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Research report

Contextual constraints on lexico-semantic processing in aging: Evidence from single-word event-related brain potentials

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ABSTRACT

The current study reports the effects of accumulating contextual constraints on neural indices of lexico-semantic processing (i.e., effects of word frequency and orthographic neighborhood) as a function of normal aging. Event-related brain potentials were measured from a sample of older adults as they read sentences that were semantically congruent, provided only syntactic constraints (syntactic prose), or were random word strings. A linear mixed-effects modeling approach was used to probe the effects of accumulating contextual constraints on N400 responses to individual words. Like young adults in prior work, older adults exhibited a classic word position context effect on the N400 in congruent sentences, although the magnitude of the effect was reduced in older relative to younger adults. Moreover, by modeling single-word variability in N400 responses, we observed robust effects of orthographic neighborhood density that were larger in older adults than the young, and preserved effects word frequency. Importantly, in older adults, frequency effects were not modulated by accumulating contextual constraints, unlike in the young. Collectively, these findings indicate that older adults are less likely (or able) to use accumulating top-down contextual constraints, and therefore rely more strongly on bottom-up lexical features to guide semantic access of individual words during sentence comprehension.

1. Introduction

Normative age-related neural changes have widespread effects on systems that support higher-order cognitive functioning (e.g., reasoning, working memory, decision making; see Cabeza et al., 2016). Given the sheer complexity involved in effective language comprehension, one may expect similar declines as people age. However, at least at the level of behavior, much of comprehension remains relatively intact over the adult lifespan in the absence of dementing diseases and non-normative cognitive impairments (Grossman et al., 1996; Payne and Stine-Morrow, 2016). For instance, healthy aging largely spares verbal semantic memory and word recognition (Cohen-Shikora and Balota, 2016; Payne et al., 2012), with older adults exhibiting larger vocabularies (Verhaegen, 2003), preserved lexical access in word recognition (Laver and Burke, 1993; Federmeier et al., 2003), and increased automaticity in lexical processing (Lien et al., 2006), particularly among highly-literate older adults who benefit from decades of additional experience with language (Payne et al., 2012, 2014).

At the same time, aging can have substantial impacts on more effortful top-down comprehension processes that require building and maintaining complex message-level meaning representations from text (Stine-Morrow et al., 2008; Payne et al., 2014; Federmeier, 2007; Wlotko et al., 2012; Noh and Stine-Morrow, 2009; Wingfield and Grossman, 2006). The effects of aging on comprehension are substantial in studies that directly probe end-state memory representations, with older adults showing sizable deficits in immediate memory for message-level information from both text and speech (Payne et al., 2014; Johnson, 2003), suggesting either that message-level semantic representations are fleeting with advancing age or that aging impairs the construction of such representations. This developmental divergence between preserved word-level processing and diminished message-level processing presents an interesting challenge for understanding how aging may impact the top-down use of context representations to modulate word recognition in aging.

Young adults rapidly make use of contextual constraints to facilitate word processing during reading and listening, with evidence converging on this conclusion from multiple methodologies, including studies of self-paced reading (e.g., Dagerman et al., 2006), eye-movement control (e.g., Rayner and Well, 1996), fMRI (e.g., Schuster et al., 2016), and a sizeable electrophysiological

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literature probing both neural oscillatory activity (e.g., Rommers et al., 2017) and event-related brain potentials (ERPs; see Federmeier, 2007; Van Petten and Luka, 2012 for reviews). Indeed, one of the most robust and reliable effects of context on word processing comes from ERP studies showing facilitation of the N400, a component implicated in semantic memory access and retrieval processes. The N400 is a negative-going centro-parietally distributed waveform feature, peaking approximately 400 ms after stimulus onset, and is part of the typical brain response to all meaningful or even potentially meaningful stimuli, including written, spoken, and signed words, images, and environmental sounds (see Kutas and Federmeier, 2011 for a review).

One prominent theory of the N400 is that it reflects activity within a widespread domain-general and multimodal semantic memory network, with its amplitude reflecting the amount of new semantic information becoming active in response to the input (for reviews see Kutas and Federmeier, 2000; Federmeier and Laszlo, 2009; Kutas and Federmeier, 2011). This tight link between N400 activity, semantic access, and context has made it an important neural marker for studying meaning processing in language comprehension. The amplitude of the N400 shows graded modulation based on the degree to which a stimulus is congruent with its prior semantic context, whether that context comes from lexical cues (e.g., lexical associative priming; Kutas, 1993), sentential context (e.g., cloze probability, e.g., Kutas and Hillyard, 1984), or the larger discourse (van Berkum et al., 1999). Moreover, 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 (Payne et al., 2015; Van Petten and Kutas, 1991).

Older adults appear to gain less facilitation from sentential context compared to young adults, as reflected in reduced effects of context on the N400 in aging (Federmeier and Kutas, 2005; Federmeier et al., 2003, 2010; Ford et al. 1996; Gunter et al., 1992; Hamberger et al., 1995; Wlotko et al., 2012; Wlotko and Federmeier, 2012; Woodward et al. 1993; see Wlotko et al., 2010 for a review). These findings have been taken to suggest that older adults are less efficient in being able to construct or maintain a message-level representation of the context (Federmeier, 2007; Wlotko et al., 2010). At the same time, behavioral studies have shown a more mixed pattern of findings, including studies reporting age-invariance in effects of cloze probability (Rayner et al., 2006; Stine-Morrow et al., 1999), age-related reductions in online sensitivity to context (Dagerman et al., 2006), and evidence that older adults can show larger and perhaps compensatory sensitivity to context, particularly in cases wherein the perceptual input is degraded (e.g., speech or reading in auditory noise) or working memory is taxed (Madden, 1988; Stine-Morrow et al., 1996). One similarity between many of these studies is that they make inferences regarding the use of context (and age-related changes in context use) by examining effects on the processing of a single (typically sentence-final) target word that varies in cloze probability. However, context exerts graded, incremental, and cumulative effects on word processing that unfold over an entire sentence or discourse, and sentence-final word processing reflects only a snapshot of part of this effect (one that is also confounded with end-of-sentence wrap-up processes that change with age as well, Payne and Stine-Morrow, 2012, 2016).

If aging modulates the ability to construct a message-level semantic representation as the context continually unfolds, then this may be more clearly observed in measures of processing that track the incremental accrual of context. More recently, behavioral psycholinguistics has begun focusing on immediate and incremental online processing in sentence comprehension (Altmann and Kamide, 2007; Kamide, 2008; Rayner, 2009). However, evidence from event-related brain potentials (ERPs) for the incremental formation of semantic representations has existed for nearly 30 years (Kutas et al., 1988; reviewed in Kutas and Van Petten, 1994). One key piece of evidence for the incremental formation of context representations comes from studies showing that N400 amplitudes manifest a well-replicated *word position effect.* In congruent sentence contexts, the N400 to open class (e.g., meaning bearing) words is inversely related to ordinal position in the sentence, reflecting the real-time incremental accrual of contextual constraints on semantic processing (Van Petten and Kutas, 1990, 1991; Dambacher et al., 2006; Payne et al., 2015) in the absence of any explicit experimental manipulations or task demands. In isolated contexts (i.e., no discourse-level constraints; cf. Van Petten, 1995), a reader begins a sentence without message-level semantic information. With increasing progress into a sentence, a conceptual representation is incrementally built, 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 (cf. Federmeier, 2007; Kutas and Van Petten, 1994). Together, this accumulated context-related semantic activation and increased predictability result in a reduction of N400 amplitude with increasing intrasentential word position.

