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What's “left”? Hemispheric sensitivity to predictability and congruity during sentence reading by older adults

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ABSTRACT

A number of studies have found that older adults' sentence processing tends not to be characterized by the prediction-related effects attested for young adults. Here, we further probed older adults’ sensitivity to predictability and congruity by recording event-related brain potentials (ERPs) as adults over age 60 read pairs of sentences, which ended with either the expected word, an unexpected word from the same semantic category, or an unexpected word from a different category. Half of the contexts were highly constraining. Consistent with patterns attested when older adults listened to these same materials (Federmeier et al., 2002), N400s, on average, were smaller to expected than to unexpected words, but did not show constraint-related reductions for unexpected words that shared features with the most predictable completion (an effect well-attested in young adults). This pattern resembles that seen in young adults for right-hemisphere-biased processing. To assess whether older adults retain young-like hemispheric asymmetries but recruit right hemisphere mechanisms more, we examined responses to the target words using visual half-field presentation. Whereas young adults show an asymmetric pattern, with prediction-related N400 amplitude reductions for left- but not right-hemisphere-initiated processing (Federmeier and Kutas, 1999b), older adults showed no reliable processing asymmetries and no evidence for prediction with left hemisphere-initiated presentation. The results suggest that left hemisphere mechanisms important for prediction during language processing are less efficacious in older adulthood.

1. Introduction

Language comprehension is a multifaceted cognitive skill, involving the rapid apprehension of complex, often ambiguous sensory inputs (i.e., spoken, written, or signed words), access to long term memory in the service of building meaning and syntactic structure, and various forms of attentional and executive control. Given that all of these component processes are known to change with normal aging (reviewed in Cabeza et al., 2005), it is notable that many aspects of comprehension, at the level of outcome, remain relatively stable across the adult lifespan (in the absence of non-normative cognitive decline and when sensory changes, such as hearing loss, can be successfully accommodated). It has long been known that language-related knowledge, such as vocabulary, is maintained and, in some cases, even augmented with advancing age (Salthouse, 1993; Verhaegen, 2003). Performance on tasks that rely on word recognition (e.g., pronunciation, lexical decisions, semantic judgments; Cohen-Shikora and Balota, 2016) and electrophysiological indices of lexical processing and semantic access (Federmeier et al., 2003; Federmeier et al., 2010; Payne and Federmeier, 2018) also remain relatively stable. In particular, older adults seem to be able to take advantage of their generally more extensive experience with language to make aspects of language processing more efficient and automatic, resulting in good performance not only for word recognition but also sentence processing (Lien et al., 2006; Payne et al., 2012; Wingfield, 1996).

This ability to maintain successful outcomes in the face of critical alterations and declines in the requisite resources and processing mechanisms is a testament to the flexibility of the human brain. Indeed, studies that focus on the process of comprehension, rather than the outcome, have revealed notable differences in how older adults (typically ~55–80 years old), compared to younger adults, go about comprehending language. Behavioral studies, especially those using degraded input (e.g., auditory signals in noise) have shown that older adults may tend to weigh contextual information more than their younger counterparts (Rogers et al., 2012). At the same time, studies measuring ERPs have uncovered differences in not only how much older adults use content, but in how effectively they do so, and with what kinds of cognitive mechanisms. Older adults show reduced

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incremental accrual of context information (Payne and Federmeier, 2018) and, correspondingly, reduced context-based facilitations of semantic access from words, as indexed by N400 amplitudes (Federmeier and Kutas, 2005; Wlotko and Federmeier, 2012; Wlotko et al., 2012). At least part of this reduction in the accrual and use of context information seems be due to an age-related shift in the impact of predictive processing mechanisms during comprehension.

Although comprehension was long thought to be a process that, in its early stages, is fundamentally bottom-up, work over the past two decades has established a critical role for predictive processing. Early evidence for predictive processing during comprehension came from facilitated gaze to predictable objects in the Visual World paradigm (Altman and Kamide, 1999) and N400 reductions ("facilitations") to implausible words that shared features with predictable ones (Federmeier and Kutas, 1999a). Subsequent work has yielded considerable evidence that the brain prepares for likely upcoming words by pre-activating their features at multiple levels of representation. Behaviorally, reading times pattern with surprisal, a measure of predictability (Demberg and Keller, 2008; Smith and Levy, 2013), and predictable words are skipped more often and fixated for less time (reviewed in Clifton et al., 2016). In ERPs, prediction is seen in a pattern of effects distributed over time, including effects of contextual constraint that build across a sentence (Payne et al., 2015; Van Petten and Kutas, 1990) and that impact semantic processing of incoming words (Brothers et al., 2017; Federmeier et al., 2002; Wlotko and Federmeier, 2015). Unexpected but plausible words that violate the most likely predictions also elicit a frontally distributed post-N400 positivity (Federmeier et al., 2010; Federmeier et al., 2007; Van Petten and Luka, 2012).

All of these ERP effects associated with prediction are less characteristic of processing by older adults. For example, although older adults also show post-N400 frontal effects differentiating expected from unexpected words overall (Dave et al., 2018; DeLong et al., 2012), they do not show the more specific effects associated with prediction violations. Different from young adults, older adults do not show augmented frontal positivity to unexpected words that violate a prediction compared to equally unexpected words that are not prediction violations, either during sentence processing (Wlotko et al., 2012) or when linking words to a phrasal cue (Federmeier et al., 2010). Older adults also fail to show prediction-related facilitations on N400 amplitude. For young adults, N400 amplitudes are reduced to contextually incongruous words that share semantic features with the word expected to come next. For example, given a sentence pair like, "The snow had piled up on the drive so high that they couldn't get the car out. When Albert woke up, his father handed him a …" young adults not only elicit a notably smaller N400 to the expected word "shovel" than to an incongruous word like "saw", they also show a smaller N400 for a word like "rake", which, although as incongruous as "saw" in the context, shares more semantic features with the expected word. Importantly, this facilitation for incongruous but related words is graded by the strength of the prediction for the unseen expected word. Such prediction-related facilitations have been seen consistently in young adults, both when they are reading word by word (Federmeier and Kutas, 1999a; Wlotko and Federmeier, 2015) and when they are listening to natural speech (Federmeier et al., 2002). Older adults also show N400 facilitations for words that are congruous in the context compared to those that are not. However, as a group they do not show the prediction-based facilitation for incongruous but related words (Federmeier et al., 2002). Thus, across modality, paradigm, and measure, there is evidence that older adults' sentence comprehension unfolds differently, including less influence from predictive processing mechanisms.

