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Thinking ahead or not? Natural aging and anticipation during reading

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Abstract

Despite growing evidence of young adults neurally pre-activating word features during sentence comprehension, less clear is the degree to which this generalizes to older adults. Using ERPs, we tested for linguistic prediction in younger and older readers by means of indefinite articles (*a*'s and *an*'s) preceding more and less probable noun continuations. Although both groups exhibited cloze probability-graded noun N400s, only the young showed significant article effects, indicating probabilistic sensitivity to the phonology of anticipated upcoming nouns. Additionally, both age groups exhibited prolonged increased frontal positivities to less probable nouns, although in older adults this effect was prominent only in a subset with high verbal fluency (VF). This ERP positivity to contextual constraint violations offers additional support for prediction in the young. For high VF older adults, the positivity may indicate they, too, engage in some form of linguistic pre-processing when implicitly cued, as may have occurred via the articles.

Keywords

Aging; Language; Comprehension; Prediction; Event-related brain potentials; N400; Frontal positivity; Verbal fluency; Implicit cueing; Executive processes

1. Introduction

The anonymously-authored quote, "I still have a full deck; I just shuffle slower now," not only captures what some have described as the feeling of aging, but also reflects a commonly observed change in cognitive functioning during the later years of life; that is, while older adults have certain knowledge stores that appear to be relatively immune to age-related deterioration and while they are generally considered to comprehend well, there is often a decline in their ability to operate in a timely manner on such structures (e.g., Myerson, Hale, Poon, Wagstaff, & Smith, 1990; Salthouse, 1996). Language comprehension is one domain that reflects this "mixed bag" of preservation and decrement. Despite the age constancy of various comprehension-related processes (e.g., vocabulary size, Verhaeghen, 2003; contextual facilitation in sentence interpretation, Madden, 1988; organization of knowledge stores, Burke & Peters, 1986, etc.), older adults appear less likely than their

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younger counterparts to engage in pre-activating information (unconsciously anticipating upcoming input) during sentence processing (e.g., Federmeier, Kutas, & Schul, 2010; Federmeier, Mclennan, De Ochoa, & Kutas, 2002; Wlotko, Federmeier, & Kutas, 2008) as well as during more general cognitive processing (Bar, 2007).

Historically, psycholinguists have found predictive language comprehension contentious. While incremental language processing has been well established, with sentential inputs processed as they are encountered without delay, distinguishing evidence for neural pre-activation from integration has proven challenging. Pre-activation entails unconsciously building representations for upcoming concepts, features or forms that may never be encountered in the input. In contrast, integration entails activating and processing representations as they are triggered by physical input. Primarily through on-line studies conducted over the past decade, evidence has accrued showing that young, healthy adults' receptive language – like other perceptual and cognitive brain functions – operates proactively (DeLong, Urbach, & Kutas, 2005; Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007; Kamide, Altmann, & Haywood, 2003; van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Wicha, Moreno, & Kutas, 2004).

With evidence for routine context-based pre-activation of syntactic, semantic, and phonological features in younger adults, a natural question is what the consequences of normal aging are on the availability and use of anticipatory processes. At a performance-based level, there has been some debate in the literature regarding the top-down use of language context by older adults. In particular, some behavioral studies (e.g., Stine-Morrow, Miller, & Nevin, 1999; Wingfield, Alexander, & Cavigelli, 1994) have found that older adults – perhaps even more so than younger adults – take advantage of contextual constraint to facilitate lexical decision and word identification. Self-paced reading comprehension studies, too – which minimize possibilities of inducing strategic approaches related to overt task goals – have shown that with increased age, contextual knowledge facilitates discourse-embedded word processing (e.g., Stine-Morrow, Miller, Gagne & Hertzog, 2008) and reduces working memory load, leading to increased reading efficiency (Miller, Cohen, &Wingfield, 2006). On the other hand, ERP work (with its high temporal resolution and sensitivity to qualitative processing differences) has indicated that older adults are less able than younger adults to make use of highly constraining sentence context to rapidly facilitate semantic processing (e.g., Federmeier & Kutas, 2005). So when relatively age-preserved vocabulary and semantic knowledge interacts with processing speed and/or working memory or other more general processes – which are in decline from early adulthood onward (Craik, 1994; Park, Smith, Lautenschlager, Earles, Frieske, & Zwahr, 1996) – online context-building, integration and comprehension may not occur dynamically enough for upcoming input to be (effectively) pre-activated prior to its anticipated occurrence. In order to accommodate their decreasing processing abilities, older adults may rely more on external cues to support behaviors such as language comprehension (Craik, 1983) and thus may be biased toward top-down sentence comprehension only when task demands require it or when the input cues them to do so. Stine-Morrow et al. (2008) propose a self-regulated language processing model by which older readers, particularly those with high verbal ability, may allocate additional resources for semantic analysis during reading to offset some of their processing deficiencies. One such deficit that could potentially interact with language comprehension is older adults' decreased inhibitory control (e.g., Hasher & Zacks, 1988) – an issue relevant for linguistic prediction in light of what may be happening during the course of lexical access/ activation. Still other less generalized accounts have proposed certain asymmetries in effects of aging on language processing, with production being more negatively impacted than comprehension (e.g., Burke & MacKay, 1997), and relatively stronger reliance by older individuals on semantic rather than phonological information (e.g., Cortese, Balota, Sergent-Marshall, & Buckner, 2003; Taylor & Burke, 2002).

There may be good reasons to expect such performance-based differences given age-related anatomical changes. For instance, aging has been proposed to compromise several brain regions that may constitute a network of association-based prediction: e.g., the medial temporal lobe, the medial parietal cortex, and the medial prefrontal cortex (Bar, 2007). Additionally, age-related volumetric or neurotransmitter changes to the prefrontal cortex (PFC), linked to changes in PFC activity during executive processing tasks, could result in decreased performance under conditions, for instance, of high working memory load, when there is interference, or when task-switching is involved – some or all of which may be involved in the comprehension of more or less predictable input strings (e.g., Gunning-Dixon & Raz, 2003; Head, Raz, Gunning-Dixon, Williamson, & Acker, 2002). Still other studies have found that there tends to be less lateralization (more bilateral activity) for a variety of cognitive tasks in older, relative to younger, adults (e.g., Cabeza, Anderson, Locantore, & McIntosh, 2002; Reuter-Lorenz et al., 2000). This is a relevant point because some proposals for context- based linguistic prediction have suggested that pre-activation is a left hemisphere-biased process (e.g., Federmeier & Kutas, 1999b).

Other theories argue that shifts in cognitive processing strategies from younger to older adults may arise not necessarily as a consequence of age-related anatomical changes per se, but rather may develop through the nonuse of certain cognitive functions – with the flip side being that certain skills or activities may serve to buffer against decline (e.g., Hultsch, Hertzog, Small, & Dixon, 1999). For instance, Salthouse (1991) suggests that declines in activity patterns of older adults may lead to atrophy of various cognitive skills (the “use it or lose it” hypothesis). The extent to which older adults rely on alternative strategies to cope with such declines (e.g., Logan, Sanders, Snyder, Morris, & Buckner, 2002) is a potentially important area of investigation for the study of prediction in language processing.

Relatively few studies have attempted to directly test the nature of predictive language processing in older adults using on-line methods. Electrophysiological studies by Federmeier and colleagues (e.g., Federmeier et al., 2002; Federmeier et al., 2010; Wlotko, Federmeier, & Kutas, 2008) have found that as a generalized comprehension strategy, individuals over 60 years of age are less likely to pre-activate upcoming semantic information in a similar manner or to the same extent as younger adults. Their conclusions have primarily been based on findings relating to two ERP effects: the N400 and a late frontal positivity.

