in the form of cloze probability) features on single-trial event-related brain potentials in a self-paced reading paradigm. Critically, we examined whether individual differences in reading speed modulated single-trial effects on the N400, an ERP component linked to semantic memory access. Consistent with past work, we found that word frequency effects on the N400 were attenuated with increasing predictability. However, effects of orthographic neighborhood density were robust across all levels of predictability. Importantly, individual differences in reading speed moderated the influence of both frequency and predictability (but not orthographic neighborhood density) on the N400, such that slower readers showed reduced effects compared to faster readers. These data show that different lexical factors influence word processing through dissociable mechanisms. Our findings support a dynamic semantic-memory access model of the N400, in which information at multiple levels (lexical, sentential, individual) simultaneously contributes to the unfolding neural dynamics of comprehension.

Keywords: Lexical processing; reading; event-related brain potential; EEG; semantics

Introduction

A large literature in psycholinguistics addresses how various word- and context-level properties affect ease of comprehension. Across this literature, however, findings arising from different methods have not always been well-integrated. One widely-used method for studying visual sentence processing is "self-paced reading" (Henderson & Ferreira 1990; Jegerski 2014; Mitchell 2004), in which readers use a button press to move word by word through a text at a speed that is under their control. The amount of time readers choose to spend on a particular word in a particular sentence can reveal the impact of both lexical and contextual factors on comprehension. Comprehension has also been studied using measures of brain electrophysiology in the form of event-related potentials (ERPs), derived from the electroencephalogram (EEG) recorded concurrently with a reading task (see Payne & Silcox 2019; Rommers & Federmeier 2017 for recent reviews). ERP studies provide a powerful

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means of tracking the dynamics of comprehension as it unfolds over time and have also revealed the impact (and interactions) of lexical and contextual properties. Although both methods converge in highlighting the importance of factors such as word frequency, orthographic neighborhood density, and context-based word predictability on comprehension, very little work has attempted to bridge the existing methodological and theoretical gaps between these approaches.

One critical difference between these two paradigms is that self-paced reading allows for individual differences in volitional control over the rate of input. To avoid electrical artifacts from eye movements, ERP studies of visual sentence processing have largely used "rapid serial visual presentation" (RSVP) paradigms, in which sentences are presented word by word at fixation. Most RSVP studies present words at a fixed rate (e.g. 2 or 3 words per second), and, even when presentation rates are more varied (e.g. by word length or number of syllables), they tend to nevertheless be experimentally controlled. This approach thus potentially occludes the influence of individual differences in reading speed. Indeed, reading speed varies substantially across even highly-skilled readers, with fast and slow readers showing considerable differences in word recognition and reading behavior (Andrews 2012; Rayner et al. 2010; Ashby et al. 2005). Moreover, experiments explicitly manipulating presentation rate in ERP paradigms have shown that timing is a critical factor, modulating the impact of other variables on comprehension (Camblin et al. 2007b; Swaab et al. 2004). However, there has not yet been a systematic investigation of whether neurophysiological indices of word processing vary for faster and slower readers reading at their preferred pace. Thus, in the current study, we combined the two measures in a self-paced reading ERP paradigm to examine how lexical and contextual factors impact comprehension as indexed by ERPs (in particular, the N400 component, which has been linked to semantic access), among faster and slower readers.

ERPs and the N400

ERPs are neuro-electric responses that are consistently linked in time and phase with specific sensory, cognitive, or motor events. ERPs are derived from the continuous EEG by time-aligning segments of the EEG signal relative to an event of interest, such as a stimulus onset (e.g. visual presentation of a word) or a participant's response. The alignment and averaging of many of these similar EEG segments reveals consistent neural activity that is time and phase locked to the event of interest. The resulting ERP is typically depicted as a waveform of voltage over time and space (electrode location). Stereotyped features of the ERP, defined by a combination of their polarity, timing, scalp distribution, and sensitivity to task manipulations, are known as "components" (Fabiani et al. 2007; Kappenman & Luck 2012).

ERPs have proven to be critically important tools for the study of human language comprehension, production, acquisition, and learning. The fact that ERPs can be continuously monitored with high temporal resolution and even in the absence of explicit tasks or behaviors has allowed for an expanded empirical study of the often covert and temporally extended neurocognitive phenomena underlying language processing. Moreover, the multidimensional nature of ERPs offers researchers a much richer set of measurements than the data obtained from behavioral studies of language processing alone, as different components of the ERP have been linked to specific cognitive processes and neural mechanisms. More recently, ERPs have been recorded in combination with typical behavioral measures used in psycholinguistics, such as self-paced reading (Payne & Federmeier 2017) and eye tracking (i.e. "fixation- related potentials"; Dimigen et al. 2011), producing rich data about the relationship between the neural processes that underlie language processing and resulting behavioral outcomes associated with comprehending, remembering, and making decisions about verbal information.

One of the ERP components most widely-used in the context of language is the N400. The N400 is a negative-going component, peaking just before 400 ms after stimulus onset (in young adults), with a typically central-parietal distribution. Decades of research have shown that the N400 is part of a characteristic brain response to all meaningful stimuli (Kutas & Federmeier 2011 for a review). The N400 is observed to words in all formats and modalities (i.e. spoken, signed, written as visual text or in Braille), as well as to a whole host of meaningful extra-linguistic information, including faces, pictures, and environmental sounds (Kutas & Federmeier 2000). Collectively, this work has strongly suggested that the N400 is a domain-general (i.e. not language specific) brain potential, reflecting activity within a widespread multimodal semantic memory network (Lau et al. 2008; Van Petten & Luka 2006), with its amplitude reflecting the amount of new semantic information becoming active in response to the current input (for reviews see Kutas & Federmeier 2000; Federmeier & Laszlo 2009; Kutas & Federmeier 2011).