In young adults, prediction in comprehension has been linked to processing mechanisms in the left cerebral hemisphere, which, in most people, is also dominant for key aspects of language production (reviewed in Federmeier, 2007). Although the frontal positivity to prediction violations is not always observed for words presented outside of foveal vision (Wlotko and Federmeier, 2007), when it has been reported in studies using visual half-field presentation methods to study hemispheric processing biases, it is associated with processing biased to the left hemisphere (i.e., for words presented in the right visual field; DeLong and Kutas, 2016). Similarly, the pattern of prediction-related N400 facilitations already described is observed with left-hemisphere initiated and thus left-hemisphere biased processing but not with right-hemisphere biased processing (Federmeier and Kutas, 1999b; cf. Federmeier and Kutas, 2002, showing the same effect for picture processing). Both hemispheres consistently show N400 reductions for words that are congruous in sentence contexts compared to those that are not (Federmeier and Kutas, 1999b; Coulson et al., 2005; Federmeier et al., 2005; Wlotko and Federmeier, 2007, 2013), and the right hemisphere (but not the left) shows N400 reductions for unexpected words that are related to the overall event (Metusalem et al., 2016). However, the pattern seen for central presentation in young adults, wherein there is facilitation for incongruous words that share features with the word most likely to occur imminently in the unfolding language sequence, is observed only when processing is biased to the left hemisphere. Processing biased to the right hemisphere manifests just the more basic, overall difference between expected and unexpected words – namely, the same pattern seen overall for older adults (Federmeier et al., 2002, when participants listened for comprehension).

The similarity in the pattern observed for older adults and for right-hemisphere-biased processing in the young is provocative, and, here, we assess two explanations for what could underlie it. On the one hand, there is an extensive body of work showing bilateral patterns of activity in older adults for tasks that are lateralized in younger adults (reviewed in Park and Reuter-Lorenz, 2009). Across a variety of tasks ranging from sensory processing (Grady et al., 2000) to episodic encoding and recall (Cabeza et al., 1997; Logan et al., 2002) and working memory maintenance (Reuter-Lorenz et al., 2000), brain activation patterns that are typically lateralized (either to the left or the right hemisphere) in young adults have been found to become more bilateral in older adults; this is especially evident in pre-frontal areas, but also occurs in parietal cortex and the hippocampus (Nielson et al., 2002; Maguire and Frith, 2003). The use of hemispheric processing resources is under dynamic control (e.g., Banich, 1998; Belger and Banich, 1998; Weissman and Compton, 2003). For example, visual half-field ERP studies with young adults have shown that, for different stimuli and tasks, effect patterns observed with central presentation sometimes align with those only observed for left-hemisphere-biased presentation (e.g., Federmeier and Kutas, 1999b) or only observed for right-hemisphere-biased presentation (Metusalem et al., 2016), sometimes reflect a combination of patterns seen with lateralized presentation (Wlotko and Federmeier, 2013), and other times emerge through interhemispheric interaction, resulting in patterns that are not seen at all when processing is biased to a single hemisphere (Wlotko and Federmeier, 2007). Older adults clearly recruit hemispheric resources differently, seeming to more often engage both hemispheres. This may reflect some kind of neural and functional "dedifferentiation" (e.g., Baltes and Lindenberger, 1997) that arises, for example, because of changes in the corpus callosum that make it more difficult for older adults to selectively activate one hemisphere (see review by Fling et al., 2011). Alternatively, bilateral engagement may be strategic (Park and Reuter-Lorenz, 2009; Cabeza, 2002), perhaps in part a response to age-related increases in subjective task demands, which also have been associated with greater levels of bilateral recruitment in younger adults; Höller-Wallscheid et al. (2017); Schneider-Garces et al. (2010). Whatever the underlying mechanism, the finding that older adults' processing more often seems to draw from both hemispheres offers one explanation for the differing effect patterns seen in older versus younger adults. As discussed, patterns seen in young adults for tasks probing predictive processing suggest a primary reliance on left-hemisphere mechanisms. If language comprehension mechanisms remain asymmetric across age, but older adults recruit the right hemisphere more, their responses during central presentation would be expected to show more influence from the effect pattern typically observed in young adults for right-hemisphere-biased processing.

On the other hand, older adults may show less evidence for predictive processing because neural mechanisms important for prediction, as well as for a range of other comprehension processes, tend to become less efficacious with age. Aging affects neural connectivity that is important for long-range communication, with impact on functions like executive control, attention, and memory retrieval (e.g., Fjell et al., 2017; Kennedy and Raz, 2009; Shaw et al., 2015). For example, normal aging impacts the ability to effectively deploy attentional resources during reading (Payne and Federmeier, 2017) and to engage imagery when processing concrete expressions (Huang et al., 2012). Moreover, age-related differences are seen in the tendency to recruit selection mechanisms important for ambiguity resolution, with concomitant impact on text comprehension, as revealed in both ERPs and eye movement patterns during reading (Lee and Federmeier, 2011, 2012; Stites et al., 2013). Both selection and prediction have been associated with left hemisphere mechanisms (see reviews in Federmeier, 2007; Thompson-Schill, 2005), and there seem to be links between observed age-related differences in prediction and selection. In particular, the tendency to show predictive processing during comprehension and the tendency to show effective meaning selection are similarly modulated by individual differences in verbal fluency: Older adults with high verbal fluency are more likely to show young-like patterns for both prediction (Federmeier et al., 2002; Federmeier et al., 2010) and selection (Lee and Federmeier, 2011, 2012; Stites et al., 2013). Thus, it may be that left-hemisphere-mediated language functions, including prediction, unfold differently in older adults. In this case, we would expect visual half-field presentation to reveal that the asymmetric patterns documented for young adults do not manifest for an older adult population.

At issue, then, is whether the processing asymmetries documented in the young remain stable with age but come to have differential impact on the emergent pattern seen during normal comprehension, or whether left hemisphere predictive processing mechanisms themselves are less viable in older adults. In the present work, therefore, we test for predictive processing patterns as a function of visual field in a sample of older adults, using the same materials and procedures that have been used across a number of studies with young participants. In this paradigm, older adults read for comprehension pairs of sentences with three types of endings: (1) expected words, (2) words that share semantic features with the expected ending but are contextually incongruous ("within category violations"), and (3) similarly incongruous words that share fewer features in common with the expected ending ("between category violations"). Sentences vary in contextual constraint and, hence, the degree to which they lead to a strong prediction for the expected item. Predictive processing yields facilitation for within category violations, which is greater in strongly compared to weakly constraining sentences (see Federmeier and Kutas, 1999a; Federmeier et al., 2002; Wlotko and Federmeier, 2015). Using these same materials, we showed, for listening, that older adults failed to show prediction-related patterns of facilitation (Federmeier et al., 2002). Here, we will first ascertain that older adults also do not show the predictive processing pattern for word by word reading. As discussed previously, other work using word by word reading has suggested that older adults are less likely to show effects associated with prediction (Federmeier et al., 2010; Wlotko et al., 2012), making it likely that the same pattern will obtain. However, it is nonetheless important to empirically demonstrate this, as, among other differences, word by word reading is slower than natural speech, and timing does affect prediction in young adults (Wlotko and Federmeier, 2015). We will then employ a visual half-field presentation paradigm, randomly lateralizing the target words to the left and right visual fields, to test whether the asymmetry observed for young adults (Federmeier and Kutas, 1999b) is also present in older adults, or whether, instead, left hemisphere processing mechanisms are less predictive in older comprehenders.