Recently, Payne et al. (2015) revisited the impact of accumulating contextual constraints on the N400 in college-aged adults by adopting 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 (cf. Van Petten and Kutas, 1991). Importantly, by adopting a single-item linear-mixed effects modeling approach, Payne et al. could examine the simultaneous and continuous contribution of both contextual constraint (i.e., word position) and lexical variation (e.g., word frequency, orthographic neighborhood) on the N400.

Conceptually replicating effects originally reported by Van Petten and Kutas (1991), Payne et al. (2015) found evidence for reliable linear word position effects on single-trial variation in the N400—effects that were present for congruent sentences only, but not for sentences that lacked any message-level context representation, such as random word strings or so-called "syntactic prose" (e.g., *The infuriated water grabbed the justified dream*; Marslen-Wilson and Tyler, 1980). Moreover, they conceptually replicated Van Petten and Kutas (1991) in showing that word-level variation in lexical frequency predicted single-item variation in N400 amplitudes to words at the beginning of sentence contexts, with larger N400 amplitudes to less frequent words. Importantly, this effect of frequency was reduced with increasing word position in sentences with congruent semantics, but persisted in syntactic prose sentences and random word strings. Payne et al. (2015) further showed that the N400 was independently modulated by a word's orthographic neighborhood (i.e., the number and features of orthographically similar strings: Coltheart et al., 1977; Yarkoni et al., 2008), such that words with more orthographic neighbors showed larger (more negative) single-trial N400 amplitudes, replicating prior work in visual word recognition (e.g., Laszlo and Federmeier, 2009). Importantly, orthographic neighborhood effects, unlike those of word frequency, were unaffected by accumulating context, with effects persisting throughout all sentence contexts.

Payne et al. (2015) argued that these results were consistent with the dynamic semantic memory access view of the N400 in visual word recognition proposed by Federmeier and Laszlo (2009). Federmeier and Laszlo argued that the divergent effects of context on N400 frequency and orthographic neighborhood effects can be predicted based on the features of semantic memory use indexed by these lexical variables. Frequency effects reflect transient and malleable "baseline" activation states in semantic memory. With the accumulation of contextual constraints, these states are modulated, functionally reflecting a shift from the system being generally more prepared for high frequency words (in the absence of contextual constraints or task demands), to the activation states in long-term semantic memory reflecting influences from recently encountered words and the emerging message. In contrast, neighborhood effects reflect intrinsic structural organization within the semantic system, which is not retuned by contextual constraints. To the extent that visual access to the semantic system is organized by similarity among orthographic inputs, effects of neighborhood will persist even in the presence of strongly constraining sentence contexts. Thus, accumulating semantic context exerts selective influences on features of lexical processing in younger adults.

At the same time, little research has examined how lexical properties impact neural indices of semantic memory access in aging (but see Federmeier et al., 2003), with no studies to our knowledge examining N400 responses as a function of variation in lexical frequency or orthographic neighborhood in older adulthood. Moreover, despite the highly replicable finding of reduced cloze probability effects on the N400 in aging, there has yet to be a direct examination of incremental context processing on the N400 in older adulthood. Thus, in the current study, we report the first direct test of incremental context use in older adulthood by tracking the effects of accumulating context on lexical variation in single-word N400 responses as sentences unfold word-by-word, in real-time. If older adults do not incrementally construct a robust message-level representation as the sentence unfolds (cf. Wlotko et al., 2010), then we would expect the canonical word position N400 effect to be reduced in older adults. Importantly, if older adults rely less on contextual constraints to guide lexical processing, we should observe that older adults' N400 responses would show a *greater* sensitivity to word frequency than the young in the face of accumulated contextual constraints. That is, the word frequency effect should persist into later word positions in congruent sentences, given that frequency effects would not be expected to be overridden by accumulating contextual constraints in older adults. Importantly then, our prediction is not simply that N400 effects will be reduced in aging, as such findings could be partially explained by overall age-related changes in brain morphology that change the scaling properties of the N400 (cf. Wlotko et al., 2010), but specifically that the N400 will show a reduced sensitivity to top-down contextual constraints in aging with a concomitant preservation or even increase in sensitivity to bottom-up lexical features.

2. Results

2.1. Recognition memory accuracy

Age differences in behavioral performance were assessed by calculating the discriminability index d′ for sentence recognition in the older adults, and comparing that with the young adult data from Payne et al. (2015). Overall, both groups showed large effect sizes for recognition memory, with young adults showing a d′ = 2.55 (SE = 0.24) and older adults showing a d′ = 1.84 (SE = 0.59). Thus, participants appeared to be attending to the experimental materials. Importantly, although older adults had numerically smaller d′ scores, this difference was not statistically significant (t = 1.11), indicating comparable overall behavioral performance between the groups.

2.2. Incremental effects of syntactic and semantic context

2.2.1. ERPs

Fig. 1 shows grand-average ERPs at a representative midline parietal electrode (where N400 effects are typically largest) at early (2nd word) and late (last word) sentence positions for congruent, syntactic prose, and random sentence constructions for the old adult sample (right) and the young adult sample (left) from Payne et al. (2015) for comparison. The waveform morphology is typical for visual word presentation in both younger and older adults. On the N400 component, we observed a clear impact of congruent contexts on the N400, but only at late positions within the sentence, when contextual constraints have accumulated. Importantly, this effect is observed in both the young and old adults, but it appears to be reduced in magnitude in the older sample.

2.2.2. Single-Item analysis

In the following section, we explore these context effects on the N400 at the single-item (word) level in order to track the incremental accumulation of contextual constraints on the N400. Following Payne et al. (2015), we first test the degree to which N400 amplitudes vary with word position as a function of sentence context in the old. A linear mixed-effects model with a continuous linear word position by Context (C1: Congruent vs. Syntactic Prose, C2: Congruent vs. Random) interaction was fit to the data, with a maximal random-effects structure (see Barr et al., 2013). This maximal model did not converge, so a simplified model was fit with a variance components structure (e.g., covariance terms were constrained to 0; see Barr et al., 2013). Of key interest here is the test of whether word position interacts with each sentence context contrast.

The WP × C1 interaction was not statistically significant (b = −0.17; 95% CI = [−0.37, 0.04]) suggesting that the effect of word position was not reliably different between congruent and syntactic prose sentences. However, there was a small but significant WP × SC2 interaction indicating that the word-position effect was reliably larger in congruent sentences than in random word strings (b = −0.21; 95% CI = [−0.42, −0.005]). To visualize this effect, Fig. 2a presents the linear word position effect for each sentence context. As a point of comparison, the same results are plotted from the young adults in Payne et al. (2015). As can be seen, the older adults show the same overall pattern of results as what we observed in young adult samples reading the same exact sentences (see also Van Petten et al., 1990, 1991; Dambacher et al., 2006), although the context effect appears reduced in magnitude in the older adult sample (see below for a direct statistical comparison).