The amplitude of the N400 shows a graded facilitation (amplitude reduction) based on the degree to which a stimulus is congruent with its prior context at multiple levels. In sentence processing, N400 amplitudes are elicited as a monotonic inverse function of the cloze probability (Taylor 1953) of the presented word – i.e. the proportion of people who give that particular word as the most likely completion of that particular sentence fragment. Thus, more predictable words, with high cloze probabilities, elicit smaller N400s than words with low cloze probabilities (Kutas & Hillyard 1984; Wlotko & Federmeier 2012). Such effects at the sentence level are, in turn, shaped by discourse-level constraints (St. George et al. 1994; Berkum et al. 1999; Nieuwland & van Berkum 2006).

N400 amplitudes index the build-up of message-level context information. Indeed, effects of context on the N400 are highly incremental in nature, with the N400 showing graded sensitivity to the accrual of contextual constraints as a sentence unfolds from word to word (Payne et al. 2015; Payne & Federmeier 2018; Van Petten & Kutas 1990, 1991). For example, a well-replicated finding is that the N400 to an open-class (i.e. meaning bearing) word exhibits a clear inverse relationship with the word's ordinal position within a sentence (i.e. the *word position* effect). It has been argued that this effect indirectly reflects the incremental accrual of message-level semantic conceptual representation as a sentence unfolds, reducing the demands on semantic access for subsequent words and, in some cases, also allowing the comprehender to anticipate and pre-activate semantic features of likely upcoming words (e.g. Federmeier 2007). Together, this accumulated context-related semantic activation and increased predictability result in a reduction of N400 amplitude with increasing intrasentential word position. Such effects arise in congruent sentences, but not in sentences that provide only syntactic constraints (i.e. syntactic prose: "*The infuriated water grabbed the justified dream.*") or in randomly shuffled words, suggesting that this effect is driven by the accumulation of message-level semantic context rather than a generalized habituation of the N400.

In studies examining visual recognition of words presented in isolation, the amplitude of the N400 is largely determined by lexical features, including average frequency of occurrence (Rugg 1990; Vergara-Martínez & Swaab 2012), and orthographic neighborhood size (i.e. the number of words that are orthographically similar to a target word; Holcomb et al. 2002; Laszlo & Federmeier 2009), among other features (e.g. concreteness, imageability, Barber et al. 2013; Laszlo & Federmeier 2014). For example, more frequent words show reduced (facilitated) N400 activity, and words with more orthographic neighbors show larger (more negative) N400 amplitudes, such that words with many orthographic neighbors engender more activation in the semantic memory system.

A number of studies have examined dynamic interactions between contextual and lexical factors on the N400 (Dambacher et al. 2006; Kretzschmar et al. 2015; Payne et al. 2015; Payne & Federmeier 2018; Van Petten & Kutas 1990, 1991). Nearly all of these studies have shown that some (but not all) word-level attributes on the N400 can be overridden by higher-order semantic context. For example, Payne et al. (2015) (see also Payne & Federmeier 2018) recently reported a single-trial measurement and analysis approach to model the continuous effects of word position on the N400 and to examine how accumulating context dynamically interacts with the sensitivity of the N400 to variability in the lexical properties of individual words. They showed that word frequency effects were reduced with increasing word position. However, effects of orthographic neighborhood, unlike those of word frequency, were unaffected by accumulating context, with effects persisting throughout all word positions (Laszlo & Federmeier 2009).

We have argued that effects of orthographic neighborhood are stable because they reflect intrinsic structural organization within the semantic system, which is not retuned by contextual constraints (reviewed in Federmeier & Laszlo 2009). Under this model, visual access to the semantic system is organized by similarity among orthographic inputs, such that effects of neighborhood should persist even in the presence of strongly constraining sentence contexts. In contrast, word frequency effects arise from transient and malleable activation states in semantic memory. These effects are task-dependent even for single words. For example, Fischer-Baum et al. (2014) found robust effects of word frequency on the N400 in a single word naming task, but no frequency effects when the same words were, instead, presented in a proper name detection task. This pattern suggests that frequency effects are not "built in" to the system, but are dynamically instantiated. Transiently increasing the activation of more frequent words may be useful when preparing to name words out of context, but frequency is not a good cue (and indeed could be distracting) when searching for proper names. Similarly, frequency-based activations may be useful early in a sentence, when there is little other information to guide predictions about what words are likely to be encountered, but such activation states are then modulated by local changes in probability due to recent context. The observed pattern thus reflects a shift from the system being globally more prepared for high frequency words, to activation states reflecting influences from the emerging message. Thus, accumulating semantic context exerts selective influences on features of lexical processing.

Individual differences in reading speed

A major goal of the current study is to examine the influence of contextual and lexical features on the N400 among individual readers who vary in reading speed. The effects of reading speed have been widely studied in the behavioral psycholinguistics literature. Although skilled readers can process text at a very high rate (up to 500 wpm), there is substantial variability in reading speed even within highly literate skilled adult readers (Andrews 2012; Rayner et al. 2010). Some investigators have used reading speed as a proxy measure of overall literacy skill in prior work (e.g. Slattery & Yates 2018; Hawelka et al. 2015). However, although reading is slowed in populations that have shown limitations in fluent comprehension, such as early developing readers (Leinenger & Rayner 2017), aging readers (Payne & Stine-Morrow 2014), and adults with poor literacy skills (Steen-Baker et al. 2017), it is not necessarily the case that slow readers are poorer comprehenders on balance. Indeed, reading speed appears to be partially dissociable from overall comprehension ability (Everatt & Underwood 1994; Underwood et al. 1990; Kintsch & Keenan 1973), such that individual differences in reading speed may reflect an important and unique dimension of comprehension skill.