2. Methods

2.1. Materials

Stimulus materials were taken from Federmeier and Kutas (1999a,b). They consisted of 132 pairs of critical sentences, each of which were completed with three ending types. *Expected exemplars* were the highest cloze probability ending for a given sentence pair. Note that cloze probabilities were obtained from both younger and older adults and did not differ substantially across these populations (see Federmeier and Kutas, 1999a, and Federmeier et al., 2002, for details of cloze probability and plausibility norming). Mean cloze probability for the expected exemplars was 0.74 and mean plausibility (rated on a percentage scale) was 95.6%. All expected exemplars described picturable objects from 66 categories (two items from each). *Within category violations* were unexpected (cloze probability always < 0.05; average cloze probability 0.004) exemplars from the same taxonomic category as (but not lexically related to) the expected exemplar. *Between category violations* were also unexpected (cloze probability always < 0.05; average cloze probability 0.001) but came from a different category than the expected exemplar and within category violation. Both violation types were rated as having low plausibility, with higher overall ratings for within (28.3%) than between (15.3%) category violations.

To examine effects of contextual constraint and concomitant effects of plausibility, the sentences were divided into two groups, "high constraint" and "low constraint", by a median split on the cloze probability of the expected exemplar. High constraint expected exemplars had a mean cloze probability of 0.9 (range 0.78-1) and a mean plausibility of 97.7%. Low constraint expected exemplars had a mean cloze probability of 0.59 (range 0.17-0.77) and a mean plausibility of 93.5%. Importantly, whereas plausibility was higher for high than for low constraint expected exemplars [$t = 5.00$; $p < 0.001$], it was lower for high than low constraint violations, both for within category violations (high constraint 23.6%, low constraint 30.2%; [$t = 3.54$; $p < 0.001$]) and for between category violations (high constraint 11.9%, low constraint 18.7%; [$t = 8.21$; $p < 0.001$]). This fact allowed Federmeier and Kutas (1999a) to separate N400 effects based on plausibility from those based on prediction (similarity to the expected exemplar), since plausibility should lead to greater facilitation of the violations in low compared to high constraint sentences, whereas prediction will lead to the opposite – a pattern in which within category violations, in particular, are more facilitated in high than low constraint sentences (because the expected exemplar is more strongly predicted and can thus better spread facilitation to related items).

The first sentence of each sentence pair established the expectation, while the second sentence, when separated from the first, could be plausibly completed by any of the three possible target words. Target words were rotated across the stimulus set such that each word appeared once as each type of ending. Thus, across the experiment, the critical words and sentences were both perfectly controlled across ending type. See Table 1 for an example of the rotation; Appendices A and B in Federmeier and Kutas (1999a) list all of the target words/categories and provide an extensive and representative sample (1/3 of the total set) of the critical sentences. The experimental sentences were divided into three lists of 132 sentences each. Sentence contexts and items were used only once per list; each list consisted of 44 of each type of target (expected exemplars, within category violations, between category violations). For lateralized presentation, the lists were further subdivided so that half of the targets of each type were randomly assigned to each visual field, and a mirror image list was created with visual field reversed. Within each list, the target conditions were matched for mean word length and frequency. To balance the number of

Table 1
Example set of sentences. EE = expected exemplar; WCV = within category violation; BCV = between category violation.

SENTENCE CONTEXT	EE	WCV	BCV
Pablo wanted to cut the lumber he had bought to make some shelves. He asked his neighbor if he could borrow her	saw	hammer	rake
Tina lined up where she thought the nail should go. When she was satisfied, she asked Bruce to hand her The	hammer	saw	shovel
The snow had piled up on the drive so high that they couldn't get the car out. When Albert woke up, his father handed him a	shovel	rake	saw
The yard was completely covered with a thick layer of dead leaves. Erica decided it was time to get out the	rake	shovel	hammer

plausible and implausible sentences read by each participant, the same 44 plausible filler sentence pairs were added to each list. Stimuli were randomized once within each list, with the constraint for lateralized presentation that no more than three items in a row be shown to the same visual field, and were then presented in the same order for each participant.

2.2. Participants

A total of 36 healthy older adults were recruited from the local San Diego community, participated in the experiment after giving written, informed consent, and were compensated with a cash payment. All were monolingual English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. They were right-handed, as assessed by the Edinburgh Inventory (Oldfield, 1971), with no familial sinistrality. Average education level was 16 years (bachelor's degree), with a range from 12 (high school graduate) to 18.5 (master's degree). Twelve of these older adults (6 male, 6 female; mean age 67, age range 60-81) were used in the central presentation condition, with four randomly assigned to each list. The others participated in the lateralized presentation condition. Three datasets from that condition had too much contamination from eye movement artifact and were dropped. Data for the lateralized presentation condition thus came from 21 older participants (6 male; 15 female; mean age 67, range 59-79), evenly divided across lists[1].

2.3. Experimental procedures

Participants were seated 100 cm in front of a CRT in a soundproof, electrically-shielded chamber. They were instructed to read the sentences carefully for comprehension, with the aim of being able to succeed at a recognition test over the experimental materials at the end of the session. The session began with a short practice designed to reiterate the experimental instructions and to acclimate volunteers to the experimental conditions and the task.

Each trial began with the first sentence of each pair appearing in full. Participants read this sentence at their own pace and pressed a button to view the second sentence. Presentation of the second sentence was preceded by a series of crosses to orient the participant toward the center of the screen, where the second sentence was then presented one word at a time. Stimuli subtended between 3.7 and 10.3 degrees of horizontal visual angle and approximately one degree of vertical visual angle. Non-sentence final words were presented for 200 ms with a stimulus-onset asynchrony of 500 ms. Sentence final words in the central presentation condition were presented for 500 ms (as in Federmeier and Kutas, 1999a). In the lateralized presentation condition, sentence-final words were presented for 200 ms in the left or right visual hemifield, with inner edge two degrees of visual angle from fixation (as in Federmeier and Kutas, 1999b). A central fixation point remained visible throughout the trial, positioned ½ degree below the bottom-most edge of the centrally-presented words. Participants were asked to minimize eye movements and blinks during the second sentence. The final, target word was followed by a blank screen for 3000 ms, after which the next sentence appeared automatically. Participants were given a short break after every 17 sentence pairs.

At the conclusion of the recording session, participants took a recognition memory test consisting of 50 sets of sentence pairs: 10 new ones, 20 unchanged experimental pairs (of which 10 ended with expected exemplars, 5 with within category violations, and 5 with between category violations), and 20 modified sentence pairs in which the final word had been changed from that originally viewed (10 in which violations had been changed to expected exemplars and 10 in which expected exemplars had been changed to violations). Participants were instructed to classify the sentences as new, old, or similar (changed).

2.4. EEG recording parameters

The electroencephalogram (EEG) was recorded from twenty-six evenly spaced tin electrodes embedded in an Electro-cap, referenced to the left mastoid. Fig. 1 in Federmeier and Kutas (1999a) shows the arrangement. Blinks and eye movements were monitored via electrodes placed on the outer canthus and infraorbital ridge of each eye. Electrode impedances were kept below 5 KΩ. EEG was processed through Grass amplifiers set at a bandpass of 0.01-100 Hz. EEG was continuously digitized at 250 Hz and stored on hard disk for later analysis.