Fig. 2b presents the scalp distribution of the word-position effect in congruent sentences for young adults from Payne et al. (2015) and old adults in the current study. To confirm that our effects have the expected distribution for an N400, channel-specific best linear unbiased predictors (BLUPs) of the effect of word position on N400 amplitudes were estimated across all scalp channels for open-class words within congruent sentences only. A scalp topography map of the word-position effect was created by mapping the channel-specific data to a two-dimensional circular head and using spherical spline interpolation of values between channels on a fine Cartesian grid via the topoplot function in the EEGLAB (Delorme and Makeig, 2004) toolbox for MATLAB (The MathWorks, 2014). The resulting figure represents the spatial distribution of the effect size of word position on N400 amplitudes across the scalp. This figure clearly shows that the word- position effect follows a characteristic N400 scalp distribution in both younger adults and older adults, with the largest effects over centro-posterior electrode sites, consistent with the N400 scalp distribution in both young and old adults (cf. Wlotko et al., 2014).

Following Payne et al. (2015), we also conducted a control analysis to determine the extent to which the word-position effects on the N400 detailed above might be related to confounding factors early in the waveform that could influence component measurement at the item level (due to e.g., slow potentials, early sensory

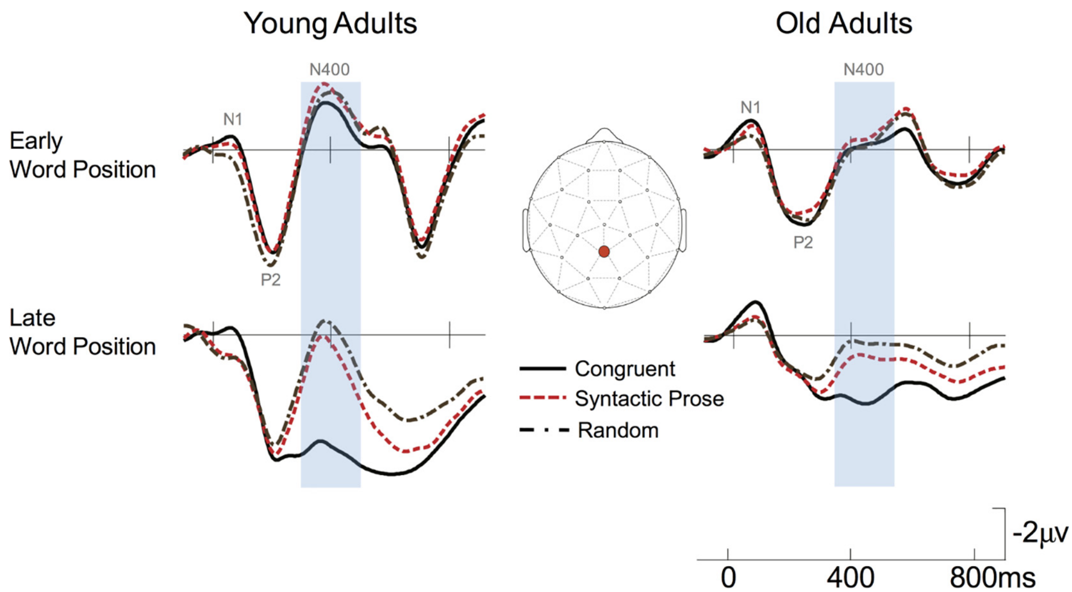

Fig. 1. Grand-averaged ERPs waveforms for early (2nd position) and late (last position) words in congruent, syntactic prose, and random sentence contexts for young adults and old adults. The N400 single-trial measurement window is illustrated for each group. At early word positions, there are no differences between sentence types in either group. However, by the end of the sentence, young adults show a reduced N400 only to congruent sentences. In older adults, a similar effect is observable, although the overall magnitude is reduced. Note that negative is plotted up. Note also that in the late word position, no sensory potentials are observed following the N400, since it is the last word of the sentence.

differences, or preceding component overlap). A model was fit that was identical to the initial WP × SC model described above, except that it was fit to word-level mean amplitudes in the period from 0 ms to 200 ms poststimulus onset. This period is the same size as the N400 latency measurement window, but is one in which semantic influences would be unexpected (Laszlo and Federmeier, 2014). We found no reliable interactions, nor any evidence for reliable word-position effects within any sentence type, suggesting that the N400 word-position effect is not driven by early or general item-level fluctuations in amplitude.

Collectively, the overall findings suggest that older adults may benefit to some degree from the incremental accrual of contextual constraints, but that these influences on semantic memory access for subsequent words are small and appear less robust than the benefit observed in young adults. Now, we turn to examining the degree to which word-level lexical variation (word frequency and orthographic neighborhood) contributes to N400 amplitude in older adults and to study how these lexical effects are impacted by semantic and syntactic contextual constraints.

2.3. Lexico-semantic modulation of the N400 in older adulthood

The findings thus far indicate that the responsiveness of the N400 to incremental contextual constraints may be less robust in older adulthood. However, these findings do not speak to how lexico-semantic processing *per se* is modulated by context in aging. Indeed, very little is known about lexical influences on the N400 in aging. As such, our aim was twofold: to report the effects of variation in lexical properties (word frequency and orthographic neighborhood) on the single-trial N400 in aging, as well as to characterize whether and how these lexical influences are modulated by accumulating contextual constraints. In the young, as message-level information accrues, certain lexical level influences (e.g., word frequency) are correspondingly weakened (Payne et al., 2015; Van Petten and Kutas, 1991). If older adults are not using contextual constraints to the same degree as the young to incrementally build a message-level semantic representation, we should expect to see a reduced impact of those constraints on lexical processing in aging, resulting in older adults showing persisting effects of lexical characteristics such as word frequency, regardless of contextual constraint.

The aim of this model was to test the effects of accumulating sentence contexts on lexical processing, as indexed by frequency and neighborhood effects on the N400. Thus, we were testing for the presence of three-way interactions between sentence context, word position, and frequency/neighborhood. In Payne et al. (2015), the 3-way interaction was reliable for word frequency, replicating the finding that frequency effects are overridden by accumulating contextual constraints in young adults (see also Van Petten and Kutas, 1991; Dambacher et al., 2006). However orthographic neighborhood effects were not modulated by accumulating semantic context in the young. Following Payne et al. (2015), effects are adjusted for variation in concreteness (Wilson, 1988), word length, and sentence length. Concreteness and length are included as control variables because they are correlated with both frequency and orthographic neighborhood. Moreover, concreteness has been shown to be an important independent predictor of N400 amplitude in a recent single-item ERP investigation of word recognition (Van Petten, 2014). Sentence length is also included as a covariate, because variability in overall length may contribute to the strength of word position as a moderator of lexical effects.