The N400 is a well-established negative-going ERP component prominent over posterior scalp sites, peaking around 400 ms post-item onset. Its amplitude correlates with degree of semantic activation and the fit of any potentially meaningful item with its preceding or surrounding context (Kutas & Hillyard, 1980; for a review, see Kutas & Federmeier, 2011). Notably, for young comprehenders N400 amplitude has been shown to be inversely correlated (r~−.9) with the offline cloze probability of an eliciting item (e.g., DeLong et al., 2005; Kutas & Hillyard, 1984), although it appears to be insensitive to the degree to which less expected items violate contextual constraint (defining “context” here as a preceding word, phrase, sentence, or discourse; or an environmental surrounding, internal state, etc.). Federmeier et al. (2002) demonstrated that while young comprehenders showed reduced amplitude N400s to implausible spoken sentence continuations categorically related to expected continuations (relative to categorically unrelated implausible continuations), older adults on the whole did not show this pattern. For younger adults, this pattern reliably emerged in highly constraining sentence contexts (e.g., to *baseball* in ‘*He caught the pass and scored another touchdown. There was nothing he enjoyed more than a good game of. . . football/baseball/monopoly.*’), but not weakly constraining ones. Since the categorically related violations (*baseball*) were rated as implausible as the unrelated ones (*monopoly*), it followed that the facilitation for the related items was due to the overlapping features with

the expected item (*football*) already having been pre-activated. Although this "predictive" ERP pattern was not observed across all older adults in the study, a subset of them with relatively high offline verbal fluency scores *did* show the reduced within-category violation young adult N400 response pattern. From these findings, it was hypothesized that although older adults are generally less likely (or able) to use context predictively, certain resource availability may be important for preservation of predictive language comprehension abilities with aging.

Another relatively less explored ERP response – a late frontal positivity sensitive to contextual constraint violations – has also been linked to predictive language processing. It has been suggested that this effect may reflect a processing consequence for not receiving an item highly pre-activated by its preceding context – i.e., "mispredicting". In studies of young adults described by Federmeier et al. (2007) and DeLong, Urbach, Groppe, and Kutas (2011), anterior positivities following (and concurrent with) the N400 were observed to constraint violations. For instance, Federmeier et al. (2007) crossed high and low sentence constraint with more and less expected sentence endings and found that young adults showed increased ERP frontal positivity between 500 and 900 ms post-target onset to unexpected words continuing high constraint contexts. However, when Wlotko et al. (2008) presented older adults with these same types of materials, older adults, as a group, did not elicit the constraint violation-related frontal positivity. Federmeier et al. (2010) also capitalized on this component's sensitivity to determine if the lack of a prediction effect in older adults might be due to working memory load or timing pressures imposed during sentence processing. Limiting their experimental task to one where participants were presented with phrasal cues for category exemplars (e.g., '*an insect*') followed by either high typicality ('*ant*'), low typicality ('*hornet*') or incongruent ('*gate*') delayed (non)exemplar probes, they observed that younger adults, but not older adults (on average), exhibited the increased late, prefrontal positivity to the low typicality probes, consistent with expectancy violation. Moreover, these results obtained despite the fact that older adults were as fast as the young in supplying category exemplars in a cued production variant of this same task – indicating that though older adults are capable of generating speeded linguistic output, whether or not they actually do so may be a function of task demands and strategic recruitment of such processes. Notably, those older adults who scored high on an offline test of verbal (category) fluency (Benton & Hamsher, 1978) showed the positivity similar to the young. This association of verbal fluency (hereafter, VF) with a potentially prediction-related ERP effect has been interpreted by Federmeier and colleagues as being suggestive of the predictive comprehension system tapping into the same neural resources used during language production.

Although these findings indicate that older adults are generally less inclined to show evidence for linguistic prediction than younger adults, in the current study we set out to test – using a paradigm that would allow for pre-target examination of predictive ERP effects – whether older adults, like the young, would exhibit any evidence for graded, probabilistic pre-activation of linguistic input during sentence reading. If there is evidence, we also want to determine if there are individual differences in older adults' prediction- related ERP effects based on offline VF scores.

To do this we employed an ERP paradigm that utilized English indefinite articles (*a*, *an*) preceding more and less expected noun continuations to probe for lexical prediction (e.g., *Dale was very sorry and knew he owed Mary a check/an apology for what he had done.*) in younger and older adults. Although cloze-related modulation of N400 mean amplitude at the noun (e.g., *check* or *apology*) could be interpreted as either a consequence of the brain's processing of a word pre-activated to varying degrees as a function of contextually- based expectancies (prediction view) *or* as greater difficulty integrating the received word into the

sentence representation (integration view), the same is not true of the prenominal articles. For the semantically identical *a* and *an*, one of these article types should not be harder to contextually integrate unless comprehenders had already unconsciously pre-activated an upcoming noun. If specific, highly constrained target nouns are being preactivated prior to encountering them for older adults as they are for the young (DeLong et al., 2005), we might expect to observe a graded prediction-related N400 effect at the prenominal articles correlated with varying degrees of offline expectancy (as determined through cloze probability norming). Another possibility, however, is that unlike the young, older individuals may not be predicting at the lexical level, because they cannot process the incoming words quickly enough and/or because they must rely on some alternative comprehension mechanism or strategy. In this case, N400-like prediction effects at the prenominal target articles might not obtain for older adults.

In addition, for both groups, we expect to observe some modulation of target noun N400 amplitude with varying cloze probability, as has been previously reported. In particular, we want to determine whether older – like younger – adults exhibit a *graded* sensitivity to the semantic relations of nouns with their preceding contexts. Correlational patterns of increasing noun N400 mean amplitude with decreasing noun cloze would indicate that older adults continue to be sensitive to a range of contextual fit over a time window that remains relatively constant over the course of normal aging. To our knowledge, observing such a pattern would be the first demonstration of this fully-graded effect in older comprehenders.

Another aim of the current study is to investigate whether a possible ERP response in the form of an increased late frontal positivity to less expected nouns (e.g., *check* in the previous example) might offer any clues into the differential nature of predictive language comprehension in younger and older adults. DeLong et al. (2011), which tested younger adults using the same *a*/*an* paradigm, showed such an effect to less probable nouns continuing higher constraint contexts. Other work (Federmeier et al., 2007) suggests that the late frontal positivity may not just be a functional mirror of the N400 cloze effect, in that unlike the N400 it is related more to the degree of *constraint* violation. If this positivity is reflecting some kind of neural processing invoked when continuations are highly pre-activated but not actually encountered, then an outstanding question is whether older adults will show a similar effect, given that the article N400 and the noun late positivity occurred in tandem for younger adults, and we do not yet know if older adults will exhibit an article effect. Yet another possible outcome is that the older adults will show neither the prediction-related article N400 effect nor the late positivity to less expected noun continuations – a pattern which would suggest a lack of prediction and thus no consequences for any form of "misprediction".

A final question is whether there might be individual differences in older comprehenders' abilities to engage in linguistic pre-activation as a function of a production measure – namely, offline VF. If we observe such differences in the post-target noun late frontal positivity region (as has been previously noted in older comprehenders with high VF) it is possible that in that same sub-group we might also observe article cloze-based differences in the article N400 time window, even if, as a whole, older participants do not show this pattern. Such a finding would prove intriguing with respect to linking the post-noun onset positivity more directly to a functional account of the effect in terms of prediction.

2. Material and methods

Our aim was to determine whether younger and older adult language comprehenders similarly engage in graded, probabilistic prediction. To that end we tested college-aged and 60+ year-old adults using sentences varying in constraint that led to stronger and weaker

expectations for more or less likely consonant or vowel-initial nouns (materials from DeLong et al., 2005). The experiments reported here were conducted according to human subject protocols approved by the University of California, San Diego Institutional Review Board and all participants provided their informed consent in writing before participating in the experiment.

2.1. Participants

Thirty-two young adult volunteers from the University of California, San Diego and the surrounding community (23 women, 18–37 years of age, mean age 21 years, seven reporting a left-handed parent or sibling) and 36 older adults from the San Diego community (23 women, 60–86 years of age, mean age 70 years, 14 reporting a left-handed parent or sibling) participated in the ERP experiments for course credit or cash. All were right-handed, native monolingual English speakers with normal or corrected-to-normal vision, and no history of reading difficulties or neurological/ psychiatric disorders. All participants had completed high school, and 24 of the older participants had some college education, with another 7 having advanced degrees.