An open question in this literature concerns what factors contribute to individual differences in reading skill. Some work suggests that fast and slow readers show substantial differences in low-level perceptual factors that influence reading. For example, slower readers have smaller perceptual spans (i.e. useful field-of-view during reading; Rayner et al. 2010; Ashby et al. 2005; Häikiö et al. 2009), as well as differences in the use of visuospatial frequency information in reading (Jordan et al. 2016). Similarly, lexical-quality based theories of skilled reading (e.g. Perfetti 2007; Andrews 2012;) argue that fast readers are facilitated by bottom-up processes that enable readers to gain rapid visual access to high-quality lexical representations, whereas slow readers have poorer access to and less-well specified lexical representations. Indeed, highly skilled readers have been shown to elicit facilitated word naming, lexical decision, and reading times, particularly for lower frequency words (Krieber et al. 2016; Perfetti 2007; Payne et al. 2012).

Another way in which faster readers may potentially achieve high rates of fluent reading is by making rapid use of top-down contextual constraints to predict and preactivate semantic features of likely upcoming words. A number of behavioral studies have found evidence that less-skilled readers do not utilize contextual constraints to facilitate word recognition to the same degree as highly-skilled readers (Murray & Burke 2003; Ashby et al. 2005; Hersch & Andrews 2012). Indeed, in a recent self-paced reading and ERP study, Ng et al. (2017) showed that adults with low literacy skill have longer reading times and reduced sensitivity of the N400 to contextual constraints compared to their higher-literate counterparts. At the same time, very few studies have examined individual differences in context processing among literate readers as a function of speed alone. Testing the effects of reading speed within a more homogenous literate adult sample is important in order to examine whether reading speed is an important factor contributing to individual differences in sentence processing and context use over and above literacy and reading skill. One exception to this is a recent eye-movement study by Hawelka et al. (2015), who showed that slow readers exhibited a greater sensitivity to cloze probability for a currently fixated word, but exhibited reduced effects of predictability for an upcoming word (word $n+1$). They argued that these findings were consistent with a predictive coding model in which slower readers generated forward (predictive) inferences to a lesser extent compared to their faster counterparts.

To our knowledge, no work to date has examined individual differences in reading speed and semantic processing within a highly literate adult sample. As previously described, this gap has arisen in large part because of the nature of the typical RSVP paradigm typically used with ERPs, which precludes individual differences in reading behavior. We (Payne & Federmeier 2017) recently reported the results of a novel analysis of a self-paced reading and ERP co-registration experiment, in which we examined within-subject (intra-individual) variability in behavioral and ERP indices of context use during sentence comprehension. These findings revealed substantial variability in neural responses elicited by trials that were read more slowly versus more quickly, relative to each individual readers' average reading speed (i.e. intra-individual variability). Although our findings highlighted that context use varied substantially within individual participants, the analyses did not speak to the impact of individual differences in overall reading speed.

The current study

To examine the relationship between individual differences in reading speed and the impact of lexical and contextual factors on word processing, in the current study we conducted a secondary analysis of the Payne and Federmeier (2017) dataset to examine whether lexical (word frequency and orthographic neighborhood) and contextual (word predictability) influences on the N400 were modulated by *inter-individual* differences in overall reading speed. To the extent that frequency and predictability effects both arise from a comprehension system that dynamically modulates activation states to ready itself for likely input, then individuals who are capable of relying more strongly on these lexical and contextual information sources may be able to use this information flexibly to maintain a higher reading rate, consistent with aspects of both bottom-up (lexical quality) and top-down (forward inference) accounts, respectively.

In contrast, it is less clear how reading speed might relate to effects of orthographic neighborhood density. The lexical quality hypothesis argues that faster readers have more precise access to representations, suggesting that faster reading might be associated with reduced effects of orthographic neighborhood density (i.e. less spreading activation among orthographically similar inputs). However, if faster reading primarily reflects a better ability to dynamically modulate activation states, then we may expect no effects of reading speed on orthographic neighborhood density effects, as these effects have been hypothesized to arise from the structure of the mapping between inputs and semantics, in contrast to effects of predictability and frequency, which we have postulated as reflecting more malleable and transient activation states.

Method

Participants

Twenty-eight adults (11 women, mean age = 20 years, range = 18–35) from the University of Illinois at Urbana- Champaign community participated in the experiment for course credit. All were right-handed native speakers of English as assessed by the Edinburgh Handedness Inventory (Oldfield 1971), reported near 20/20 corrected or uncorrected vision, and had no prior history of neurological or psychiatric issues. Portions of these data were originally reported in a prior study, focusing on experimental manipulations of constraint and expectancy (Payne & Federmeier 2017). In the current study, we further explore the impact of variation in lexical features on target word processing on single-trial N400s (Payne et al. 2015) and examine how these effects vary as a function of individual differences in reading speed.

Materials

Sentences were 282 sentence frames, taken from Federmeier et al. (2007) that varied with respect to sentence-final expectancy and prior sentence constraint. A follow-up sentence appeared after each critical sentence-final word, so that end-of-sentence reading times were not confounded with the end of the trial. This follow-up sentence was held constant across conditions. In the current study, sentence-final words were examined with respect to word expectancy (cloze probability) and two lexical features that have been shown to previously influence N400 amplitudes: word frequency and orthographic neighborhood density (Payne et al. 2015). Word predictability was derived from a norming study originally reported by Federmeier et al. 2007. In accordance with standard cloze norming procedures, participants were asked to read each sentence frame and to write down the word they "would generally expect to find completing the sentence fragment." Word frequency (log transformed) was derived from the SUBTLEX-US frequency norms (Brysbaert & New 2009). Orthographic neighborhood density was estimated via the orthographic Levenshtein distance 20 (OLD20) measure (Yarkoni et al. 2008). OLD20 reflects the mean distance (in number of steps) from each word to the 20 closest Levenshtein neighbors in the lexicon. Levenshtein distance (Levenshtein 1966) is the minimum number of substitutions, insertions, or deletion operations required to turn one word into another. Thus, words with higher OLD20 scores are considered orthographically sparse (have relatively fewer neighbors), whereas words with lower OLD20 scores are considered orthographically dense (have relatively more neighbors). This measure is, thus, negatively correlated with other common measures of neighborhood size, such as Coltheart's *N* (e.g. the number of words that can be obtained by changing one letter while preserving the identity and positions of the other letters; Coltheart et al. 1977). OLD20 was estimated via the *vwr* package in R. Cloze probabilities ranged from 0 to 100% (mean = 28.41, $SD = 34.88$). Word frequencies ranged from .3 to 5.5 (mean = 3.24, $SD = .79$). OLD20 estimates ranged from 1 to 4.4 (mean = 1.79, $SD = .64$). These measures exhibited modest intercorrelations among the target stimuli ($r_{(\text{freq, cloze})} = .25$; $r_{(\text{freq, old20})} = -.41$; $r_{(\text{old20, cloze})} = -.19$).