Fig. 2c presents the standardized fixed-effects parameter estimates and corresponding 95% Profile confidence intervals for the critical 3-way interactions testing whether lexical processing is differentially modulated by accumulating semantic contextual constraints in the current sample of older adults. Results from the same model fit to the young adult data, as reported in Payne et al. (2015), are presented for comparison. Older adults showed no reliable 3-way interactions between sentence type, word position, and lexical variables (frequency or neighborhood), whereas young adults showed a reliable interaction specifically for word frequency (Fig. 2c). To visualize the impact of sentence type, word position, and lexical variation on the single-trial N400 in older adults, Fig. 3 depicts the partial-effects plot (Preacher et al., 2006) of model predicted N400 amplitudes as a function of continuous variation in (log) word frequency (top) and orthographic

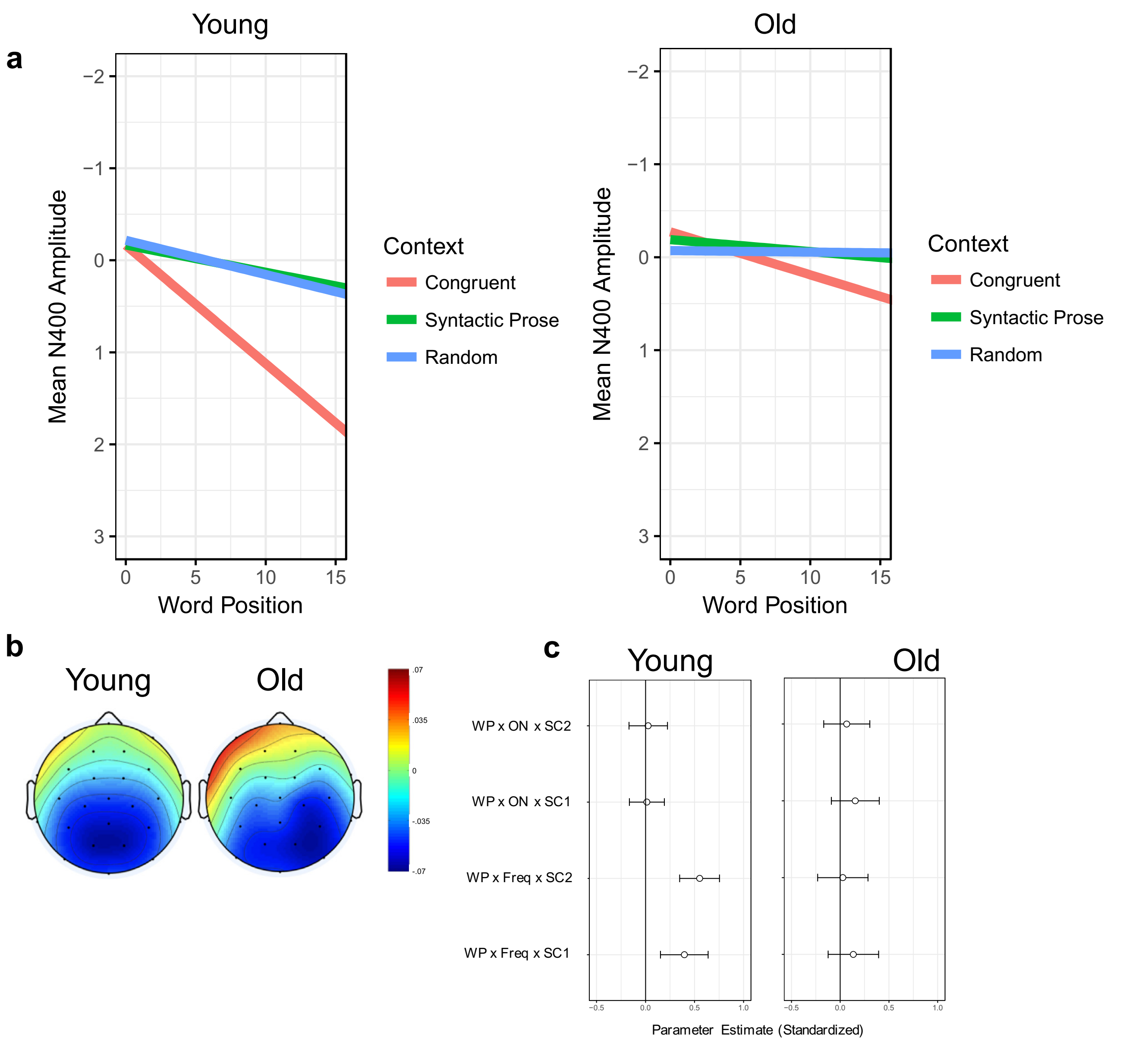

Fig. 2. (a) Linear word-position effects on single-word N400 amplitudes as a function of sentence context and age group. Note that negative is plotted up. (b) Scalp topography of the best linear unbiased estimates of word- position effects on N400 amplitude in congruent sentences in young and older adults. The color scale is in μV/word (see text for details). (c) Fixed-effect parameter estimates of the critical Word Position × Lexical Feature × Context interactions and corresponding 95% profile confidence intervals. These interactions were not significant in older adults, suggesting that the incremental accrual of context did not modulate lexical processing in aging.

neighborhood (bottom), presented separately at conditional levels of word position— early words (25th percentile), medial words (50th percentile), and late words (75th percentile). Plots are presented separately for congruent, syntactic prose, and random sentences. In all three sentence types, more frequent words showed reduced (more positive) N400 amplitudes, consistent with prior work in young adults (but, to our knowledge, never previously tested in older adults). Critically however, word frequency effects appeared invariant to changes in word position, in contrast to typical findings in younger adults (Dambacher et al., 2006; Van Petten and Kutas, 1991; Payne et al., 2015). Moreover, orthographic neighborhood modulated the N400 in older adults, such that words with more neighbors (lower OLD 20 scores) showed greater N400 activity, again replicating prior work in young adults and extending it to the older adult population. As in the young adult results from Payne et al. (2015), neighborhood effects did not appear to be modulated by word position.

Simplified follow-up models were tested by removing the non-significant 3-way interactions in order to test the lower-order 2-way interactions between sentence context and lexical features, and between word position and lexical features, with random slopes fit across subjects for all 2-way interactions. Only one significant interaction was found, between SC2 and orthographic neighborhood ($b = -0.31$, 95% CI: [−0.56, −0.06]), indicating that neighborhood effects were reliably larger in the congruent sentences compared to syntactic prose (see Payne et al., 2015, for a similar finding in the young). Finally, the simple effects of orthographic neighborhood ($b = .30$, 95% CI: [0.08, 0.51] and word frequency ($b = 0.93$, 95% CI: [0.77, 1.07]) were reliable in a model testing only lexical influences on N400 amplitude (correcting for word length, concreteness, sentence length, and word position).

Collectively, these results suggest that the N400 in older adults shows a bias towards lexical influences and away from message-level contextual constraints, consistent with prior work suggesting