2.2. Materials

Sentence stimuli consisted of 80 sentence contexts with two possible target types, relatively more expected (higher cloze) and less expected (lower cloze) indefinite article + noun pairs. Sentence stimuli were constructed in pairs such that the expected and less expected article + noun target for the first sentence reversed conditions for the second sentence of each pair. Targets were sentence medial and congruent (i.e., there were no agreement violations such as "*a airplane*"). One quarter of sentences were followed by yes/no comprehension questions.

Across sentences, target nouns (and preceding indefinite articles) ranged from highly probable to unlikely. See Table 1 for representative stimuli and comprehension questions.

2.2.1. Cloze probability norming—Cloze probabilities were obtained separately for younger and older adults. Each of the 80 experimental sentence contexts was normed in three different ways: ending with *a*, with *an*, and without a target indefinite article provided. Each variation was normed in an off-line sentence completion task by 30 younger adults attending UCSD and by 15–17 San Diego area older adults (above the age of 60), who were paid for their participation. Participants were instructed to continue each context with the word(s) they felt best completed each sentence. Cloze probability for a given article or noun in a context was calculated as the proportion of individuals providing that particular word as a continuation. Table 2 summarizes the results of the article and noun cloze norming for the two groups.

2.2.2. Experimental design—For ERP testing of both younger and older adults, the 160 stimuli were divided into two lists of 80 sentences, each participant viewing one list. Sentence contexts and article + noun targets were used only once per list. Each list contained equal numbers of relatively expected and unexpected (as well as *a* and *an*) article and noun targets with large ranges of cloze. Across participants the same sentence context appeared with both higher and lower probability articles and nouns. Importantly, although some continuations were more probable than others, none were nonsensical, barring participants from developing a strategy, conscious or unconscious, whereby an improbable article was taken to predictably signal an impending semantic anomaly.

2.3. Procedures

Participants' brainwaves were recorded in a single experimental session conducted in a sound-attenuating, electrically shielded chamber. They were seated in a comfortable chair approximately one meter in front of a computer monitor and were instructed to read the stimulus sentences for comprehension. They were also informed that some of the sentences would be followed by yes/no comprehension questions, to which they were to respond by pressing one of two hand-held buttons. Response hand was counterbalanced across participants and lists. A brief practice session included sentences with both expected and unexpected targets, as well as filler sentences. Participants were asked to remain still during testing, and to avoid blinking and moving their eyes while the sentences were being presented. Stimuli were presented in 10 blocks of 20 or fewer sentences, with short breaks between blocks.

Sentences were presented visually on a CRT screen. Each trial began with an empty fixation frame appearing in the center of the screen for a random duration between 2.5 and 3.5 s. Sentences were presented one word at a time in the center of the frame for a duration of 200 ms and an inter-stimulus interval of 300 ms. The fixation frame remained on screen between 1.5 and 2.5 s following the offset of the sentence final word, after which a comprehension question (if there was one) appeared in its entirety on the screen. If a comprehension question did appear, the participant's buttonpress served to advance the screen to the next sentence. Whether or not there was a comprehension question, there were 2 s of blank screen before the next sentence automatically appeared.

In a separate session, each older adult participant completed a battery of neuropsychological tests in the lab, including, most relevantly, tests of verbal fluency (letter and category: Benton & Hamsher, 1978), among others.

2.4. Electroencephalographic recording parameters

The electroencephalogram (EEG) was recorded from 26 electrodes arranged geodesically in an Electro-cap (Fig. 1), each referenced online to an electrode located over the left mastoid. Blinks and eye movements were monitored from electrodes placed on the outer canthi and under each eye, also referenced to the left mastoid process. Electrode impedances were kept below 5 kX. The EEG was amplified with Grass amplifiers with a pass band of 0.01–100 Hz and was continuously digitized at a sampling rate of 250 samples/s.

2.5. Data analysis

Trials contaminated by eye movements, excessive muscle activity, or amplifier blocking were rejected offline before averaging. Data with excessive blinks were corrected using a spatial filter algorithm. For older adults, trial loss averaged 11.4% for the target articles and 11.9% for the target nouns; for younger adults, 10.7% of the articles and 11.4% of the nouns were lost. A third order Butterworth band-pass filter set from 0.2 to 15 Hz was used on all data to reduce high frequency noise. Data were re-referenced offline to the algebraic mean of the left and right mastoids and averaged for each experimental condition, time-locked to the target article and noun onsets. ERPs were computed for epochs extending from 500 ms before stimulus onset to 1540 ms after stimulus onset.

3. Behavioral results

3.1. Accuracy

For yes/no comprehension questions, younger participants correctly answered an average of 95% (range = 88–100%) of the time. Older adults' performance was similar in that they correctly answered an average of 95% of the questions (range = 83–100%). These results

indicated that both groups were attending to and comprehending the experimental sentences during the recording session.

3.2. Response time

For both groups, we also calculated average response times for answering the questions, though participants were not explicitly instructed to answer in a timely manner. Response times were calculated from the onset of the entire question being presented on screen. After removal of one young participant's extreme outlier button press data, the response times of 31 young participants (M = 3651 ms, SD = 972 ms) were found, on average, to be significantly shorter than those of the 36 older participants (M = 4166 ms, SD = 1085 ms), $t(65) = 2.03$, $p = .0467$.

4. ERP results

To investigate possible cloze-related effects in both age groups, we were primarily interested in examining ERP effects between 250–400 ms post-article onset, 300–500 ms post-noun onset, and 500–900 ms post-noun onset. The article time window was selected in order to examine potential N400-like effects that might occur rapidly (due to the short word length and high natural language frequency of *a* and *an*) and therefore during the earlier portion of a typical N400 time window for content words. Our noun time windows included one for both a typical noun N400 effect (300–500 ms post-noun onset) as well as a later time window in which previous studies have noted late positivities to constraint violating nouns (500–900 ms post-noun onset, e.g., Federmeier et al., 2007).

The statistical method we employed was repeated measures ordinary least squares regression analysis (Lorch & Myers, 1990). We utilized the 160 experimental sentences over the 26 scalp channels, examining the potentially linear relationships of article cloze with article ERP mean amplitude and noun cloze with noun ERP mean amplitude. Groups of 32 younger comprehenders and 36 older comprehenders were analyzed separately. Additionally, we analyzed two sub-groups of the older participants (18 participants/ group) based on a median split of their offline verbal fluency (VF) scores: mean VF scores (letter and category combined) were 128.2 (range: 115–169) for High VF scorers and 93.3 (range: 50– 114) for Low VF scorers. In each analysis, the response variable was mean EEG amplitude and the predictor variable (in addition to an intercept term) was either target article or target noun cloze probability (ranging in both cases from 0% to approximately 100%). For each participant, a slope coefficient was estimated for each electrode and time point/window pair. To determine if slope coefficients significantly differed from zero, a one sample *t*-test was applied to the coefficients from all participants.

For each analysis, the Benjamini and Hochberg (1995) false discovery rate (FDR) control procedure was used to protect against a large proportion of false discoveries due to the multiple comparisons using an FDR of 0.05. Studies of simulated ERPs (Groppe, Urbach, & Kutas, 2011) have found that this FDR procedure provides accurate control of the FDR rate for ERPs. For these analyses, on average, each young participant provided 68.3 article and 68.5 noun trials, and each older participant provided an average of 71.4 article and 67.9 noun trials. High VF older participants provided an average of 72.3 article and 68.2 noun trials, and Low VF older participants provided an average of 71.1 article and 68.5 noun trials.

We conducted the regression analyses in two ways. First, for each participant group, we regressed article or noun cloze with the relevant ERPs at all 26 electrode locations over our three mean amplitude time windows of interest. These mean amplitude analyses were meant to maximize our power to detect expected effects, to parallel more typical ERP analyses of

mean amplitude time windows, and to provide a comparable picture of the ERP effects of interest within the individual subject groups. Second, we performed mass univariate tests on correlations of cloze probability and ERP amplitude at all 26 electrode locations and at all sampled time points within our article and noun time windows for each group. This method would allow us to examine effects with greater temporal resolution than conventional ANOVAs while maintaining a desired family-wise alpha level (i.e., the test corrects for the large number of comparisons). For time points between 250 and 400 ms post-article onset, there were 1014 total comparisons per subject group analysis. For the nouns, in order to examine the potential overlap of the N400 with a possible late frontal positivity, all time points between 200 and 900 ms at all 26 scalp electrodes were included (i.e., 4576 total comparisons per subject group analysis).