EEG recording

EEG was recorded from 26 evenly spaced silver–silver chloride electrodes embedded in an EasyCap (Electro- Cap, Inc., Eaton OH), following the same montage as in Federmeier et al. 2007. Electrodes were referenced online to the left mastoid and re-referenced offline to the average of the right and left mastoids. In addition, one electrode was placed on the left infraorbital ridge to monitor for vertical eye movements and blinks, and another two electrodes were placed on the outer canthus of each eye to monitor for horizontal eye movements. Electrode impedances were kept below

5 kΩ. The continuous EEG was amplified with a BrainAmpDC (Brain Vision, LLC, Morrisville, NC) amplifier (bandpass filtered: 0.02–250 Hz) and recorded to hard disk at a sampling rate of 1000 Hz. The continuous EEG was further high-pass filtered offline (30 Hz), and epochs of EEG data were taken from 100 msec before stimulus onset to 1500 msec post- stimulus onset. Epochs were examined and marked for artifacts (drift, muscle activity, eye blinks, and eye movements). On average, a total of 5% ($SD = 6\%$; range across participants ≤ 1–20%) of critical trials were marked as artifacts and not included in subsequent analyses. There were no reliable differences in artifact rates across conditions. One participant was dropped following artifact detection for an excessive number of artifacts (43% of trials), leaving $n = 27$ participants in the final analysis. ERPs were computed using the ERPLAB toolbox (Lopez-Calderon & Luck 2014) within the EEGLAB toolbox (Delorme & Makeig 2004). Statistical analyses on behavioral and electrophysiological data were carried out using the R language for statistical computing.

Procedure

Participants were seated 100 cm in front of a 21-in. CRT computer monitor. Stimuli were presented using Presentation experimental control software (Neurobehavioral Systems, Albany, CA). Each trial began with a warning sign (several plus signs on the screen) presented for 500 msec; the blank screen between the warning sign and the first word of the sentence varied randomly from 500 to 1200 msec (to prevent the consistent buildup of anticipatory slow-wave activity). Sentences were then presented word by word in the center of the screen. Each word was presented for a minimum duration of 100 msec, with an ISI of 300 msec. Thus, the minimum possible SOA was 400 msec. The overall SOA was determined by participants pressing the button to advance each word. A 3-sec pause separated each sentence. Response hand was counter-balanced across participants, such that half of the participants advanced to the next word using their left thumb and the other half of participants used their right thumb (see Ditman et al. 2007).

Participants were asked to minimize blinks, eye movements, and muscle movements while reading. They were instructed to read for comprehension and told that they would be asked questions about what they had read at the conclusion of the recording session. The recording session began with a short set of practice sentences to acclimate the participants to the task situation. The main experimental session was divided into four blocks of sentences, with participants taking a short rest between each block; recording time was approximately 1 hr. Participants could also take brief breaks between each trial as needed.

Data analysis

Analyses of word-level N400 amplitudes were conducted using linear mixed-effects models via restricted maximum likelihood estimation. All analyses were conducted with the lme4 package (Bates et al. 2014) in the R language for statistical computing. We defined the random-effects structure of our models to represent the inherent experimental design and nested sampling structure of our data (Barr et al. 2013). Thus, variance across subjects, items, and channels were modeled as random intercept terms in the statistical model. Analyses of N400 effects were conducted across eight a priori chosen centro-parietal electrode sites (LMCe, RMCe, LDCe, RDCe, LDPa, RDPa, MiCe, MiPa), where N400 effects are typically largest. Mean amplitudes were measured within an a priori window of 300–500 ms. All continuous variables were standardized, such that parameter estimates reflect change in mean amplitude per standard deviation change in the variable. Effects sizes are presented as model-derived fixed-effect parameter estimates (i.e. regression weights), along with corresponding 95% profile likelihood confidence intervals for statistical inference (Cumming 2014). Conditional plots probing key higher-order interactions are included to aid in interpretation (Bauer & Curran 2005; Curran et al. 2004). Further specification of the random effects structure was modeled following the recommendations of Barr and colleagues (Barr 2013; Barr et al. 2013; but see Bates et al. 2015). Initial models were fit with random slope parameters across subjects for all corresponding within-subject effects warranted by the design. Note that because our word-level effects of interest were not experimentally crossed, but rather properties of the words (e.g. position in the sentence, frequency), by-word random slopes for word-level predictors were not considered. Moreover, by-channel random slope parameters were estimated at zero, resulting in failures to converge to an optimal solution. This likely reflects the limited variance in effects across the selected centro-parietal channels due to volume conduction. Therefore, random slopes of effects across channels were not fit in final models.[1]

Results

Figure 1a shows grand-average ERPs at a representative midline parietal electrode (where N400 effects are typically largest) for words with high, moderate, and low cloze probability. The waveform morphology is typical for visual word presentation. There is a clear impact of cloze probability on the N400, replicating prior work.