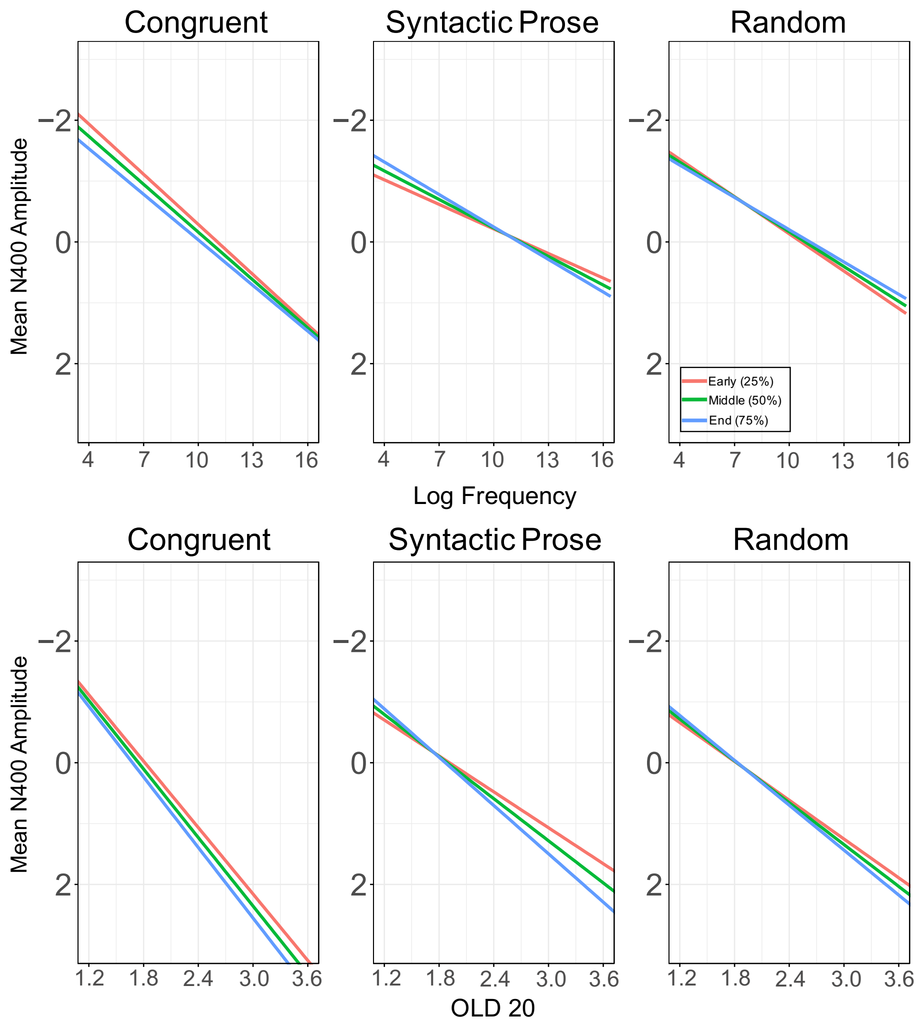

Fig. 3. Model estimated partial-effects plots of the (log) Word frequency × Word position × Context interaction (top) and the Orthographic neighborhood (OLD20) × Word position × Context interaction (bottom) in the older adult sample. Words that were more frequent (larger values) showed lower N400 amplitudes, and words that had larger orthographic neighborhoods (smaller OLD20 scores) showed greater N400 amplitudes. These effects were not modulated by word position in any sentence type.

that older adults take less advantage of context to facilitate ongoing neural processing of semantics. To provide further evidence of age-related reductions in incremental context use on the N400, we report a supplemental analysis pooling the current data from older adults with data from the young adult sample from the experiment in Payne et al. (2015) that used identical experimental protocols, recording parameters, and stimuli as in the current study.

2.4. Age-comparative analysis

To directly compare age-group differences in the effects of accumulating contextual constraints on lexical processing, the reported analyses are focused on selective tests of age differences in the two major findings discussed above, (1) the reduced word position effect on the N400 and (2) persistent lexical effects in the face of incrementally constraining semantic context in older adults. Therefore, to reduce model complexity and maintain a focus on targeted a priori tests, models were tested only on the critical congruent sentences, the one sentence condition that affords the construction of a message-level semantic representation.

First, a linear mixed-effects model was fit to test for the critical Word Position × Age Group interaction, with random intercepts for subjects and items, and a random slope defined across subjects for the word position effect, excluding the covariance between intercepts and slopes in order to achieve model convergence (see Barr, 2013). Of key interest is the test of whether word position interacts with age group, which would provide statistical support for the claim that the word position context effect is reduced in aging. Indeed, there was a reliable interaction, indicating age-group differences in the word position effect ($b = 0.35$, 95% CI: [0.09, 0.60]). To further probe this interaction, individual models were fit testing the word position effect separately in each age group. These models showed that the word position effect was larger in magnitude among younger adults ($b = 0.62$, 95% CI: [0.41, 0.82]) than it was in the old ($b = 0.22$, 95% CI: [0.07, 0.36]), as can be seen in Figs. 1 and 2.

Finally, a model was fit testing for age-group differences in the effects of word position on word-level variability in frequency and orthographic neighborhood effects (e.g., Age × WF × Word Position and Age × OLD20 × Word Position). All lower-order fixed effects supporting the critical 3-way interactions were included as fixed-effects in the model, and the same item-level covariates were also included as in the lexical models above (e.g., concreteness, word length, and sentence length). Finally, random slopes were included for the highest-order within-subject interactions (Word Position × Frequency, Word Position × OLD20). If older adults do not utilize accumulating contextual constraints to facilitate lexical processing, then we should expect to observe a reliable

Age × WF × Word Position interaction, indicating age differences in the influence of word position on word frequency effects. However, we did not expect age to moderate the effects of word position on orthographic neighborhood effects (Age × OLD20 × Word Position), as neighborhood effects are invariant to contextual constraints.

The Age × WF × Word Position interaction was significant ($b = -0.38$, 95% CI: [−0.75, −0.03]), indicating age-group differences in the effects of word position on frequency effects. This was further supported by fitting separate models testing for the WF × Word Position interaction separately in younger and older adults. This revealed a reliable reduction in word frequency with increasing word position in the young (WF × Word Position: $b = -0.60$, 95% CI: [−0.89, −0.31]), but not in the old ($b = -0.19$, 95% CI: [−0.42, 0.04]). A different pattern was observed for orthographic neighborhood, as the Age × OLD20 × Word Position interaction was not reliable ($b = 0.04$, 95% CI: [−0.23, 0.29]). Instead, there was an overall age difference in the magnitude of the orthographic neighborhood effect, as supported by a reliable Age Group × OLD20 interaction ($b = -0.47$, 95% CI: [−0.76, −0.21]), such that the orthographic neighborhood effect was larger in the older adults ($b = 0.45$, 95% CI: [0.14, 0.77]) than in the young ($b = 0.25$, 95% CI: [0.02, 0.51]). These findings are summarized graphically in Fig. 4, which presents partial effects plots of the effects of word frequency and orthographic neighborhood at conditional levels of word position in congruent sentences, separately for young and old adults. This plot clearly shows the reduced effects of word frequency with increasing word position in younger adults. Critically, unlike younger adults, older adults do not show evidence of reduced frequency effects with incrementally accruing context. Rather, lexical frequency remains a reliable predictor of N400 amplitudes throughout the sentence context. Moreover, the figure reveals larger orthographic neighborhood effects in older compared to younger adults, which were similarly not impacted by accumulating contextual constraints.