As aids to visualizing effects of article and noun cloze on the ERP mean amplitude of the respective words, we provide the following plots: (1) The grand average ERPs to higher cloze (50–100%) and lower cloze (0–49%) articles (Fig. 2) and nouns (Fig. 3) over all 26 electrodes for both age groups,[1] (2) topographic scalp maps of mean slope coefficients from the cloze probability/ERP mean amplitude time window repeated measures regressions for all groups (Fig. 4), and (3) raster plots representing the mass univariate regression tests in two dimensional grids for the articles and nouns for all groups (Fig. 5).

4.1. Younger adults

4.1.1. Articles—Between 250 and 400 ms following presentation of the articles, the mean time window analyses found that ERP mean amplitude in young participants was positively correlated with article cloze probability – an N400-like relationship – primarily over mediofrontal electrodes (Fig. 4A), with p-values of significant correlations ranging from $.028 \leq p \leq .035$. (Note that these and all subsequent p-values are FDR adjusted.) The time point-by-time point analysis showed that this increasingly negative ERP amplitude with decreasing article cloze probability (p-values of significant correlations ranging from $.044 \leq p \leq .049$) began as early as 254 ms, lasted as late as 357 ms, and was most widespread around 278 ms (Fig. 5A). These effects are consistent with young comprehenders showing a graded neural sensitivity to receiving articles that are more or less consistent with variably pre-activated upcoming nouns.

4.1.2. Nouns—Between 300 and 500 ms post-noun onset, the mean time window analyses found that ERP amplitude was generally positively correlated with noun cloze probability, exhibiting a canonical posterior but widespread N400 scalp topography (Fig. 4B; $.0001 \leq p \leq .026$ for all significant correlations in this time window). Some residual N400 activity carried over into the 500–900 ms time window at the most posterior scalp location (Fig. 4C; $.001 \leq p \leq .024$ for all significant correlations in this time window). The time point-by-time point analysis (Fig. 5B; $.001 \leq p \leq .049$ for all significant correlations in this analysis) indicated that the noun N400 correlations began as early as 212 ms, extended through approximately 540 ms, and were most widespread around 340 ms.

In addition to the more posteriorally distributed N400 effects, over the anterior scalp there was a reversal such that noun ERP mean amplitude became more *positive* with decreasing noun cloze probability. Mean time window analyses indicated this pattern was present

[1]Note that the statistical testing described herein does not rely on this cloze-based categorical sorting of article and noun ERPs (even though – for visualization purposes only – this is what is depicted in Figs. 2 and 3); rather, the testing we performed was regression-based and utilized continuous ranges of cloze probability. Although not reported, we did conduct conventional ANOVAs using data from all scalp electrodes on these higher and lower cloze probability discrete categorizations of the articles and nouns, over our mean amplitude time windows of interest. These analyses yielded qualitatively similar results to the more powerful repeated measures regression analyses.

already between 300–500 ms (Fig. 4B) and continued into the 500–900ms time window (Fig. 4C). Mass univariate tests between 200 and 900ms (Fig. 5B) indicated that this positivity was present over anterior and left temporal sites, beginning around 376 ms and continuing through approximately 896ms: it was most widespread around 748ms. These ERP patterns point to the positivity reflecting a similar (but opposite polarity) sensitivity to cloze as the N400, albeit with later latency and with a different scalp topography.

4.2. Older adults

4.2.1. Articles—The article mean amplitude time window (250–400 ms) regression analyses indicated that neither older participants as a whole, nor the High or Low VF sub-groups, showed significant correlations (all *p*-values ≥ .9729, ≥.7658, ≥.8231, respectively) of article cloze probability with mean EEG amplitude at any electrode site (Fig. 4D, G, and J). The time point-by-time point analyses (Fig. 5C, E, and G) supported these findings, with no significant correlations at any electrode site or time point for any of the three groups (all *p*-values ≥.999, ≥.982, ≥.990, respectively). Thus, unlike the younger adults, within the 250–400 ms article time window, older adults did not exhibit sensitivity to prenominal information more or less consistent with likely upcoming nouns.

4.2.2. Nouns

4.2.2.1. All 36 older adults: The mean amplitude time window regression analyses of all 36 older comprehenders between 300 and 500 ms (Fig. 4E; 1e-6 ≤ $p \leq .037$ for all significant correlations in this time window) found significant correlations of increased amplitude N400s with decreasing noun cloze over 13 posterior electrodes where similar correlations were observed for the young (Fig. 4B). These posterior N400 effects continued into the later 500–900 ms time window (Fig. 4F; .0005 ≤ $p \leq .011$ for all significant correlations in this time window). The time point-by-time point tests (Fig. 5D; .001 ≤ $p \leq .049$ for all significant correlations in this analysis) indicated that the N400 correlations appeared to have a later onset and to last later than for the young, beginning around 256 ms at RLOc and extending as late as 612 ms at occipital sites, with the most widespread effects around 412 ms. For the older adults, N400 correlations appeared to be less widespread than those of younger readers, with little evidence of significant correlations extending to frontal scalp locations.

There were also significant correlations of increasing ERP positivity with decreasing cloze beginning in the 300–500 ms mean amplitude time window at four frontolateral sites (Fig. 4E). These correlations continued into the 500–900 ms time window (Fig. 4F) at nine prefrontal, frontal and left lateral electrodes. The time point-by-time point analysis (Fig. 5D) indicated that this effect tended to begin earlier than for the young – around 272 ms (at LLFr). The positivity's statistical reliability continued (intermittently) as late as 900 ms (at LLTe and MiPf) and was most widespread around 576 ms. Generally, then, the positivity tended to be more prominent for the older comprehenders than for the young.

4.2.2.2. High VF older adults: The mean amplitude time window analysis between 300 and 500 ms (Fig. 4H; .003 ≤ $p \leq .019$ for all significant correlations in this time window) indicates that the older sub-group of 18 High VF participants showed significant increases in N400 amplitude with decreasing cloze at only two occipital electrode sites. The mass univariate regression tests (Fig. 5F; .009 ≤ $p \leq .050$ for all significant correlations in this analysis) indicate that the occipital N400 correlations are reliable between 340 and 548 ms; thus, the effect appears to be shorter in duration and has a more focal distribution than for the group of all 36 older comprehenders.

Beginning in the 300–500 ms time window, there were also patterns of increased positivity with decreasing cloze, which were consistent with those of all 36 older adults. The 300–500

ms mean amplitude time window analyses showed such correlations at four frontal electrodes (Fig. 4H). Between 500 and 900 ms this positivity spread to 14 frontolateral channel locations (Fig. 4I; $.005 \leq p \leq .044$ for all significant correlations in this time window). Time point-by-time point analyses (Fig. 5F) indicated that this anteriotemporal positivity was present as early as 236 ms, continued through 900 ms, and was significant at the greatest number of channels at approximately 580 ms.

4.2.2.3. Low VF older adults: The Low VF older adult mean amplitude time window analysis between 300 and 500 ms (Fig. 4K; $.0009 \leq p \leq .029$ for all significant correlations in this time window) indicated N400 correlation patterns consistent with those of the more inclusive group of all 36 older readers, with significant correlations over 16 posterior electrode sites. Mass univariate tests (Fig. 5H; $.009 \leq p \leq .050$ for all significant correlations in this analysis) revealed these effects began as early as 252 ms at LMCe, continued through approximately 572 ms, and were most widespread around 412 ms.

Unlike the High VF scorers and the younger adults, however, the mean time window analyses for the Low VF sub-group indicated no significant correlations of sustained positivity with decreasing cloze, either between 300–500 ms or 500–900 ms (Fig. 4L; all *p*values P.0621). The time point-by-time point analysis (Fig. 5H) was consistent with this in finding only sparse and sporadic significant positivity/cloze correlations at frontotemporal sites.