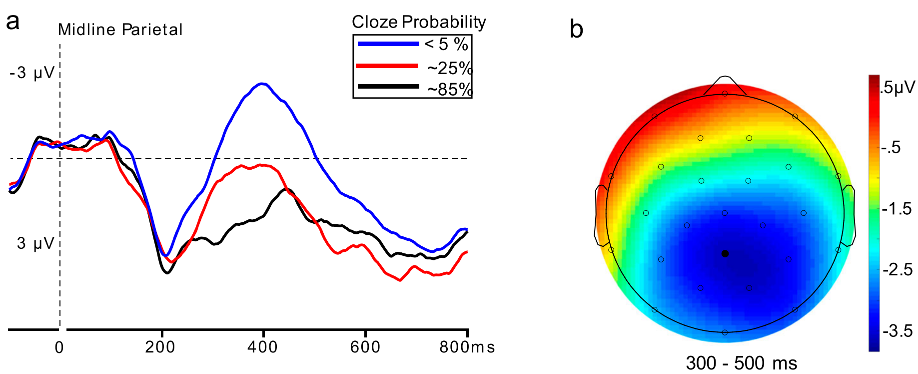

Figure 1. (a) Grand-averaged event-related brain potential waveforms as a representative midline parietal electrode for sentence-final words, as a function of cloze probability (low cloze probability: <5%, moderate cloze probability: ~25%, and high cloze probability: ~85%). The N400 shows the widely-replicated graded inverse response as a function of cloze probability. Note that negative is plotted up. The N400 single-trial measurement window is illustrated in gray. (b) Scalp topography of the canonical central-parietal distribution of the N400 context effect (low cloze – high cloze) between 300 and 500 ms. The highlighted black electrode marks the midline parietal electrode presented in Figure 1a.

Figure 1b shows the scalp topography of the high – low cloze amplitude difference from 300 to 500 ms, highlighting the canonical centro-posterior distribution of the N400 effect (Kutas & Federmeier 2011).

Single-Item analysis of the N400

In the following section, we examine the effects of lexical and contextual influences on the N400 at the single-item (word) level. Such analyses are not possible via traditionally aggregated ERP approaches, in which information across multiple items is averaged and continuous variables are discretized. First, we present a model testing the degree to which N400 amplitudes simultaneously vary as a function of variation in word frequency and orthographic neighborhood density, and importantly, whether these lexical effects are modulated by predictability. Thus, a model was fit to the data with orthographic neighborhood density, word frequency, cloze probability, and their interactions as predictors of N400 amplitude (Model 1). Table 1 presents the fixed-effects parameter estimates, standard errors, t-statistics, and 95% confidence intervals from the linear mixed-effects model corresponding to this analysis.

First, we observed that the sentence-final N400 amplitudes were independently predicted by multiple features. Consistent with the grand average data shown in Figure 1a, and replicating prior work at both the aggregate and individual item level (Kutas & Hillyard 1984; Wlotko & Federmeier 2012), N400 amplitudes were graded by cloze probability, with smaller N400s to words with higher cloze. Word frequency effects typically manifest as reduced N400 amplitudes to words with higher lexical frequency (Van Petten & Kutas 1991; Dambacher et al. 2006; Payne et al. 2015), which was again replicated here. Finally, we observed that words with more dense orthographic neighborhoods elicited larger N400s, consistent with prior experimental work (Holcomb et al. 2002). Thus, we replicated all the expected basic N400 findings for each predictor, taken independently.

Of more interest, however, was the degree to which frequency and orthographic neighborhood effects were moderated by cloze probability, given that most past work has not been able to examine this interaction. There was an interaction between cloze probability and word frequency, but no evidence for an interaction between cloze probability and orthographic neighborhood density. These interactions are presented graphically in Figure 2, which depicts the model-estimated partial-effects plot (see Preacher, Curran & Bauer 2006) of word frequency (top panel) and orthographic neighborhood (bottom panel) on N400 amplitude at conditional levels of cloze probability. Conceptually replicating effects first reported in Payne et al. (2015) (see also Payne & Federmeier 2018), we observed that frequency effects were reduced with increasing predictability (see also Van Petten & Kutas 1990; Dambacher et al. 2006). However, orthographic neighborhood effects were observed across all levels of word predictability. Thus, in contrast to the effects of frequency, it appears that orthographic neighborhood remains a reliable predictor of N400 amplitudes in the face of increasing message-level semantic constraints.[2]

Individual differences in reading time and single-trial N400 effects

Our primary aim was to examine the degree to which individual differences in overall reading speed moderate lexical and contextual influences on the

Table 1. Fixed-Effect Estimates and Confidence Intervals from Model 1 and Model 2

	Model 1					Model 2				
Effect	**Estimate**	**SE**	**t**	**2.5%-ile**	**97.5%-ile**	**Estimate**	**SE**	**t**	**2.5%-ile**	**97.5%-ile**
Cloze	1.09	.17	6.34	.75	1.43	1.11	.18	6.36	.77	1.46
Frequency	.45	.11	3.93	.22	.67	.49	.11	4.49	.27	.70
Orthographic N	.52	.13	4.12	.27	.77	.52	.12	4.21	.28	.76
Frequency x Cloze	-.28	.14	-2.05	-.55	-.01	-.29	.14	-2.14	-.56	-.02
Orthographic N x Cloze	-.12	.16	-.75	-.43	.19	-.18	.17	-1.10	-.51	.14
Reading Speed	-	-	-	-	-	.23	.39	.60	-.53	1.00
Reading Speed x Cloze	-	-	-	-	-	-.37	.17	-2.18	-.70	-.04
Reading Speed x Frequency	-	-	-	-	-	-.21	.10	-2.11	-.40	-.02
Reading Speed x Orthographic N	-	-	-	-	-	-.20	.12	-1.68	-.42	.03
Reading Speed x Cloze x Frequency	-	-	-	-	-	.05	.13	.40	-.20	.31
Reading Speed x Cloze x Orthographic N	-	-	-	-	-	-.07	.16	-.44	-.38	.24