Data were re-referenced offline to the algebraic sum of the left and right mastoids. Trials contaminated by eye movements, blinks, excessive muscle activity, or amplifier blocking were rejected off-line before averaging; approximately 13% of trials in each condition (10.3% for central presentation and 14.6% for lateralized presentation) were lost due to such artifacts. ERPs were computed for epochs extending from 100 ms before stimulus onset to 920 ms after stimulus onset. Averages of artifact-free ERP trials were calculated for each type of target word in each condition (i.e., as a function of constraint or visual half-field) after subtraction of the 100 ms pre-stimulus baseline. The time window and set of channels used to measure the N400 were determined from the prior literature: measurements were made from 350 to 550 ms (i.e., shifted 50 ms later than the window used in Federmeier and Kutas, 1999b, to reflect age-related changes in N400 timing; see Kutas and Iragui, 1998) over the 15 medial-central channels (Left and Right Medial Frontal, Left and Right Dorsal Frontal, Left and Right Medial Central, Left and Right Dorsal Central, Middle Central [equivalent to Cz], Left and Right Dorsal Parietal, Middle Parietal, Left and Right Medial Occipital, and Middle Occipital) encompassing the typical N400 distribution (e.g., Kutas and Federmeier, 2011). N400 amplitudes were analyzed with repeated measures ANOVAs; for repeated measures with greater than one degree of freedom, Greenhouse-

[1] Data for one participant in the lateralized experiment appeared to have notably smaller overall voltages than the rest, raising the possibility of an error in the voltage calibration procedure (although none had been noted during the run). To check whether this affected the results, we reprocessed this participant using an alternative calibration (taken from a different, contemporaneously-run participant) and redid the analyses using the reprocessed data. No statistical outcome was affected. Thus, we here report all analyses using the data as originally calibrated.

Geisser correction was used for sphericity violations. Because measurements were made from individual electrodes, all ANOVAs included Electrode Site (15 levels) as a factor. As differences across electrodes were not of theoretical interest, they are not reported; i.e., we assess effect patterns at the level of the whole region of interest.

Although not part of our original analysis plan, during the review process we were directed to perform statistical comparisons between the older adult data and young adult data from Federmeier and Kutas (1999a, 1999b). Raw waveform comparisons across conditions that yield different waveform morphologies (e.g., age groups or stimulus locations) are problematic to interpret due to, among other factors, the presence of differences earlier than the time windows of theoretical interest (e.g., on sensory potentials; see Luck, 2014, page 315). To mitigate against these issues, age-group comparisons, presented in the captions of Figs. 2 and 4, which also plot the corresponding young adult data for visual comparison, were done on difference waves; t-tests used the Satterthwaite approximation for unequal samples sizes and variances.

3. Results

3.1. Behavior

Participants correctly classified an average of 69% (range 44%–88%) of the items on the recognition memory test (66.4% for central presentation and 70.8% for lateralized presentation). The most common type of error was a misclassification of "similar" sentences (those in which only the final word had been altered from that actually shown in the experiment) as "old", followed by a misclassification of "old" sentences (those seen in the same form during the recording session) as "similar". Together, these two error types account for 75% of all errors observed. Participants were unlikely to forget that they had seen a sentence and even more unlikely to classify new sentences as "old" or "similar"). Overall, the behavioral results indicate that participants were attending the experimental sentences during the recording session.

3.2. ERPs: central presentation

We first used a small sample of older adults to confirm that the pattern established for listening (Federmeier et al., 2002) also would obtain for word-by-word reading. Grand average ERPs are shown in the top half of Fig. 1.

N400 amplitudes were assessed with a repeated measures ANOVA using 2 levels of Constraint (high and low) and 3 levels of Ending Type (expected exemplars, within category violations, and between category violations). There was a robust effect of ending type, with more positive (i.e., facilitated) responses to expected exemplars (4.1 μV) compared to within (2.3 μV) or between (2.2 μV) category violations [$F(2,22) = 22.95$; $p < 0.001$; $\varepsilon = 1$]. Follow-up comparisons confirmed that expected exemplars elicited smaller (more positive) N400 responses than did within category exemplars [$F(1,11) = 34.10$; $p < 0.001$] but that responses to the two violation types did not differ [$F(1,11) = 0.67$; $p = 0.67$]. The effect pattern, and its topography, are shown in Fig. 2.

Although there was a tendency for more positive amplitudes overall in high than in low constraint sentences [$F(1,11) = 3.26$; $p = 0.10$], there was no interaction of Constraint and Ending Type [$F(2,22) = 0.38$; $p = 0.55$; $\varepsilon = 0.66$]; see Fig. 3. Planned comparisons of the effect of constraint on each ending type revealed no significant effects: expected exemplars (4.2 μV in high vs. 3.9 μV in low) [$F(1,11) = 0.58$; $p = 0.46$]; within category violations (2.7 μV vs. 1.9 μV) [$F(1,11) = 2.12$; $p = 0.17$]; between category violations (2.5 μV vs. 1.9 μV) [$F(1,11) = 2.41$; $p = 0.15$]. The most diagnostic test for prediction, a comparison between within and between category violations in the high constraint sentences, also revealed no reliable effect [$F(1,11) = 0.46$; $p = 0.51$].

In summary, responses to expected words showed N400 reductions compared to unexpected words, but there was no prediction-related facilitation of within compared to between category violations. This replicates the pattern observed for older adults in the auditory modality (Federmeier et al., 2002), and, as can be seen in Fig. 2, differs from the pattern attested for young adults in both the visual (Federmeier and Kutas, 1999a; Wlotko and Federmeier, 2015) and auditory (Federmeier et al., 2002) modalities.

3.3. Lateralized presentation

To allow comparison with the central presentation ERP data, we first collapsed across visual field and assessed the overall pattern of ending type effects with a repeated measures ANOVA using 2 levels of Constraint (high and low) and 3 levels of Ending Type (expected exemplars, within category violations, and between category violations). The bottom half of Fig. 1 shows the effect pattern. Absolute voltages were more positive overall with lateralized presentation (as has been seen previously in Federmeier and Kutas, 1999a, 1999b; Fig. 2), but the effect pattern replicated that seen for central presentation. There was a robust effect of Ending Type, with more positive responses to expected