4.3. Summary of group cloze probability/ERP amplitude regression analyses[2]

4.3.1. Articles—Young comprehenders showed significant, graded increases in N400-like negativity to less expected articles over mediofrontal scalp areas – an ERP pattern that has previously been linked to predictive sentence processing in this subject group (e.g., DeLong et al., 2005). In contrast, this effect was not detected in older adults, either on the whole or when the older participants were subdivided according to their offline VF scores.

4.3.2. Noun N400s—For younger adults, regression analyses indicated significant cloze-graded N400s over posterior sites (a canonical N400 pattern). For older adults overall, the graded noun N400 pattern at posterior sites was consistent with that seen for younger participants in the present and previous studies (e.g., Kutas & Hillyard, 1984), with the older readers' N400s exhibiting topographical overlap with scalp areas where noun cloze/N400 correlations have been shown to be maximal. To our knowledge, this is the first demonstration of the graded sensitivity of the N400 to noun cloze in older readers. Notably, the young adults' significant N400 correlations appeared to begin and end earlier than those of older participants. When older adults were subdivided by VF scores, the widespread distribution of N400s in Low VF participants resembled the overall group's pattern more than the High VF participants' N400s did: High VF older adults showed relatively fewer sites with significant N400 correlations.

4.3.3. Noun late positivities—For both younger and for older participants overall, the N400 pattern reversed at frontotemporal sites, with significant increases in ERP positivity with decreasing noun cloze (as described for young comprehenders in DeLong et al., 2011).

[2]Although not described herein, we also conducted mean time window between-subjects comparisons (Younger versus All Older Adults and High VF versus Low VF Older Adults) of the regressions at the 26 electrode sites, over the article and two noun time windows. Again, the Benjamini & Hochberg FDR correction method was used to correct the p-values for multiple comparisons. These analyses found no significant (i.e., $p < .05$) differences between Younger and Older Adults or between High VF and Low VF Older Adults; consequently, the between group differences are not clearly reliable. However, given the preponderance of evidence (see Section 5), we believe this lack of significance is likely due to insufficient statistical power to overcome the substantial individual variability that clouds between-subjects comparisons.

For both age groups, this positivity began as early as the N400 time window and continued into the later time window. However, separate analyses of the High and Low VF scorers' ERPs indicated that in the older adults, this pattern was generated only by the High VF scorers. Additionally, the frontal positivity for the High VF older adults appeared to have an earlier onset and a more widespread distribution than that of younger adults. This is somewhat unexpected given that there have been few reported findings of low cloze sentential continuations associated with increases in frontal ERP positivity during the N400 time window (cf. Thornhill & Van Petten, 2012), particularly in older comprehenders. Notably, such patterns have been observed over a later 500–900 ms time window in younger adults by Federmeier et al. (2007) to low cloze words continuing strongly, but not weakly, constraining contexts, and for both younger adults as well as older adults with high category fluency to low typicality category targets in Federmeier et al. (2010).

5. Discussion

To understand whether or the degree to which older individuals may be relying upon prediction as a reading comprehension mechanism, it is critical that we understand and draw comparisons with the predictive comprehension patterns of younger adults. While previous studies have found no evidence for generalized predictive processing during comprehension across older adults, the current paradigm offers the benefit of allowing for detection of linguistic pre-activation *preceding* more or less expected target content words (nouns) by means of prenominal indefinite articles (*a*/*an*). Despite this advantage in the current study, reliable prenominal evidence for older comprehenders pre-activating upcoming target noun continuations was not observed, as it was for the young.

At the target nouns, however, both age groups exhibited graded N400 sensitivity to constraint-noun cloze combinations. Additionally, young adults and a subset of the older adults with high verbal fluency exhibited a sustained leftish, frontal ERP positivity to less expected sentence continuations – a brainwave pattern that resembles one hypothesized to reflect a consequence of constraint violation (DeLong et al., 2011; Federmeier et al., 2007). Our observed positivity is consistent with previous research in which older individuals with high letter and category fluency also exhibited a frontal positivity (Federmeier et al., 2010). These results also accord with previous studies proposing that older adults with high verbal fluency are more likely to successfully engage in predictive language comprehension than those with lower scores (Federmeier et al., 2002).

Before interpreting the ERP findings that we will suggest may be linked to predictive processing, we will discuss our noun N400 results. We demonstrate here, for the first time, that older, like younger adults exhibit a graded N400 ERP sensitivity to the semantic relations of content words (nouns) within sentence contexts. Both age groups showed significant correlations of noun cloze with ERP mean amplitude over posterior scalp areas, where noun N400 effects are typically maximal. This systematic modulation of noun N400 amplitude in older comprehenders indicates that within a similar time window as the young (300–500 ms), the older adult brain responds to the semantic probability of encountering at least certain linguistic features of items, if not the items themselves. In line with previous findings (e.g., Kutas & Iragui, 1998), older adults appear to show slight age-related delays in N400 onset (around 44 ms) and in the timing of the most widespread effects relative to the young (around 72 ms delay). So although both groups appear to rapidly, incrementally integrate incoming words into evolving mental sentence representations, this process generally occurs slightly later for older than younger adults. When divided by offline VF scores, high scoring older adults appeared to show less topographically widespread posterior N400 effects. We propose that this ultimately may result from temporal overlap of the N400 with the more frontal positivity in this same time window – which could effectively "wash

out" N400 effects (that are already typically smaller in older than in younger readers) at more central scalp regions.

Overall, the similarity in the noun N400 cloze sensitivities of younger and older adult comprehenders is notable given the differences in their cloze probability-related ERP effects at the prenominal articles. Our analyses revealed that younger comprehenders engaged in graded, probabilistic pre-activation of particular word forms as reflected in the brain responses to the prenominal target articles between 250 and 400 ms post-article onset. Although the anterior scalp topography of our article ERP effect diverges from the typically more posterior N400 to open class (content) words, their similar polarity, timing, and, importantly, graded sensitivity to cloze probability indicate that the effects are likely related. Therefore, as has been argued before (DeLong et al., 2005), younger adults' article cloze-graded N400-like response at the prenominal articles makes a strong case for probabilistic pre-activation of upcoming word forms prior to receipt of the physical input. Moreover, these results suggest that at least for young adult readers, pre-activation of upcoming linguistic input appears to be an unconscious, generalized comprehension mechanism. Older adults, on the other hand, demonstrated no such article prediction-related ERP effects in the same time window. So while this group's significant noun N400 effects argue for incremental processing of sentential input, the lack of a reliable ERP effect at the articles in older comprehenders indicates that this processing is not necessarily predictive – or at least not fast enough to be observed prior to the target noun's onset.

On one hand, then, we do not find evidence that older adults are probabilistically pre-activating upcoming word forms during sentence comprehension in the same manner or at the same rate as the young. However, further along in the comprehension stream, there is evidence that at least a subset of older, like younger, comprehenders differentially process less versus better fitting continuations to constraining sentence contexts. For both the young and the High VF older comprehenders, there is a prolonged frontotemporal ERP positivity in response to low cloze noun continuations, evident as early as the 300–500 ms noun time window and continuing through 900 ms. The mean amplitude of this positivity shows a pattern of negative correlation – i.e., increasing positivity with decreasing cloze – with a broadening scalp distribution over time. As revealed through mass univariate regression tests, the onset of this positivity occurs earlier and is more widely distributed for High VF older comprehenders than for younger adults. This is notable given that older adults rarely, if ever, exhibit any type of neural processing more rapidly than their younger counterparts – an observation that compels us to explore possible explanations.