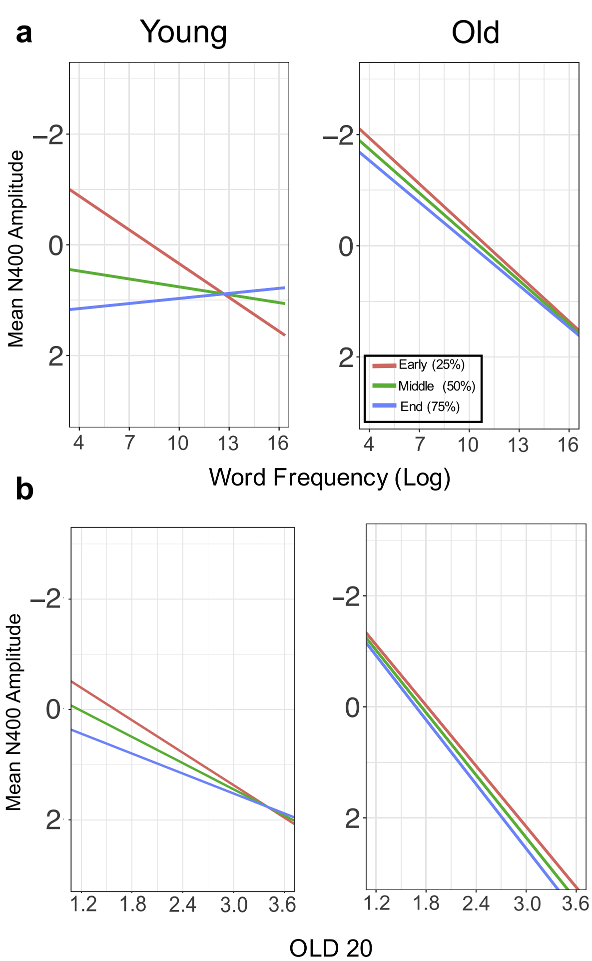

Fig. 4. Age differences in lexical effects across congruent sentences. Model estimated partial-effects plots of the effects of Word Frequency (top) and Orthographic Neighborhood (OLD20) at conditional levels of Word Position in Young and Older adults. Young adults showed reduced Frequency effects with increasing word position, while older adults did not. In addition, effects of orthographic neighborhood are larger in the old than the young.

3. Discussion

The goal of this study was twofold. First, we aimed to probe older adults' ability to make use of accumulating context information to shape word processing by examining the impact of incrementally accrued context information on the N400. Second, we aimed to characterize word-level variation in lexical frequency and orthographic neighborhood effects in older adulthood and to probe whether and how these lexical-level effects are modulated by accumulating contextual constraints in aging. To achieve this, we examined responses in a sample of healthy older adults using identical materials and adopting the same single-trial analysis approach as first conducted by Payne et al. (2015) in young adults, in order to facilitate age-related comparisons.

Towards addressing our first goal, we found that older adults did exhibit a canonical N400 word position effect: N400 amplitudes to open-class words decreased with ordinal word position within coherent sentences that provided a message-level semantic context. This finding conceptually replicates a number of findings previously observed in younger adults (Van Petten and Kutas, 1990, 1991; Dambacher et al., 2006) and directly replicates the single-trial word position effects observed in Payne et al., (2015), with the same stimuli, recording parameters, and analysis techniques. At the same time, the magnitude of the word position effect was strikingly smaller than that observed in younger adults, with the word position effect showing no significant difference between congruent and syntactic prose sentences. These findings are consistent with the idea that older adults' do not utilize contextual information to the same degree as young adults in facilitating semantic retrieval of individual words, as reflected in the N400.

Similar age differences in N400 effects of contextual expectancy (i.e., cloze probability) of sentence-final words have been widely reported (see Wlotko et al., 2010 for a review). Many of these studies have argued that the reduced effects of cloze probability reflect a reduced reliance on prior context information. For instance, Wlotko et al. (2012) found that although older adults elicited N400 differences between expected and unexpected words when words appeared in strongly constraining contexts, expectancy effects were reduced to the point of being undetectable in weakly constraining contexts. The authors inferred that older adults are less effective in making use of accruing context information, and thus need substantial contextual support to facilitate semantic processing. No prior studies to our knowledge have examined age related changes in the use of prior information in the preceding context. The present study thus provides more direct evidence in support of the hypothesis that the accrual of context information is less robust in aging.

Several authors (Federmeier, 2007; Wlotko et al., 2010; DeLong et al., 2012) have argued that if older adults do not (or cannot) rely as strongly on top-down context-driven mechanisms, they may instead adopt a more bottom-up stimulus-driven integrative processing strategy. For example, Federmeier (2007) argued that age-related decreases in context-based predictive processing are driven by in part by a reduced engagement of left hemisphere prefrontal language production pathways in aging. In young adults, left-hemisphere language production networks are engaged in a top-down manner to use accumulating context in the service of pre-activating semantic features of likely upcoming information. Evidence for this comes from hemispheric asymmetry experiments using visual half-field paradigms to bias processing to either of the cerebral hemispheres. Using this approach, Federmeier and colleagues (Federmeier, 2007; Federmeier and Kutas, 1999; Wlotko and Federmeier, 2007) have shown that only the left hemisphere uses context-based representations to predict upcoming input, while the right hemisphere adopts a bottom-up "wait and see" integrative processing approach. This bottom-up right-hemisphere biased processing in young adults directly patterns with older adults' use of contextual constraint (Federmeier, 2007; Wlotko et al., 2012), suggesting that older adults revert to bottom-up processing, perhaps due to age-related changes in left-hemisphere predictive networks. Further evidence for this comes the finding that older adults with high verbal fluency, who presumably have intact left hemisphere generative language production networks, show young-like patterns of anticipatory context-based processing (Federmeier et al., 2002, 2010).

Importantly, the availability of an integrated context representation is critical for context-based prediction. Thus, an open question in the aging and context processing literature concerns whether reductions in the use of predictive strategies during language comprehension in aging are driven in part by age-related changes in the incremental construction of message-level context representations, thus reducing the foundation for making context-based predictions in the first place. The current data suggest that this may be at least one factor playing a role in age-related changes in predictive processing (Federmeier et al., 2010; Wlotko et al., 2012; DeLong et al., 2012). At the same time, it remains to be seen exactly why older adults rely less on contextual constraints. One possibility, as discussed above, is that this reflects a strategic age-related difference in the propensity to engage in incremental language processing: older adults' adoption of a bottom-up "wait and see" strategy might result in a delayed on-line use of context to aid in word recognition. These findings would also be consistent with findings showing that older adults show larger "wrap-up" effects at major syntactic boundaries, effects that have been observed to be beneficial to subsequent comprehension and memory in aging (Miller and Stine-Morrow, 1998; Stine-Morrow et al., 2010; Payne and Stine-Morrow, 2012, 2016). Indeed, older adults' have been shown to be able to benefit from prior context to aid in off-line recognition and memory tasks, despite showing a reduced on-line use of context (Dagerman et al., 2006).

Towards our second goal of directly probing the effects of accumulating contextual constraints on the processing of lexical-level information in older adults, we modeled single-word variability in word frequency and orthographic neighborhood effects across sentence contexts. Overall, older adults showed a clear sensitivity to variation in word frequency and orthographic neighborhood density, such that the N400 was larger to words that were lower in frequency and that had more orthographic neighbors. Very few studies have examined the neurophysiological mechanisms underlying age-related changes in lexical processing outside of isolated visual word recognition contexts; to our knowledge, this is the first electrophysiological study to examine orthographic neighborhood and frequency effects in sentence processing among older adults.

We found that older adults showed robust effects of orthographic neighborhood density, effects that were actually larger in the old than in the young. Age-related increases in orthographic neighborhood effects could be due to multiple, non-mutually-exclusive sources. First, one possibility is that this effect reflects an increase in baseline visual perceptual noise in older adulthood (cf. Owsley, 2011), which could act to decrease the fidelity of bottom-up orthographic information, resulting in more uncertainty in the perceptual input and thus broader semantic activation of orthographically-related words. This is consistent with work from Taler et al. (2010) in speech processing, who found that older adults showed larger behavioral effects of phonological neighborhood density on spoken word recognition particularly when speech was embedded in auditory noise.