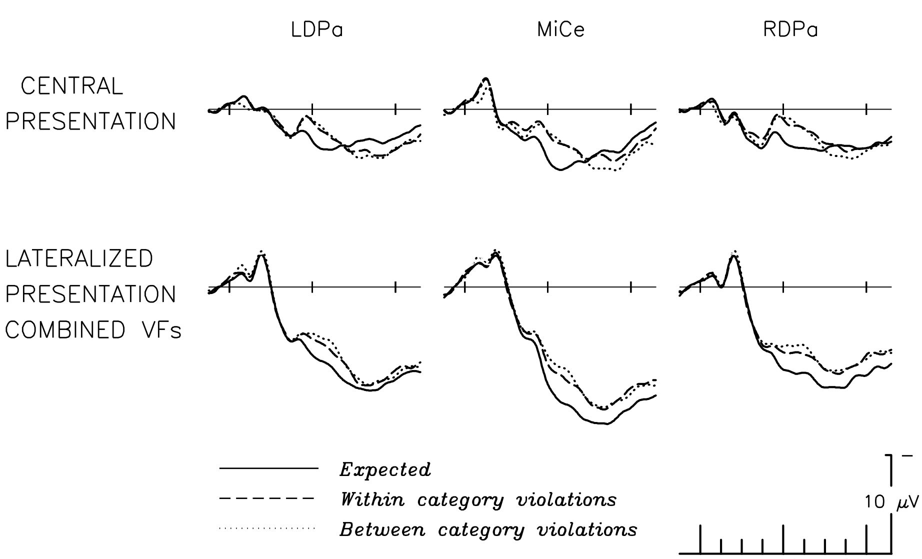

Fig. 1. Grand average ERP waveforms for the three ending types shown at a representative set of medial, centro-posterior electrode sites. Negative is plotted up in this and all subsequent figures. The top row plots ERPs obtained with central presentation and the bottom row plots ERPs obtained with lateralized presentation, combined across visual field. In both, the ending types are characterized by the same set of early (sensory) components. In the 350–550 ms (N400) time window, responses to expected exemplars (solid line) are more positive than responses to both within category violations (dashed line) and between category violations (dotted line).

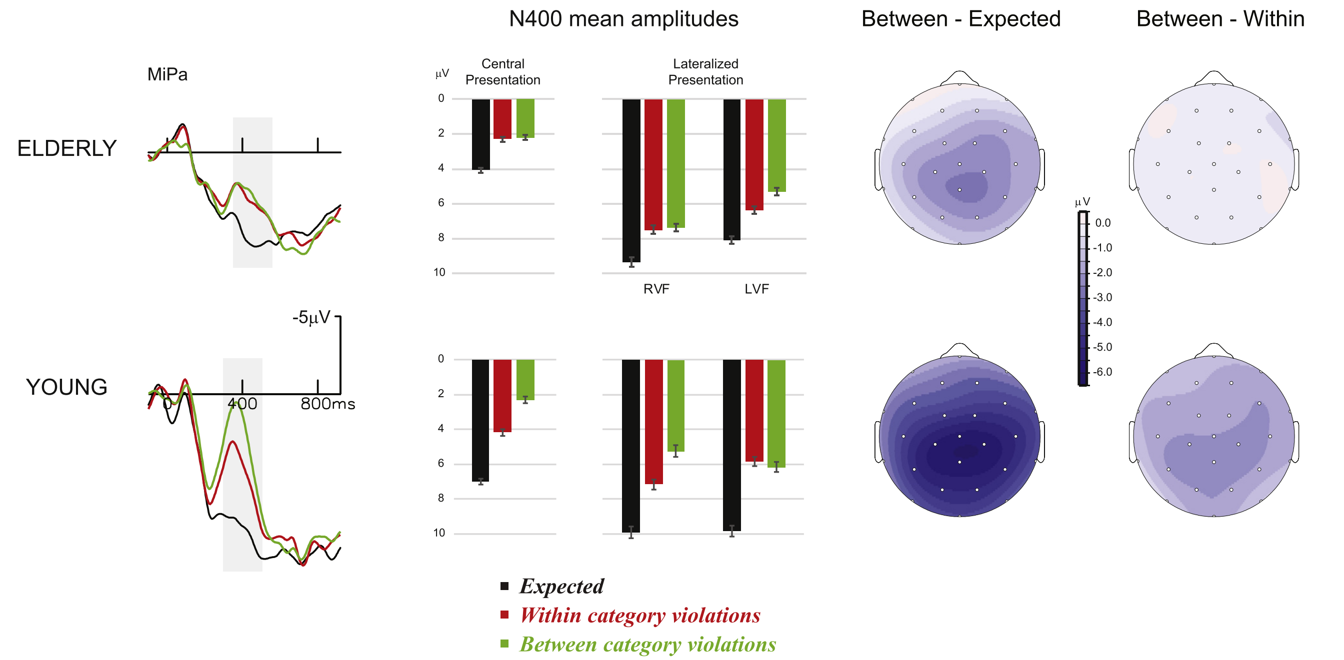

Fig. 2. Comparison of effect patterns observed for the current sample of older adults ("elderly", at top) and the young adult samples from Federmeier and Kutas (1999a, 1999b) (at bottom). On the left are grand average ERPs for the three ending types at MiPa; shading shows the time window of analysis for the N400. In the middle is a bar plot of the mean amplitudes measured across all sampled electrodes, both for central and lateralized presentations. Error bars show standard errors. On the right are topographic maps showing the distribution in the N400 time window of the basic congruency effect (between category violations minus expected exemplars) and the prediction-related effect (between category violations minus within category violations). Both elderly and young show N400 congruency effects with a typical centro-posterior distribution. Young adults, but not elderly, also show a typically-distributed N400 prediction effect. Prediction effects (difference between responses to between and within category violations) were larger in young than in elderly adults [t(26) = 2.65, p (two tailed) < 0.05].

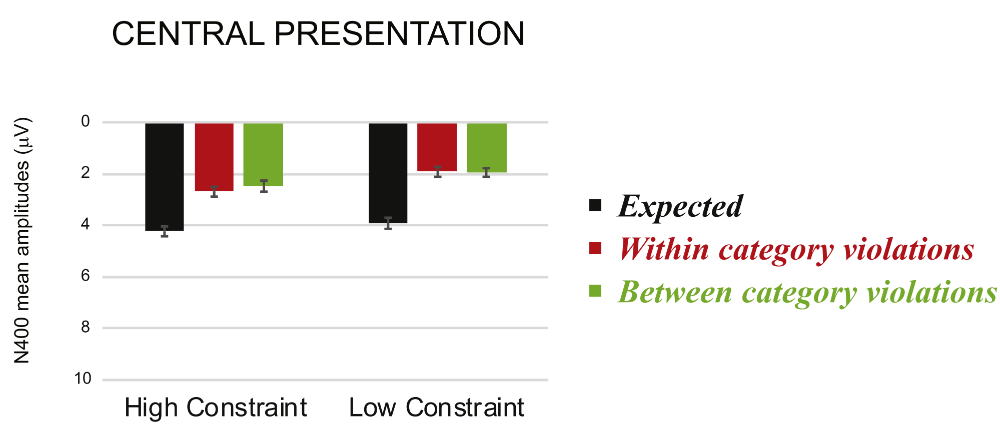

Fig. 3. Bar graph of the constraint effect, measured at all sampled electrodes across the N400 time window. Error bars show standard errors.

exemplars (8.8 µV) compared to within (6.9 µV) or between (6.4 µV) category violations [$F(2,40) = 17.67$; $p < 0.001$; $\varepsilon = 1$]. There was no main effect of Constraint [$F(1,20) = 0.05$; $p = 0.82$] and no interaction of Constraint and Ending Type [$F(2,40) = 1.44$; $p = 0.25$; $\varepsilon = 1$].