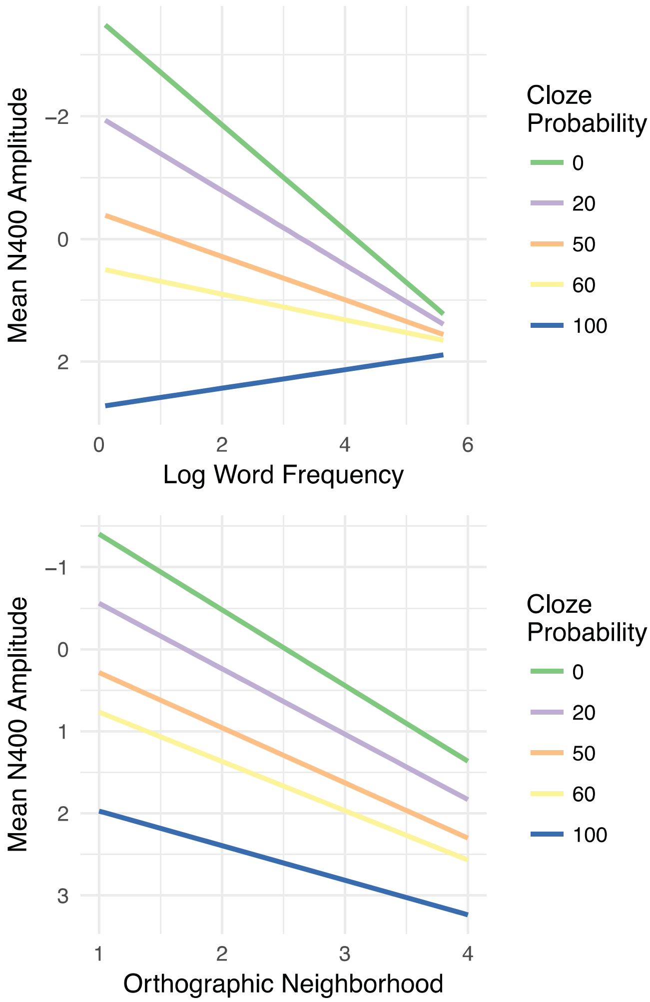

Figure 2. Modulation of lexical features by contextual expectancy. The top figure plots the model-estimated partial-effects plot of the (log) Word frequency X Cloze probability interaction. The bottom figure plots the model-estimated partial-effects plot of the OLD20 X Cloze probability interaction. Words that were more frequent (larger values) showed lower N400 amplitudes, and words that had larger orthographic neighborhoods (smaller OLD20 scores) showed greater N400 amplitudes. Effects of word frequency were attenuated with increasing cloze probability, whereas effects of orthographic neighborhood were invariant to cloze.

N400. Towards that end, we fit a model building off of model 1 that additionally included individual differences in target word reading time, aggregated to the subject level, as a predictor of single-trial N400 amplitudes, as well as a cross-level interaction predictor of each lexical effect in model 1. Results from this model are presented in Table 1.

Average reading speed was 277 ms per word ($SE = 13.51$), with a range across subjects from 200 to 478 ms. Overall individual differences in reading time did not predict the magnitude of the N400 on average. Thus, there was no indication that faster

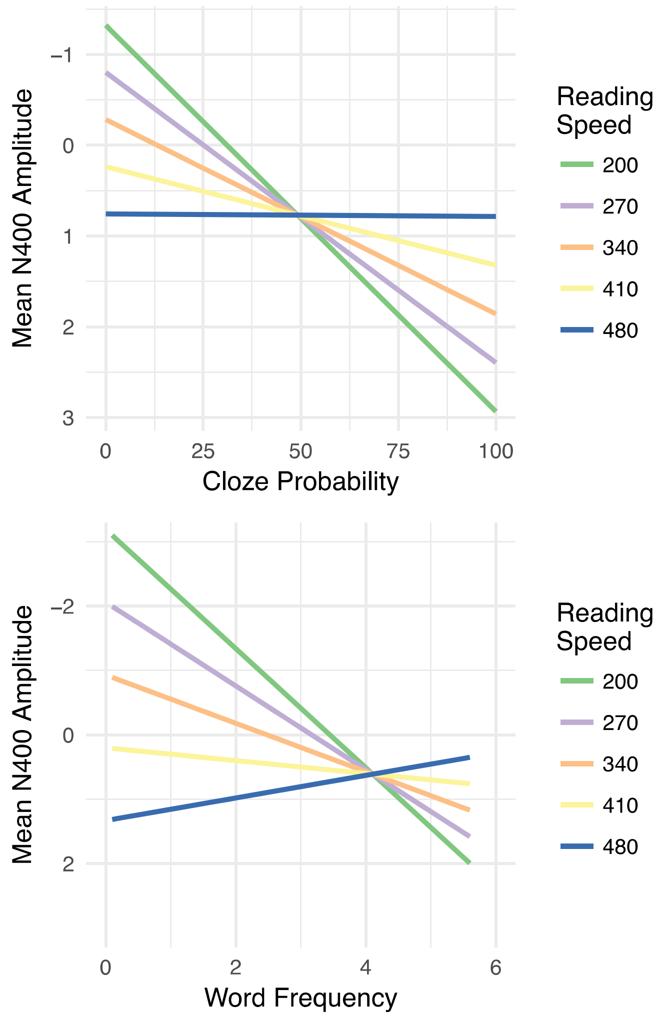

Figure 3. Modulation of word frequency and cloze effects by individual differences in reading speed. The top figure plots the model-estimated partial-effects plot of the (log) Word frequency X Reading speed interaction. The bottom figure plots the model-estimated partial-effects plot of the Cloze probability X Reading speed interaction. Faster readers showed larger effects of both word frequency and cloze probability on the N400 compared to slower readers.

readers have overall larger or smaller ERPs in this time window. However, reading speed did modulate the *effect* of the variables of interest and, moreover, did so selectively. These interactions are presented graphically in Figure 3, which depicts the model-estimated partial-effects plot (see Preacher, Curran & Bauer 2006) of word frequency (top panel) and orthographic neighborhood (bottom panel) on N400 amplitude at conditional levels of reading speed. Faster readers showed increased cloze probability effects – i.e. a greater amplitude difference between higher and lower cloze probability words. Fast readers also showed increased frequency effects – again, greater N400 amplitude differences between lower and higher frequency words. Interestingly, reading speed did not affect the interaction of these variables, meaning that both fast and slow readers showed a similar "transition" from relying on frequency to relying on message-level context information. Reading speed, however, did not have a robust impact on orthographic neighborhood density effects (nor on any interaction including neighborhood).