On the face of it, the positivity finding seems to indicate similar functional sensitivities of the N400 and the frontal positivity to variability in the cloze probability of sententially more or less expected nouns. However, experimentally similar (late) frontal positivity- eliciting manipulations from other studies (Federmeier et al., 2007; Federmeier et al., 2010) suggest that a purely cloze probability- based explanation may not capture the component's true sensitivities. In our estimation, the frontal positivity in the current work most closely resembles one observed between 500 and 900 ms to unexpected words continuing strongly versus weakly constraining sentence contexts in young adults (Federmeier et al., 2007). Additionally, though not reported in their original publication, a similar effect was observed for low cloze probability word endings in highly constraining sentences for a number of participants in Kutas & Hillyard's (1984) study which crossed sentence constraint and target noun cloze probability (from personal communication and data inspection with M. Kutas). In both these studies, sentential constraint, in addition to cloze probability, was directly manipulated as a factor; this is relevant because constraint and cloze probability are confounded in their upper ranges. In other words, by definition a high cloze probability continuation defines a highly constraining context. Therefore, to investigate effects of

constraint violation, ideally one would contrast only the less expected nouns continuing high versus low constraint contexts. In this way, low cloze probability could be held relatively constant. Due to the generally higher constraint of the sentence contexts used in the current study (see Fig. 6), our experimental design did not afford the opportunity for performing such (post hoc) analyses.

However, the low cloze nouns in our study are comparable to the high constraint/low cloze nouns which elicited the enhanced frontal positivity relative to both high constraint/high cloze and low constraint/low cloze nouns in Federmeier et al. (2007). Our observed frontal positivity to strong constraint violations is in line with those researchers' proposal that the (late) frontal positivity may reflect some aspect of a prediction cost. Through this lens, our positivity finding is consistent with the idea that even if preactivation is not reliable enough to be the "first line" of comprehension in older adults, the High VF older adult parser may still be sensitive to the cue value of the less expected articles and may use this information to, for example, engage executive processing to prepare for an upcoming low probability event. For instance, a low cloze "*a*" in a sentence where "*an*" has a high cloze probability may serve to constrain the pool of phonologically appropriate post-article continuations, and thus may signal the brain to devote more resources to processing whatever it encounters next. In other words, although older adults' brains may not routinely contextually pre-activate specific anticipated upcoming lexemes, a subset of them – when (implicitly) cued to do so – may recruit more top-down networks to deal with upcoming input that is likely to have high informativeness. This also may help explain why the frontal positivity to low cloze nouns was detected so early (concurrent with the N400 time window) compared to a similar but later (500–900 ms) frontal positivity observed by Federmeier et al. (2007) for young comprehenders. The positivity may be a response to some combination of processing both an incoming noun *and* its preceding article, with no (or only very weak) evidence for well-formed predictions at the article. For High VF older adults, then, the constraint-violating articles may offer what effectively amounts to a head start on processing some aspect(s) of the upcoming input, for instance, with a strategic allocation of executive resources possibly being initiated to direct attention toward the received noun.

Another possible explanation for the early onset and pronounced late positivity effect in High VF older adults is that they could be using *precisely* the same comprehension strategies or mechanisms as the young, except that their activation speed is slower. Older adults may therefore be unable to pre-activate information to the same extent as the young within similar time limitations. For the younger comprehenders, we argue that the presence of a graded N400 effect at pre-target noun articles constitutes evidence for the rapid, unconscious activation of information in semantic memory, in particular at the level of specific phonological word forms. For older adults, it is possible, but unverifiable based on the current experimental design, that they may be anticipating upcoming linguistic information, but simply not at the level of lexemes – particularly if phonological access is preceded by semantic access during lexical retrieval (as proposed under some language production models, e.g., Dell & O'Seaghdha, 1992; Garrett, 1988; Levelt, 1989). Indeed, other studies that have found evidence for prediction in younger adults have done so primarily at the level of semantic and syntactic features (e.g., Federmeier & Kutas, 1999a; Kamide et al., 2003; van Berkum et al., 2005; Wicha et al., 2004). Thus, it is more of an open question as to whether this type of pre-activation is taking place in older adults. However, even at the level of semantic features, Federmeier et al. (2010) have argued that while older adults are *capable* of using semantic cues to produce speeded linguistic responses as quickly as younger adults, they do not necessarily do so automatically, for instance, when the comprehension task does not demand it.

If our observation of the constraint violation-related noun positivity in absence of a significant article N400-related prediction effect in older adults is more an issue of the *timing* of their pre-activations, then it is possible that somewhere between receipt of the low cloze article and presentation of the target noun, high probability nouns actually *do* get pre-activated (albeit not in time for this pre-activation to be reflected in the ERP response at the article). Consequently, the unexpected articles could cause generation of alternative semantically and phonologically viable continuations, with the positivity reflecting some sort of monitoring of the consistency of the encountered item with the most likely (but not received) item. Alternatively, the positivity might reflect inhibition of a highly constrained continuation, upon receiving a low cloze noun. Yet another possibility is that the positivity could index some necessary reanalysis or reevaluation of the contextual representation that has been constructed up until that point, with respect to the one already built up in working memory. Clearly, further research is needed to adjudicate between these, and surely other, competing functional explanations.

The increased ERP frontal positivity exhibited by High VF older, as well as younger, comprehenders to improbable noun continuations accords with the idea that at least a subset of older adults is capable of some form of predictive processing under certain circumstances, even though the post-target noun timing of the effect's onset is not the "smoking gun" one might wish to observe in order to make a strong case for prediction in older adults. Our observation of such effects in a sentence reading task is notable because older participants described in Wlotko et al. (2008) did not show a frontal positivity to sentential constraint violations. This difference suggests that the aging brain may benefit from even subtle, probabilistic linguistic information that may *implicitly* signal demand for additional processing resources to be recruited. Indeed, in both our study and in Federmeier et al. (2010), where older adults were provided with either implicit prenominal cues or temporally extended inter-stimulus time intervals (respectively), older adults with High VF showed a significant enhanced ERP positivity when processing unexpected noun continuations in generally highly constraining contexts. Perhaps, then, the common factor between these two studies is that additional processing time is afforded. In our study, constraint violations were presented mid-sentence, without significant pre-target delay (during rapid serial visual presentation, at a rate of two words per second), and following relatively elaborated pre-target sentential contexts – conditions under which processing load might be expected to diminish the likelihood for prediction effects to be observed. Nonetheless, the unexpected article itself might provide the processor with the requisite amount of time to develop or adjust expectations. Indeed, one possibility is that if a reading sub-process such as lexical access slows with aging as some have suggested (e.g., Balota & Duchek, 1988), then perhaps it is not so surprising that contextual pre-activation, which should rely on such a process, also might be slowed. So while it is unclear whether older adults generally or automatically predict upcoming linguistic content, a subset of them may be explicitly *or* implicitly cued to do so, with very little advanced warning required for the brain to contextually integrate linguistic cues to modulate expectancies.

Also notable in our study are the apparent differences in the noun frontal positivity between Higher and Lower VF scoring older adults. The lack of a sustained positivity in the Low VF scorers from noun onset through 900 ms suggests that it is not just a timing delay in the onset of the positivity for low scorers that may have led to these patterns. In normal aging, it has been argued that VF task performance deficits may be closely related to executive function deficits (e.g., Mayr & Kliegl, 2000). Additionally, imaging data have suggested possible roles for various frontal and prefrontal cortical areas in such executive functions as inhibition (e.g., Aron, Robbins, & Poldrack, 2004), error detection (e.g., Rubia, Smith, Brammer, & Taylor, 2003), and suppression of interfering memories (e.g., Anderson et al., 2004) – some or all of which could potentially be functionally related to our frontal

positivity to unexpected continuations. Indeed, Van Petten and Luka (2006) point out that post- N400 positivities – particularly in sentences – may have prefrontal neural generators, though they state that there is currently little knowledge of what precise functional process is being indexed. Thus, if Low VF scores result from poorer executive function, and some type of executive processing is required to elicit the frontal positivity, this may help explain the variable patterns in the older adult groups.

The hypothesis that the observed frontal positivity might reflect some kind of misprediction "cost" or "cost gradient" is, at a minimum, compatible with the probabilistic article prediction ERP effect exhibited by the young. The cloze-graded article ERP effect in the young indicates that even when the preceding context does not extensively constrain the number of possible continuations, there is some pre-activation of potential continuations. This would imply that there is always some accumulated degree of expectation (i.e., pre-activation) as the parser encounters successive words in a sentence, whether that expectation is a strong or relatively weak one. In turn, graded pre-activation might imply differences in how the parser recovers from situations in which expectations are violated by the appearance of low cloze probability items. Our graded frontal positivity effect may reflect this consequence.