Lateralized presentation yields several characteristic morphological patterns in the ERP, which have been replicated in all VF-ERP studies, including those using older adults (see, e.g., Meyer and Federmeier, 2010). Visual sensory potentials, such as the N1, are largest contralateral to VF of presentation. These are followed by a long-lasting relative negativity over contralateral sites, which may be related to similar effects seen in experiments that lateralize nonlinguistic stimuli in order to examine spatial selective attention (reviewed by Eimer, 2011). These waveform patterns in the present study can be seen in Figs. 5 and 6. Although there could be generalized effects of age on the impact of visual half-field presentation, prior work has shown that older adults' ability to extract semantic information from words in parafoveal vision is qualitatively and quantitatively similar to that of young adults (Payne and Federmeier, 2017) and that, for aspects of single word processing, they show similar patterns of asymmetry as young adults (Meyer and Federmeier, 2010). General effects of lateralization and/or aging can complicate direct comparisons across VF or age group, but here, by design, all comparisons of theoretical interest are within subjects and within VF.

To assess ending type effects with lateralized presentation, we first performed a repeated measures ANOVA using 2 levels of Visual Field (RVF/LH and LVF/RH) and 3 levels of Ending Type (expected exemplars, within category violations, and between category violations). These effects, and corresponding ones from the young adult sample in Federmeier and Kutas (1999b), are shown in Fig. 4. There was a main effect of Visual Field [$F(1,20) = 15.42$; $p < 0.001$], with overall more positive voltages to words presented in the RVF/LH (8.1 µV) compared to the LVF/RH (6.6 µV). There was also the main effect of Ending Type, described above. Critically, there was no interaction between Visual Field and Ending Type [$F(2,40) = 1.36$; $p = 0.27$; $\varepsilon = 0.95$]; thus,

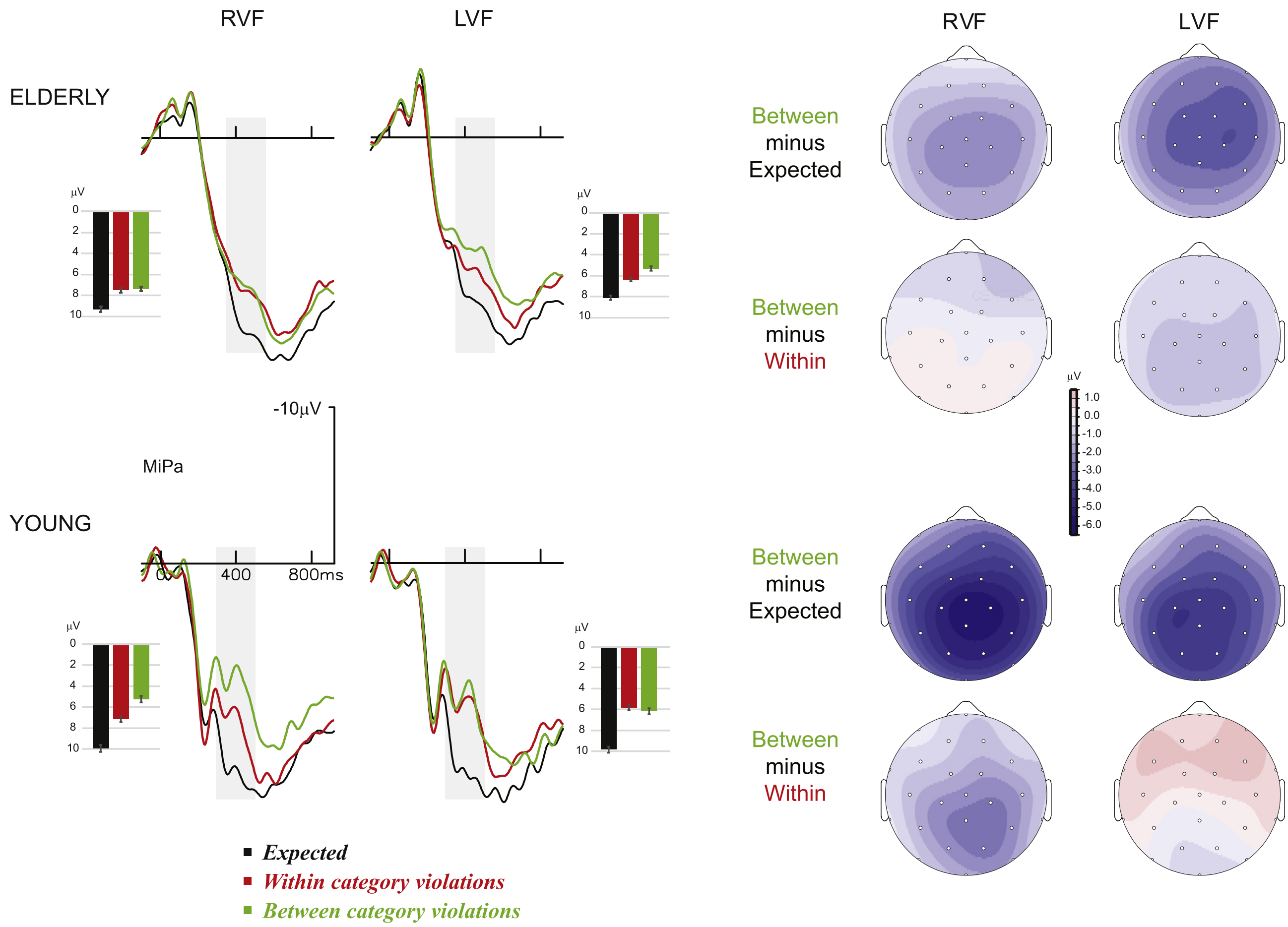

Fig. 4. Comparison of lateralized effect patterns observed for the current sample of older adults ("elderly", at top) and the young adult samples from Federmeier and Kutas (1999b) (at bottom). On the left side of the figure are grand average ERPs for the three ending types at MiPa; shading shows the time window of analysis for the N400. Alongside each waveform is a bar plot of the mean amplitudes measured across all sampled electrodes. Error bars show standard errors. On the right side of the figure are topographic maps showing the distribution in the N400 time window of the basic congruency effect (between category violations minus expected exemplars) and the prediction-related effect (between category violations minus within category violations). Both elderly and young show N400 congruency effects with a typical centro-posterior distribution in both visual fields; this effect was reliably larger for young compared to elderly with RVF presentation [$t(31) = 2.53$, p (two tailed) < 0.05] but not with LVF presentation [$t(29) = 1.15$, p (two tailed) $= 0.26$]. Young adults also show a typically-distributed N400 prediction effect limited to RVF presentation. This effect was reliably smaller in the elderly sample [$t(36) = 2.08$, p (two tailed) < 0.05].

different from the pattern seen for young adults (Federmeier and Kutas, 1999b; see Fig. 4), older adults' responses did not show a reliably asymmetric pattern.

Because characterizing the pattern within each hemisphere was a core goal of the study, we conducted planned comparisons separately within visual field. In each case, we used a repeated measures ANOVA with 2 levels of Constraint (high and low) and 3 levels of Ending Type (expected exemplars, within category violations, and between category violations).