Discussion

In the current study, we examined how contextual factors (word predictability) interact with lexical features (word frequency and orthographic neighborhood) in determining the magnitude of the N400 response on the single trial level. By using data from a self-paced reading ERP paradigm, rather than traditional RSVP, we could also, for the first time, assess whether these effects differ as a function of individual differences in natural reading speed.

We observed reliable modulation of the N400 by single-word variation in frequency, orthographic neighborhood density, and cloze probability, all factors which have been previously shown to modulate the N400 in independent experimental investigations (using experimenter-fixed pacing). We additionally observed that effects of word frequency are modulated by cloze probability, whereas effects of orthographic neighborhood density remain stable across differing levels of contextual predictability. For words with low predictability from the prior context, word frequency was a robust predictor of N400 amplitude. However, for words that were more predictable from the prior sentence context, we observed diminished effects of word frequency on the N400. This accords with findings using both averaged (Van Petten & Kutas 1990, 1991) and single trial (Payne et al. 2015, 2018) data showing that effects of word frequency on the N400 decrease as a function of word position. The fact that such word-position-based interactions with frequency obtain only for congruent sentences has led to the inference that frequency effects are diminished by increasing contextual constraints. Here, we see the same pattern with word position held constant and predictability measured by cloze probability.

Only two other studies to our knowledge have examined the interaction between word frequency and cloze probability in predicting N400 amplitudes (Dambacher et al. 2006; Kretzschmar et al. 2015). Dambacher et al. (2006) used a repeated-measures regression approach (e.g. Lorch & Myers 1990) to examine interactions between word frequency and word predictability in a corpus of 144 sentences. Notably, they had sequential cloze norms on all words in the sentence. They observed a reliable interaction between word frequency and predictability, such that N400 effects were largest for low cloze probability and low frequency words and were smallest among all high cloze probability words (regardless of frequency). Said another way, word frequency effects were largest among those items that were least predictable, consistent with our findings. However, Dambacher et al. (2006) also offered an alternative explanation for the pattern, which was that word frequency itself may modulate the magnitude of context effects, such that low frequency words are differentially facilitated by context. Their argument rested on the claim that early effects in the P200 component window were sensitive to frequency, but not predictability. According to their claims, high-frequency words can be accessed early (and thus are less dependent on context), whereas activation of low-frequency words benefits more from contextual information. Although we cannot rule out this explanation in the current study, the competing hypothesis, that building context-based activations act to over-ride other factors (such as frequency) that change activation states in long-term memory, is supported by the larger pattern of findings across the N400 literature. On the one hand, it is not the case that higher frequency words are always less likely to show N400 modulations from other sources of facilitation. For example, N400 amplitudes are strongly modulated by repetition, and the effect of repetition and frequency on the N400 is additive rather than interactive (e.g. Rugg 1990). This thus argues against the idea that higher frequency words are inherently less able to be affected by other sources of facilitation (i.e. due to their 'earlier' access). On the other hand, the ability of context information to override other sources of facilitation on the N400 is seen not just for word frequency, but also for lexical association and word priming effects, which show a similar interaction with context effects as that seen here and previously for frequency (Camblin et al. 2007a; Ledoux et al. 2007; Van Petten & Kutas 1991).

Kretzschmar et al. (2015) also examined N400 amplitudes in a fixation-related potential paradigm, using an extreme-group sample design, crossing items high and low in cloze probability and word frequency. They replicated strong effects of cloze probability on the fixation-related N400 to the target word, but obtained no evidence that word frequency interacted with cloze probability or modulated the N400 at all (despite showing effects of frequency on fixation durations). They argued that word frequency may not be a reliable contributor to N400 activity in general. Under their account, the N400 is not 'sensitive to difficulty in lexical processing itself', but instead is sensitive to the interaction between top-down predictions and bottom-up information. They further claim that there is not convincing evidence that there is "any frequency effect at all on N400 amplitude when a word occurs relatively late in a sentence, even when its overall predictability is low". Taken together, their argument is that lexical frequency does not provide bottom-up information relevant to meeting top down predictions during natural comprehension, and, as such, will not predict N400 amplitude in any natural comprehension context.

Although such a view overlaps conceptually with the dynamic nature of the N400 in the semantic memory activation theory discussed above (see also Kutas & Federmeier 2000, 2011), it is inconsistent with the substantial number of studies showing that certain lexical features, including frequency, but also concreteness and orthographic neighborhood density, impact the N400, with several demonstrations that these effects can be observed across an unfolding sentence and at the ends of sentences during comprehension, including in the current study. For example, in the current study we replicated robust effects of orthographic neighborhood density on the N400 even at sentence-final positions for highly predictable words, consistent with several other studies that have shown persistent effects of orthographic neighborhood across word position and at the end of highly predictive sentences (Payne et al. 2015; Payne et al. 2018). That the N400 shows robust sensitivity to orthographic neighborhood density regardless of contextual constraints argues against an account in which the N400 is exclusively determined by the match between bottom-up stimulus characteristics and top-down predictions.