Because orthographic neighborhood effects have been argued to reflect passive feed-forward spreading activation within the semantic memory system (Laszlo and Federmeier, 2011; Laszlo and Plaut, 2012), age-related changes in the inhibition of spreading activation may result in broader activation of orthographically similar inputs, resulting in stronger relationships between word-level variation in orthographic neighborhood and the N400 in aging. These findings are consistent with work by Robert and Mathey (2007), who demonstrated that age-related differences in neighborhood frequency effects on lexical decision times could be computationally well-captured by reducing inhibitory strength among the connections between words. At the same time, this finding may also reflect the age-related maintenance and growth of vocabulary and word knowledge, coupled with age-related increases in language experience that shape the visual word recognition system (Payne et al., 2012). That is, a combination of increased visual experience with language that comes with aging (cf. Payne et al., 2012, 2014), along with larger and presumably more interconnected lexical networks, would lead to greater spreading activation among orthographically similar inputs during semantic access.

Dunabeitia et al. (2009) reported similar results from a lexical decision time experiment that demonstrated the maintenance of orthographic neighbor effects in healthy aging and in adults with dementia of the Alzheimer's type. They took these findings to suggest that the structure of the orthographic-semantic network is maintained in both normative and non-normative aging, consistent with the conception that this effect partially reflects activation within crystallized semantic memory stores that are resistant to age and neuropathology (cf. Verhaegen, 2003). Although these possibilities are not mutually exclusive and cannot be teased apart in the current study, nevertheless, the finding that aging is associated with broader orthographically-mediated semantic activation during word recognition is intriguing in suggesting that the visual word recognition system supporting sentence understanding continues to develop throughout adulthood.

In contrast to orthographic neighborhood effects, the effects of lexical frequency are typically reduced by increasing contextual constraints in younger adults (Payne et al., 2015). This effect has been broadly argued to reflect a re-tuning of malleable baseline activation states that are initially tuned based on a lifetime of exposure. As message-level contextual constraints accrue during sentence processing, the N400 reduction reflects a shift from global probability to local probability. In line with the idea that aging impacts real-time incremental context use, we found that this reduction in frequency effects by accumulating context was not observed in older adults, resulting in stronger persisting effects of frequency throughout congruent sentences compared to younger adults.

Overall then, our data suggest that older adults rely less on top-down context representations during incremental sentence processing and, perhaps because of the lack of access to this top down representation, show a greater sensitivity to bottom-up stimulus-driven lexical properties. These age-related changes occur during the processing of normal sentences in the absence of any substantial level of task demands, and these effects accumulate continuously throughout the sentence context. Such results indicate that age-related changes in language processing are pervasive and not only limited only to complex sentences (e.g., Caplan et al., 2011) or difficult task conditions (e.g., Fallon et al., 2006).

Multiple age-related neural changes – including changes in the functional recruitment of neural networks across the cerebral hemispheres, changes in the temporal variability of neural activity, and broad-based changes in brain morphology – can complicate the interpretation of between-group comparisons of ERP components in aging. Indeed, older adults often show overall amplitude reductions and ERP responses that appear "spread-out" over time, reflecting increased neural heterogeneity with aging (Wlotko et al., 2010). Given this, it is important to emphasize that the current pattern of results cannot be simply explained by reduced or more variable N400 activity in aging.

For instance, if it were the case that the reported effects reflected general age-related changes in the overall power or variability of the N400 (which would result in scale-dependent differences in the N400 between the two groups; that is, a "removable" interaction, Wagenmakers et al., 2012), then we could not have observed the greater sensitivity of the N400 to lexical variation in older adults in the current study, including the larger overall orthographic neighborhood effects and the effects of word frequency that persisted throughout congruent sentences. Instead, taking all of our findings into consideration, our results are more clearly explained by selective age-related changes in the incremental use of context in sentence processing. Note that older adults in the current study maintained similar behavioral results to the young adults, showing no significant reduction in subsequent sentence recognition memory. Despite this similar performance, young and older adults appeared to show qualitatively different neural recruitment of top-down compared to bottom-up information processing, suggesting a shift in the reliance on different sources of information in real-time word processing in aging, perhaps as a compensatory strategy (cf. Federmeier, 2007).

A major strength of this study is the utilization of a single-trial analytical technique that can accommodate analysis of continuous variation in N400 amplitude at the word level (without averaging across items). This study is the first to our knowledge to use such methods to examine the simultaneous contribution of multiple information sources on word-by-word variation in EPRs in a study of aging. Such single-trial applications are particularly useful for revealing dynamic changes in neural activity in aging that could be obscured with traditional ERP approaches. In fact, older adults show increasing intra-individual variability across multiple domains (e.g., Hultsch and MacDonald, 2004), including language comprehension (Payne and Stine-Morrow, 2016), and recent studies have shown that single-trial dynamics of context processing can be obscured by averaging (e.g., Payne and Federmeier, 2017). Thus, using single-item analytical methods to characterize multiple sources of item-level variability is critical to understanding age-related changes in neural and cognitive processing. In conclusion, our findings suggest that older adults appear less able to take direct advantage of context during language comprehension, resulting in an apparent shift towards bottom-up lexical processing. Modeling word-level variability in ERPs revealed mechanisms by which multiple information sources simultaneously contribute to the unfolding neural dynamics of comprehension in older adulthood.

4. Experimental procedure

4.1. Participants

Data were analyzed from 24 older adults (12 females; mean age = 68, range = 60–80). Lee and Federmeier (2011) previously reported responses to a manipulation of lexical ambiguity on sentence-final words for these data (and thus, the current findings are orthogonal to those results). All participants were right-handed monolingual native speakers of English with normal or corrected-to-normal vision. None of the participants had a history of neurological or psychiatric disorders or brain damage. Participants scored within the normal range on the Mini-Mental State Exam (Mean score = 29, range = 27–30; Folstein et al., 1975). For more information on participant characteristics, see Lee and Federmeier (2011).

To directly compare ERP data of the older adults in the current study to a healthy young sample, we present an additional supplementary age-comparative analysis by pooling data from the prior experiment in our lab adopting the exact same stimuli, protocol, and analysis procedures as this study with a sample of healthy young adults, as reported in Payne et al. (2015). In that study, 28 participants (13 female, mean age = 20) from the University of Illinois participated for course credit. All participants were native speakers of English, were right-handed as assessed by Edinburgh handedness inventory (Oldfield, 1971), and had no history of neurological disease or psychiatric disorders.

4.2. Materials

Participants read a total of 172 sentences, divided into three conditions: (1) congruent sentences (e.g., *She kept checking the oven because the cake seemed to be taking an awfully long time to bake*), (2) syntactic prose sentences (*She went missing the spring because the court began to be making an awfully poor art to bake*), which provide the same syntactic structure as the coherent items, but with no coherent message-level semantics, and (3) random sentences (*The court the she spring making missing awfully art poor to because an to be went began bake*). Syntactic prose sentences were created by replacing the content words of each congruent sentence with randomly selected words of the same grammatical category from other congruent sentences. Therefore, congruent and syntactic prose sentences were matched in the relative position of closed-class words. Random sentences were created by randomly scrambling the position of the words within each syntactic prose sentence, with the exception of the sentence-final word. Sentences contained, on average, about 14 words (M = 14.20, SD = 3.39, range = 5–27).