3.3.1. *Right visual field (left hemisphere-biased processing)*

As can be seen in Fig. 5, there was a main effect of Ending Type [$F(2,40) = 5.95$; $p < 0.01$; $\varepsilon = 1$]. There was no main effect of Constraint [$F(1,20) = 0.03$; $p = 0.86$] and no Constraint by Ending Type interaction [$F(2,40) = 1.64$; $p = 0.21$; $\varepsilon = 1$]. Expected exemplars elicited positive (facilitated) responses (9.3 µV) compared to within category violations (7.5 µV) [$F(1,20) = 10.61$; $p < 0.01$]. Within and between category violations (7.4 µV) did not differ from each other [$F(1,20) = 0.03$; $p = 0.86$].

3.3.2. *Left visual field (right hemisphere-biased processing)*

As seen for the right visual field, there was a main effect of Ending Type [$F(2,40) = 23.53$; $p < 0.001$; $\varepsilon = 0.93$], but no main effect of Constraint [$F(1,20) = 0.02$; $p = 0.89$] and no Constraint by Ending Type interaction [$F(2,40) = 0.06$; $p = 0.94$; $\varepsilon = 1$]. See Fig. 6. Expected exemplars elicited positive (facilitated) responses (8.1 µV) compared to within category violations (6.4 µV) [$F(1,20) = 27.97$; $p < 0.001$]. Within category violations were also more positive than between category violations (5.4 µV) [$F(1,20) = 8.24$; $p = 0.01$]. Numerically, this tendency was greater within weakly constraining sentences (1.2 µV difference) than within strongly constraining ones (1.0 µV difference).

4. Summary

The overall effect pattern seen with lateralized presentation replicated that seen for central presentation: There was an effect of congruency, with smaller N400 responses to expected than to unexpected items, but there was no difference between the unexpected items and no impact of contextual constraint on the response pattern. Critically, there was also no interaction between visual field and ending type. In both visual fields, N400s were reduced to expected compared to unexpected items, but there was no impact of contextual constraint. In particular, the pattern indicative of prediction that is seen for left hemisphere-biased processing in young adults (Federmeier and Kutas, 1999b) was not detectable in healthy older adults.

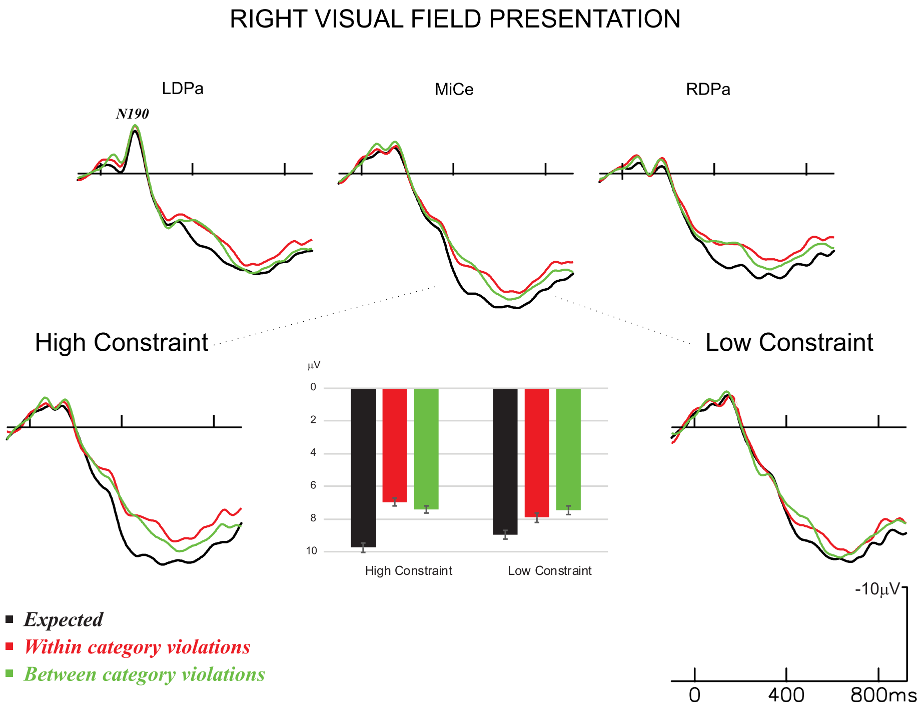

Fig. 5. Grand average ERP waveforms for the three ending types following initial presentation to the right visual field (left hemisphere), at a representative set of medial, centro-posterior electrode sites. Note the expected lateralization of early sensory components: the N1, peaking around 190 ms, is notably larger over left than over right scalp locations. The top row shows the overall effect of ending type on the N400 (350–550 ms), with more positive responses to expected exemplars (solid line) than to both within category violations (dashed line) and between category violations (dotted line). The bottom row shows responses at the Middle Central (MiCe) electrode site, split by contextual constraint. The ending type effect was not modulated by constraint. Bar graphs at center give the pattern as measured across the whole region, with standard errors provided.

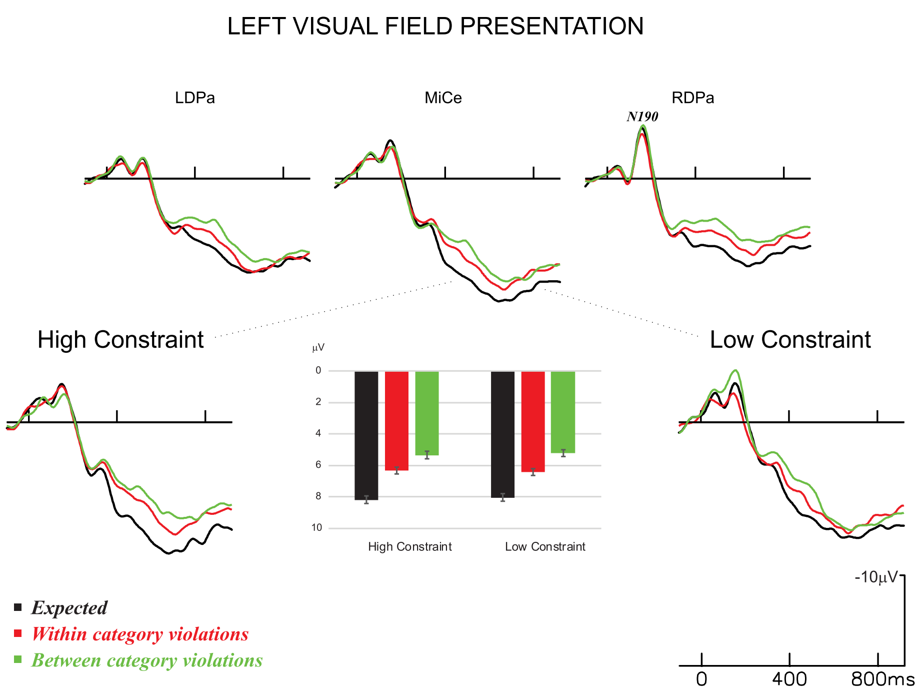

Fig. 6. Grand average ERP waveforms for the three ending types following initial presentation to the left visual field (right hemisphere), at a representative set of medial, centro-posterior electrode sites. Note the expected lateralization of early sensory components: the N1, peaking around 190 ms, is notably larger over right than left scalp locations. The top row shows the overall effect of ending type on the N400 (350–550 ms), with more positive responses to expected exemplars (solid line) than to both within category violations (dashed line) and between category violations (dotted line). N400 responses to within category violations were also more positive than responses to between category violations. The bottom row shows responses at the Middle Central (MiCe) electrode site, split by contextual constraint. The ending type effect was not modulated by constraint. Bar graphs at center give the pattern as measured across the whole region, with standard errors provided.