Having replicated and extended the extant empirical evidence about the individual and interacting influences of frequency, neighborhood density, and predictability on semantic access, as indexed by the N400, our primary aim was to assess whether individual differences in reading speed modulate those patterns of effects on the N400 during reading. To our knowledge, this is the first systematic investigation of individual differences in reading speed on the N400. This is due in part to the fact that most

ERP studies utilize an experimenter-paced RSVP paradigm (but see Ditman et al. 2007; Payne & Federmeier 2017; Ng et al. 2017), which precludes an examination of the role of pacing, volitional control over the rate of input, and individual differences in reading speed.

Our findings concerning the effects of reading speed were clear. Reading speed appeared to influence both the effects of word frequency and predictability on the N400. Faster readers showed stronger sensitivity to a word's cloze probability and to a word's frequency compared to slower readers. The effects of orthographic neighborhood density, in contrast, appeared invariant of reading speed. That is, slower and faster readers showed equivalently larger activation to words with more orthographic neighbors. Such a dissociation further argues for multiply determined effects of lexical features on the N400. Visual access to semantics requires activating semantic features of orthographically-related words in a manner that appears obligatory and invariant to effects of context and individual differences. Such effects are in contrast to the effects of frequency, which appear highly malleable and strongly modulated by both individual difference factors (i.e. reading speed) and contextual constraints (cloze probability).

The finding that faster readers showed larger predictability effects on the N400 is consistent with a forward inference account of reading speed, whereas the relationship between speed and word frequency – a classic "lexical" variable – could support a lexical quality account. However, the lack of influence on orthographic neighborhood density effects is then perhaps puzzling, since better "tuned" lexical representations might have been thought to mean less activation of neighboring words. Such findings suggest that dividing features into "lexical" and "contextual" may be misleading because, as we have argued, different lexical factors influence processing via very different mechanisms and similar mechanisms can underlie effects at both the lexical and contextual level (i.e. "priming" effects on the N400 can arise from prior contextual constraints at the word, sentence, and discourse level; Van Petten 1993). Indeed, here it would seem that fast readers may also be "better activators" – more sensitive to all variables that are associated with dynamic control of activation level, whether those features are based on global 'baseline' probabilities (such as frequency) or ones built from the immediate context.

That faster readers showed increased N400 sensitivity to cloze probability and frequency could be seen as contradictory to work showing that faster presentation rates appear to reduce the sensitivity to context (Camblin et al. 2007b; Wlotko & Federmeier 2015). Moreover, Payne and Federmeier (2017) showed that N400 facilitation from prior context is reduced on trials where readers self-pace at a rate that is considerably faster than their average reading speed. Although on the surface these findings may seem contradictory, in fact these differing patterns emphasize the importance of volitional control and the need to separate the effects of intra-individual and inter-individual variability in processing speed. When readers are presented information at a faster rate that is outside of their control, or in subsets of trials where readers are electing to read at a rate considerably faster than their average rate, N400 effects are reduced, suggesting poorer access to semantics and potentially worse comprehension (e.g. Ng et al. 2017). In contrast, the current study shows that when readers can elect to self-pace at their chosen rate, those individuals who naturally read at a faster rate on average also are more sensitive to some sources of N400 facilitation. Importantly, the current findings suggest that reading speed is a critical factor to further consider in the growing literature on individual differences in sentence processing. For instance, a growing literature has considered the effects of working memory (Payne et al. 2014), language experience (Payne et al. 2012), and reading skill (Ng et al. 2017; Payne, Federmeier & Stine-Morrow, under review; Veldre & Andrews 2014), little work has considered the role of reading speed. The current study shows robust modulations of lexical and sentential effects as a function of reading speed, even in a sample of skilled adult readers.

Finally, it was notable that we did not observe any evidence that the context by frequency interaction varied among faster and slower readers. Such findings stand in contrast with other individual difference measures, such as working memory span, which have been shown to specifically reduce the efficacy of context-based facilitations (Boudewyn et al. 2013). In contrast, reading speed did not seem to alter the "prioritization" of contextual predictability versus frequency in driving N400 facilitations. Instead, faster readers showed increased sensitivity to (i.e. elicited more activation change to) both factors in an additive fashion.

Conclusion

In the current study, we systematically examined interactions among reading speed, contextual constraints, and lexical variation on the N400 in a novel self-paced ERP paradigm with single-trial EEG analyses. The results highlighted the dynamic nature of the processes underlying semantic access, by showing that N400 amplitudes are simultaneously influenced by multiple, interacting factors at multiple levels of representation (i.e. the word, the sentence context, and the individual). Our findings showing the critical relationship between N400 effects and reading speed highlight the limitations of relying on a single methodology for a full understanding of the dynamics of semantic processing in sentence comprehension. Thus, we encourage increased research into multi-method approaches that bridge behavioral and neural levels of analysis, and moreover, the increased use of analytical methods that allow for the coordinated analysis of coupling between behavioral and neural indices of processing at not only the trial-by-trial (intra-individual) level, as well as a consideration of individual differences in comprehension abilities.

Disclosure statement

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Notes

1. Follow-up analyses were conducted to test the sensitivity of our effects to specification of electrode site in the model, including electrode as a fixed effect, picking of a single a priori representative electrode for analysis (Cz), and aggregating mean amplitudes across all 8 electrodes. Importantly, our results were robust to differences in the specification of electrode.
2. There is a sizeable correlation between word length and orthographic neighborhood that is driven by the fact that words that are quite long tend to have a sparse orthographic neighborhood space. Given the high degree of correlation between word length and ON, there is concern about collinearity influencing model parameters. Given that length effects are not

theorized to directly impact N400 amplitudes, these effects were not included in the current models. We did conduct a follow-up analysis including both length and ON; however, SEs of the fixed effects of the lexical features were considerably inflated in this model suggesting problems with high multicollinearity. Nevertheless, we conducted an additional analysis aimed at examining the effects of ON in a model without longer words (that necessarily contain fewer neighbors; see also Payne et al. 2015). This analysis was conducted on a restricted dataset excluding words longer than eight characters. Importantly, we still observed reliable relationships between ON and N400 amplitude in the restricted dataset.

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