With an awareness of the inadvisability of using the topography of scalp-recorded ERPs as a roadmap to underlying neural generators, we note that the prefrontal, left biased scalp distribution of our ERP positivity to low cloze sentence continuations overlaps with some of the same brain areas (e.g., the MTL, MPFC) cited in the Introduction as purportedly being involved in a neural prediction network (Bar, 2007). This overlap is at least suggestive, particularly if one contrasts the more frontal distribution of our late positivity with other linguistic stimulus-generated late positivities in the same time window (e.g., the P600 and the late positive component) which canonically are maximal at parietal sites and which have not been directly linked to prediction. Of course, even if such brain regions are identified as being active, clearly they need not be engaged in predictive processing (e.g., see Folstein & Van Petten, 2011, for an intriguing suggestion that late frontal positivities may be driven by coordination between working- and long-term memory); nonetheless, it is worth keeping this observation in mind as research in linguistic and general cognitive prediction proceeds.

Lastly, we consider a possibility relating to the noun late time window in our study, due to its potential relation to a recent finding by Wlotko and Federmeier (2010). In moderately strong sentence contexts, Wlotko & Federmeier have noted a left frontal negativity (600–900 ms post-stimulus-onset) whose amplitude increases as the number of unique participant-generated sentence completions in an offline cloze probability norming decreases. They interpret this effect in non-predictive terms, linking it instead to "frame-shifting" (Coulson, 2001), i.e., a sort of reinterpretation of contextual information when participants had initially built a message-level representation consistent with an alternative reading of the sentence. Clearly, there is some overlap in their study's eliciting conditions and their negativity's late timing and frontal scalp distribution, with our study's design and our late frontal ERP effect. These similarities may be relevant if it turns out that what we suggest is a constraint violation-related positivity to low cloze nouns is instead more of a frame shift-related negativity to higher cloze nouns (therefore with no link to predictive processing). However, examination of our nouns between 600 and 900 ms subdivided into 25% cloze range bins (Fig. 6) reveals that this does not appear to be the case, for either younger or older adults. In terms of ERP mean amplitude, for both groups the responses to the lowest noun cloze category (0–25% cloze) are distinguished from the other cloze levels by their relative positivity. Possible reasons for not observing such a negativity in our study might relate to any number of features of our stimuli; for instance, our items may generally not have "good" – i.e., consistent across participants – alternative completions, or alternative unique

completions for our items may not trigger “frame shifts”. A more likely possibility may be that in our study very low cloze target nouns primarily continue higher constraint contexts (see bottom panels of Fig. 6), unlike items in Wlotko and Federmeier (2010) where low cloze continuations continued lower constraint contexts.

6. Conclusions

Shifts in comprehension abilities with healthy aging occur over extended time scales, with changes that likely arise from some combination of neural change with influences of more external, personal or strategic factors on processing. Thus, if there is a shift from how young versus old comprehenders rely on pre-activation to construct meaning out of linguistic input, these differences may be ones not only of degree but ones that occur variably across individuals. It is possible, then, that whatever the mechanism by which language is processed predictively in the young, it may not act as efficiently, reliably, or rapidly in (all) older comprehenders. In turn, older comprehenders might rely more heavily on some compensatory processing triggered when the task – even if it is just comprehension – demands it.

It might be argued that “prediction” in the sense that we have referred to it for the young (in terms of observing electrophysiological evidence for the pre-activation of linguistic items or their features at a time point preceding receipt of the actual input) differs from the terms in which we describe possible prediction effects in older comprehenders herein. We have offered a number of possible interpretations of our noun late positivity finding dissociable from the prediction-related interpretation of the article N400, as well as various proposals for how older and younger brains may be functionally engaged upon receiving unexpected articles. Adjudicating these possibilities will require further research. A starting point to build on the current findings would be to utilize an experimental stimulus set that manipulates constraint violation more systematically. Observation of a late positive ERP response to constraint violations graded across a wide range of constraint would offer some support for the generalizability and automaticity of the prediction-related response.

With the precedent of a prenominal article cloze probability-modulated ERP effect in young adults, at the outset of this study we proposed that such an effect in older readers would constitute strong evidence of linguistic prediction in this age group. Although it turned out that older adults did *not* show the article ERP effect, a similarity between the *noun* time-locked ERPs of High VF older readers and younger comprehenders leads us to suggest that both groups may nonetheless exhibit a neural sensitivity to violations of sentence-based predictions. On the hypothesis that the observed enhanced frontal positivity to low cloze sentence continuations relates to some processing consequence for “mispredicting”, High VF older adults – like young adults – may be showing a graded sensitivity to violated expectancies. Given the lack of an article effect, however, it may be that linguistic pre-activation in this subset of older adults occurs in a more limited capacity or at a slower rate than the young and not necessarily as a default processing strategy. This group of older adults appears to be sensitive to implicit linguistic cues (in the present case, prediction-consistent or inconsistent indefinite articles) that signal a shift in the most probabilistic trajectory of a sentential representation. However, unlike their younger counterparts, who appear to regularly and rapidly pre-activate upcoming input based on contextual representations built up from knowledge and experience-based associations in long-term memory, older adults may *generally* rely less on top-down processing during on-line language comprehension, possibly because pre-activation in older adult brains is not rapid enough to “beat the input”. In many instances, the challenges of rapid integration and construction of rich contextual information during comprehension may be sufficiently met without the benefit of advance processing. However, it seems that at least some older

comprehenders are capable of recruiting additional resources for the processing of upcoming material when improbable input is signaled in advance.

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References

Anderson MC, Ochsner KN, Kuhl B, Cooper J, Robertson E, Gabrieli SW, et al. Neural systems underlying the suppression of unwanted memories. Science. 2004; 303(5655):232–235. [PubMed: 14716015]

Aron AR, Robbins TW, Poldrack RA. Inhibition and the right inferior frontal cortex. Trends in Cognitive Sciences. 2004; 8(4):170–177. [PubMed: 15050513]

Balota DA, Duchek JM. Age-related differences in lexical access, spreading activation, and simple pronunciation. Psychology and Aging. 1988; 3(1):84–93. [PubMed: 3268246]

Bar M. The proactive brain: Using analogies and associations to generate predictions. Trends in Cognitive Sciences. 2007; 11(7):280–289. [PubMed: 17548232]

Benjamini Y, Hochberg Y. Controlling the false discovery rate: A practical and powerful approach to multiple testing. Journal of the Royal Statistical Society. Series B (Methodological). 1995; 57(1): 289–300.

Benton, AL.; Hamsher, K. Multilingual aphasia examination manual. Iowa City, IA: University of Iowa; 1978.

Burke DM, Mackay DG. Memory, language, and ageing. Philosophical Transactions of the Royal Society of London Series B – Biological Sciences. 1997; 352(1363):1845–1856.

Burke DM, Peters LJ. Word associations in old age: Evidence for consistency in semantic encoding during adulthood. Psychology and Aging. 1986; 7:283–292. [PubMed: 3267408]

Cabeza R, Anderson ND, Locantore JK, McIntosh AR. Aging gracefully: Compensatory brain activity in high-performing older adults. NeuroImage. 2002; 17(3):1394–1402. [PubMed: 12414279]

Cortese MJ, Balota DA, Sergent-Marshall SD, Buckner RL. Spelling via semantics and phonology: Exploring the effects of age. Alzheimer's disease and primary semantic impairment. Neuropsychologia. 2003; 41:952–967. [PubMed: 12667531]

Coulson, S. Semantic leaps: Frame-shifting and conceptual blending in meaning construction. New York, NY, US: Cambridge University Press; 2001.

Craik FIM. On the transfer of information from temporary to permanent memory. Philosophical Transactions of the Royal Society of London Series B – Biological Sciences. 1983; 302(1110): 341–359.

Craik FIM. Memory changes in normal aging. Current Directions in Psychological Science. 1994; 3(5):155–158.