Open class words (typically defined as "meaning-bearing" words) included nouns, verbs, adjectives, and derived adverbs (-ly adverbs). Closed class words (semantically sparse words that mainly perform syntactic functions) included words belonging to other lexical classes (e.g., determiners, prepositions, conjunctions, and pronouns). Following the dichotomous assignment of words in Van Petten and Kutas (1991), words of ambiguous class were assigned to the closed-class category. Although identical closed-class words appeared in the three conditions, open-class words were presented across conditions with random selection, but without exhausting all possible permutations, due to limitations in the number of stimuli that could be presented in a single session. Importantly, no differences were found across sentence contexts in any of the target or control variables analyzed in the current study.

4.3. Procedure

Participants were seated 100 cm in front of a 21″ computer monitor in a dim, quiet testing room. At the start of each trial, a series of plus signs appeared in the center of the screen for 500 ms. After a stimulus onset asynchrony (SOA) ranging between 1000 and 1500 ms (randomly jittered to reduce the contribution of anticipatory potentials in the time-locked ERP), a sentence was displayed word by word in the center of the screen. Each word was presented for 200 ms, followed by a 300 ms blank screen. To ensure that participants were attending to each word, as well as attempting to integrate each word into a holistic unit, participants were administered word and sentence recognition tasks. Following each sentence, participants were presented with a probe word and asked to judge whether it had appeared in the preceding sentence. Half of the probe words were new words and half of the probes appeared in the previous sentence. The experimental session was divided into eight blocks. At the end of every two blocks, participants were also administered a brief sentence-recognition test. In total, participants were tested on 96 sentences, half of which were old (drawn in equal numbers from congruent, syntactic prose, and scrambled sentences) and half of which were new (also consisting of equal numbers of each sentence type). New sentences contained some words that the participant actually viewed, making word-level recognition alone insufficient to allow participants to succeed on this test.

4.4. EEG recording and processing

EEG was recorded from 26 evenly spaced silver-silver chloride electrodes embedded in an Electro-Cap. The sites were midline prefrontal (MiPf), (left and right) medial prefrontal (L/RMPf), lateral prefrontal (L/RMPf), medial frontal (L/RMFr), mediolateral frontal (L/RDFr), lateral frontal (L/RLFr), midline central (MiCe), medial central (L/RMCe), mediolateral central (L/RDCe), midline parietal (MiPa), mediolateral parietal (L/RDPa), lateral temporal (L/RLTe), midline occipital (MiOc), medial occipital (L/RMOC), and lateral occipital (L/RLOc). All scalp electrodes were referenced online to the left mastoid and re-referenced offline to the average of the right and the left mastoids. In addition, one electrode (referenced to the left mastoid) was placed on the left infraorbital ridge to monitor for vertical eye movements and blinks, and another two electrodes (referenced to one another) were placed on the outer canthus of each eye to monitor for horizontal eye movements. Electrode impedances were kept below 3 kΩ. The continuous EEG was amplified through a bandpass filter of 0.02–100 Hz and recorded to hard disk at a sampling rate of 250 Hz. EEG epochs were examined and marked for artifacts (drift, muscle activity, eye blinks, and eye movements). Analyses were conducted via maximum likelihood estimation on all available data (Graham, 2009; Little and Rubin, 2002). This method accommodates unbalanced designs that arise from artifact rejection by using all available data to estimate parameters, such that highly influential individual random effects (e.g., subjects or words) with fewer observations are shrunk toward the population average.

Following Payne et al. (2015), to examine word-by-word variation in N400 activity, measurements of mean N400 amplitude were collected at the level of individual words from the raw EEG across eight a priori chosen centro-parietal electrode sites (midline central and parietal, left and right medial central, left and right mediolateral central, left and right mediolateral parietal) where N400 effects are typically largest, with the exception of the distributional model described below, which was fit across all scalp channels. Continuous EEG was epoched from 100 ms prestimulus to 920 ms poststimulus. EEG was then baseline corrected by subtracting the 100 ms prestimulus baseline period, and a digital 30 Hz low-pass filter was applied to the epoched data. Single-word level N400 amplitudes were then measured from all words in each sentence, including the sentence initial and final words, as in Payne et al. (2015). Some previous studies have removed initial and final words in investigating the word position effect (e.g., Van Petten and Kutas, 1991). Nevertheless, we found that removal of these items did not alter the pattern of results. Thus, all possible words were included in the analyses. Because our sentences varied substantially in length, sentence-final words were distributed across different word positions from sentence to sentence. Because N400 amplitudes show substantial latency delays in aging (∼2 ms per year Kutas and Iragui, 1998), we used a latency band for measuring single-trial N400 effects from 350 ms to 550 ms, in line with prior studies examining age-differences in average ERPs, which was chosen via inspection of the grand-average ERP collapsing across all open-class words, regardless of sentence context, word position, or lexical properties (see Brooks et al., 2017). The resulting dataset includes measurements of mean amplitude within the N400 latency band separately for each word, channel, and participant.

4.5. Data analysis

The same analysis approach was applied as that in Payne et al. (2015). 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. Variance across subjects, individual words, and channels was modeled as random intercept terms. However, preliminary analyses revealed that there was not reliable across-channel variance in this sample. As such, observations were aggregated across channels. Further specification of the random effects structure was modeled based on current recommendations (see Barr, 2013; Barr et al., 2013; Bates et al., 2015; Matuschek et al., 2017). Models were initially fit with random slope parameters for all corresponding within-subject effects warranted by the design (i.e., a fully maximal random-effects structure, Barr et al., 2013). 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. When maximal models did not converge, simplified random effects structures were fit, aiming to reduce overfitting of the random effects structure (cf. Bates et al., 2015). As in Payne et al. (2015), simplified models included random-slope for the highest-order interactions of interest in order to selectively protect against anti-conservative estimates of the standard-errors of these critical interactions (Barr et al., 2013).

In the analyses of contextual and lexical influences, only open-class words were considered, as effects of frequency and sentential context on the N400 are largest within these words (Van Petten and Kutas, 1990, 1991). Predictors of word-level variance included sentence context (SC: congruent, syntactic prose, or random), word position (WP), word frequency, and orthographic neighborhood. Word frequency (log transformed) was derived from the Hyperspace Analog to Language (HAL) norms from the English Lexicon Project, and orthographic neighborhood size was derived from the orthographic Levenshtein distance 20 (OLD20) measure (Yarkoni et al., 2008) from the English Lexicon Project (see Balota et al., 2007). 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). (Note that this measure is, thus, negatively correlated with other, traditional measures of neighborhood size, such as Coltheart's *N* -- 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). Word length, sentence length, and concreteness ratings were also used as control variables in some analyses (see below). See Payne et al., (2015) for more information on stimuli. First, we present a model testing the degree to which N400 amplitudes vary with word position as a function of sentence context – i.e., testing the canonical word position context effect on the N400 in older adults. Following this, we simultaneously examine the impact of word frequency and orthographic neighborhood on N400 activity and how these lexical variables are moderated by sentence context and word position in aging. 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.

Author Note

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