5. Discussion

We had previously shown that older adults fail to show prediction-related N400 facilitations when listening to sentences (Federmeier et al., 2002). During both listening (Federmeier et al., 2002) and word-by-word reading (Federmeier and Kutas, 1999a), younger adults show robust N400 reductions for unexpected words that share semantic features with the word most likely to come next, an effect that is larger when predictions are stronger (i.e., in strongly compared to weakly constraining contexts). Here, we show that, as was observed for listening, older adults fail to reliably exhibit this predictive processing pattern when reading, whether the words are presented in foveal vision or parafoveally.

Having confirmed the expected sentence processing pattern in the older adult sample, our primary goal was to compare two hypotheses about the source for the differences observed for older adults compared to previous findings with young adults. In particular, it is notable that the pattern elicited in older adults resembles that observed in young adults when processing is biased toward the right hemisphere through the use of visual half-field presentation methods (Federmeier and Kutas, 1999b). Given the body of work reporting that older adults activate both hemispheres for a variety of tasks that show strongly asymmetrical patterns in younger adults (reviewed in Park and Reuter-Lorenz, 2009), one possibility for the age-related changes we have observed is that older adults tend to recruit right hemisphere processing mechanisms more. Looking across the literature, it is clear that, in young adults, the patterns observed with central presentation of stimuli can reflect different configurations of contribution from the two cerebral hemispheres. For the stimulus materials used here, the pattern observed with central word presentation (or listening) matches that seen for left hemisphere-biased processing, consistent with an important contribution from left hemisphere processing mechanisms. However, as discussed in the introduction, in other cases, the pattern observed with central presentation instead matches that seen for processing biased to the right hemisphere. For example, Metusalem et al. (2012) found N400 reductions for contextually anomalous words that are related to the overall event structure but, different from the current materials, not related to the word expected next (e.g., smaller N400 to "jacket" than to "towel" given a context like "A huge blizzard swept through town last night. My kids ended up getting the day off from school. They spent the whole day outside building a big …" where "snowman" is expected). Critically, in a visual half-field version of the experiment, Metusalem et al. (2016) found that this type of facilitation was seen exclusively for processing biased toward the right hemisphere. In still other cases, processing seems to reflect the sum of contributions from both hemispheres, neither of which alone exhibits the pattern obtained with central presentation (Wlotko and Federmeier, 2013).

Thus, the age-related shift seen for listening and, here, word-by-word reading might reflect, not a change in the underlying (asymmetric) mechanisms, but a change in how much each hemisphere is recruited. To examine this, we used visual half-field methods to assess processing asymmetries in older adults. If aging is primarily causing differential recruitment of intact, asymmetric processing mechanisms, we expected to find the same pattern of hemispheric differences attested in young adults, with the left hemisphere manifesting a predictive pattern and the right showing a non-predictive pattern (Federmeier and Kutas, 1999b, 2002). However, this was not what we observed. Older adults were able to understand the sentences and process the words in parafoveal vision. They performed as well (in fact, numerically better) on the post-experiment recognition test for lateralized as for central word presentation, and manifested the same overall ERP pattern, including significant N400 reductions for expected compared to unexpected words in both visual fields. Critically, however, in the current study we did not find any reliable processing asymmetries for our older adult sample. Different from the pattern seen in young adults, visual field did not interact with ending type for older adults. Moreover, in particular, there was no sign of predictive processing when stimuli were biased toward the left hemisphere. Constraint did not interact with ending type in either visual field, and response amplitudes to within and between category violations were essentially identical for left-hemisphere biased processing (differing by only 0.1 μV on average).

Indeed, the only difference between within and between category violations was observed when these ending types were compared directly for right hemisphere-biased processing. This effect must be treated with caution given that there was no overall interaction of visual field and ending type. However, if real, it may reflect right hemisphere sensitivity to global plausibility, which was higher for the within than the between category violations. Moreover, this effect did not pattern with contextual constraint, as prediction-related facilitations of within category violations do (Federmeier and Kutas, 1999a; Federmeier et al., 2002); indeed, the difference was numerically larger in the weakly constraining contexts. Federmeier et al. (2002) also found that older adults' N400 amplitudes were sensitive to plausibility, as they showed some facilitation for within compared to between category violations in low constraint contexts. The pattern in the current study points to the possibility that this sensitivity reflects right hemisphere processing mechanisms; however, the effect needs to be replicated and studied in more detail.

Thus, age-related differences, attested during both reading and listening, in the tendency to show evidence for prediction during sentence processing seem to emerge due to differences in the functioning of the left hemisphere, including mechanisms that have been linked to prediction. A connection between language production, which is known to critically rely on left-hemisphere mechanisms, and predictive processing during comprehension have been widely hypothesized (Dell and Kittredge, 2013; Federmeier, 2007; Pickering and Garrod, 2007). Among older adults, this hypothesis receives support from the observation that performance on cued production tasks (verbal fluency) is correlated with the tendency to show predictive processing patterns during comprehension, both for listening and for reading (Federmeier et al., 2002; Federmeier et al., 2010). Similar correlations are observed for other aspects of comprehension, including the recruitment of selection mechanisms important for ambiguity resolution, which also has been linked to the left hemisphere (see review by Novick et al., 2010) and also generally diminishes with age (Lee and Federmeier, 2011, 2012; Stites et al., 2013). The present results thus complement a body of work suggesting that normal aging impacts the efficacy with which a variety of attention-demanding and/or controlled mechanisms are deployed during comprehension (cf., Huang et al., 2012; Payne and Federmeier, 2017), perhaps due to age-related changes in neural connectivity (e.g., Fjell et al., 2017; Kennedy and Raz, 2009; Shaw et al., 2015), among other factors. Of course, in the absence of longitudinal data, it is important to bear in mind that there could be additional factors contributing to the differences in the patterns observed within younger versus older adults.

In conclusion, consistent with many reports, we found that older adults are less likely to manifest predictive processing patterns when reading for comprehension. In young adults, the left hemisphere has been shown to be important for prediction, with the right hemisphere, instead, showing the same (non-predictive) pattern as seen globally among older adults. Here, we further show that the age-related change does not simply reflect differential recruitment of otherwise intact, asymmetric processing patterns. Instead, older adults failed to manifest the kind of processing asymmetries documented in the young, and neither hemisphere in older adults showed evidence for the use of predictive processing. Our data do not rule out the possibility that older adults also recruit right hemisphere mechanisms more than younger adults. However, the results demonstrate that one salient difference in the processing mechanisms used by younger and older adults during language comprehension seems to arise in the tendency for the left hemisphere, in particular, to predict.

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