Dell GS, O'Seaghdha PG. Stages of lexical access in language production. Cognition. 1992; 42:287–314. [PubMed: 1582160]

DeLong KA, Urbach TP, Groppe DM, Kutas M. Overlapping dual ERP responses to low cloze probability sentence continuations. Psychophysiology. 2011

DeLong KA, Urbach TP, Kutas M. Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. Nature Neuroscience. 2005; 8(8):1117–1121.

Federmeier KD, Kutas M. A rose by any other name: Long-term memory structure and sentence processing. Journal of Memory and Language. 1999a; 41:469–495.

Federmeier KD, Kutas M. Right words and left words: Electrophysiological evidence for hemispheric differences in meaning processing. Cognitive Brain Research. 1999b; 8(3):373–392. [PubMed: 10556614]

Federmeier KD, Kutas M. Aging in context: Age-related changes in context use during language comprehension. Psychophysiology. 2005; 42(2):133–141. [PubMed: 15787850]

Federmeier KD, Kutas M, Schul R. Age-related and individual differences in the use of prediction during language comprehension. Brain and Language. 2010; 115:149–161. [PubMed: 20728207]

Federmeier KD, Mclennan DB, De Ochoa E, Kutas M. The impact of semantic memory organization and sentence context information on spoken language processing by younger and older adults: An ERP study. Psychophysiology. 2002; 39(2):133–146. [PubMed: 12212662]

Federmeier KD, Wlotko EW, De Ochoa-Dewald E, Kutas M. Multiple effects of sentential constraint on word processing. Brain Research. Special Issue: Mysteries of Meaning. 2007; 1146:75–84.

Folstein JR, Van Petten C. After the P3: Late executive processes in stimulus categorization. Psychophysiology. 2011; 48(6):825–841. [PubMed: 20946130]

Garrett, M. Processes in language production. In: Newmeyer, F., editor. Linguistics: The Cambridge survey III. Language: psychological and biological aspects. Cambridge: Cambridge University Press; 1988. p. 69-96.

Groppe DM, Urbach TP, Kutas M. Mass univariate analysis of event-related brain potentials/fields II: Simulation studies. Psychophysiology. 2011; 48(12):1726–1737. [PubMed: 21895684]

Gunning-Dixon FM, Raz N. Neuroanatomical correlates of selected executive functions in middle-aged and older adults: A prospective MRI study. Neuropsychologia. 2003; 41(14):1929–1941. [PubMed: 14572526]

Hasher, L.; Zacks, RT. Working memory, comprehension, and aging: A review and a new view. In: Bower, GH., editor. The psychology of learning and motivation. Vol. Vol. 22. New York: Academic Press; 1988. p. 193-225.

Head D, Raz N, Gunning-Dixon F, Williamson A, Acker JD. Age-related differences in the course of cognitive skill acquisition: The role of regional cortical shrinkage and cognitive resources. Psychology and Aging. 2002; 17(1):72–84. [PubMed: 11931289]

Hultsch DF, Hertzog C, Small GW, Dixon RA. Use it or lose it: Engaged lifestyle as a buffer of cognitive decline in aging? Psychology and Aging. 1999; 14:245–263. [PubMed: 10403712]

Kamide Y, Altmann GTM, Haywood SL. The time-course of prediction in incremental sentence processing: Evidence from anticipatory eye movements. Journal of Memory and Language. 2003; 49(1):133–156.

Kutas M, Federmeier KD. Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). Annual Review of Psychology. 2011; 62:621–647.

Kutas M, Hillyard SA. Reading senseless sentences: Brain potentials reflect semantic incongruity. Science. 1980; 207(4427):203–205. [PubMed: 7350657]

Kutas M, Hillyard SA. Brain potentials during reading reflect word expectancy and semantic association. Nature. 1984; 307(5947):161–163. [PubMed: 6690995]

Kutas M, Iragui V. The N400 in a semantic categorization task across 6 decades. Electroencephalography & Clinical Neurophysiology: Evoked Potentials. 1998; 108(5):456–471. [PubMed: 9780016]

Levelt, WJM. Speaking: From intention to articulation. Cambridge, MA, US: The MIT Press; 1989.

Logan JM, Sanders AL, Snyder AZ, Morris JC, Buckner RL. Under-recruitment and nonselective recruitment: Dissociable neural mechanisms associated with aging. Neuron. 2002; 33:827–884. [PubMed: 11879658]

Lorch RF Jr, Myers JL. Regression analyses of repeated measures data in cognitive research. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1990; 16(1):149–157.

Madden DJ. Adult age-differences in the effects of sentence context and stimulus degradation during visual word recognition. Psychology and Aging. 1988; 3(2):167–172. [PubMed: 3268255]

Mayr U, Kliegl R. Complex semantic processing in old age: Does it stay or does it go? Psychology and Aging. 2000; 15(1):29–43. [PubMed: 10755287]

Miller LMS, Cohen JA, Wingfield A. Knowledge reduces demands on working memory during reading. Memory & Cognition. 2006; 34:1355–1367.

Myerson J, Hale S, Poon LW, Wagstaff D, Smith GA. The information-loss model – A mathematical-theory of age-related cognitive slowing. Psychological Review. 1990; 97(4):475–487. [PubMed: 2247538]

Park DC, Smith AD, Lautenschlager G, Earles JL, Frieske D, Zwahr M, et al. Mediators of long-term memory performance across the life span. Psychology and Aging. 1996; 11(4):621–637. [PubMed: 9000294]

Reuter-Lorenz PA, Jonides J, Smith ES, Hartley A, Miller A, Marshuetz C, et al. Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. Journal of Cognitive Neuroscience. 2000; 12:174–187. [PubMed: 10769314]

Rubia K, Smith AB, Brammer MJ, Taylor E. Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. NeuroImage. 2003; 20(1):351–358. [PubMed: 14527595]

Salthouse, TA. Theoretical perspectives on cognitive aging. Hillsdale, NJ: Erlbaum; 1991.

Salthouse TA. The processing-speed theory of adult age differences in cognition. Psychological Review. 1996; 103(3):403–428. [PubMed: 8759042]

Stine-Morrow EAL, Miller LMS, Gagne DD, Hertzog C. Self-regulated reading in adulthood. Psychology and Aging. 2008; 23(1):131–153. [PubMed: 18361662]

Stine-Morrow EAL, Miller LMS, Nevin JA. The effects of context and feedback on age differences in spoken word recognition. The Journals of Gerontology: Series B: Psychological Sciences and Social Sciences. 1999; 54B(2):125–134.

Taylor JK, Burke DM. Asymmetric aging effects on semantic and phonological processes: Naming in the picture-word interference task. Psychology and Aging. 2002; 17(4):662–676. [PubMed: 12507362]

Thornhill DE, Van Petten C. Lexical versus conceptual anticipation during sentence processing: Frontal positivity and N400 ERP components. International Journal of Psychophysiology. 2012

van Berkum JJA, Brown CM, Zwitserlood P, Kooijman V, Hagoort P. Anticipating upcoming words in discourse: Evidence from ERPs and reading times. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2005; 31(3):443–467.

Van Petten C, Luka BJ. Neural localization of semantic context effects in electromagnetic and hemodynamic studies. Brain and Language. 2006; 97(3):279–293. [PubMed: 16343606]

Verhaeghen P. Aging and vocabulary score: A meta-analysis. Psychology and Aging. 2003; 18(2): 332–339. [PubMed: 12825780]

Wicha NYY, Moreno E, Kutas M. Anticipating words and their gender: An event-related brain potential study of semantic integration, gender expectancy, and gender agreement in Spanish sentence reading. Journal of Cognitive Neuroscience. 2004; 16(7):1272–1288. [PubMed: 15453979]

Wingfield A, Alexander AH, Cavigelli S. Does memory constrain utilization of top-down information in spoken word recognition? Evidence from normal aging. Language and Speech. 1994; 37:221–223. [PubMed: 7861911]

Wlotko EW, Federmeier KD. I didn't know you were going to say that: A left-lateralized negative brain potential for sentences of moderately strong constraint. Psychophysiology. 2010; 47(Suppl 1):S36.

Wlotko EW, Federmeier KD, Kutas M. Age-related changes in the use of sentential context. Psychophysiology. 2008; 45(Suppl 1):S33.

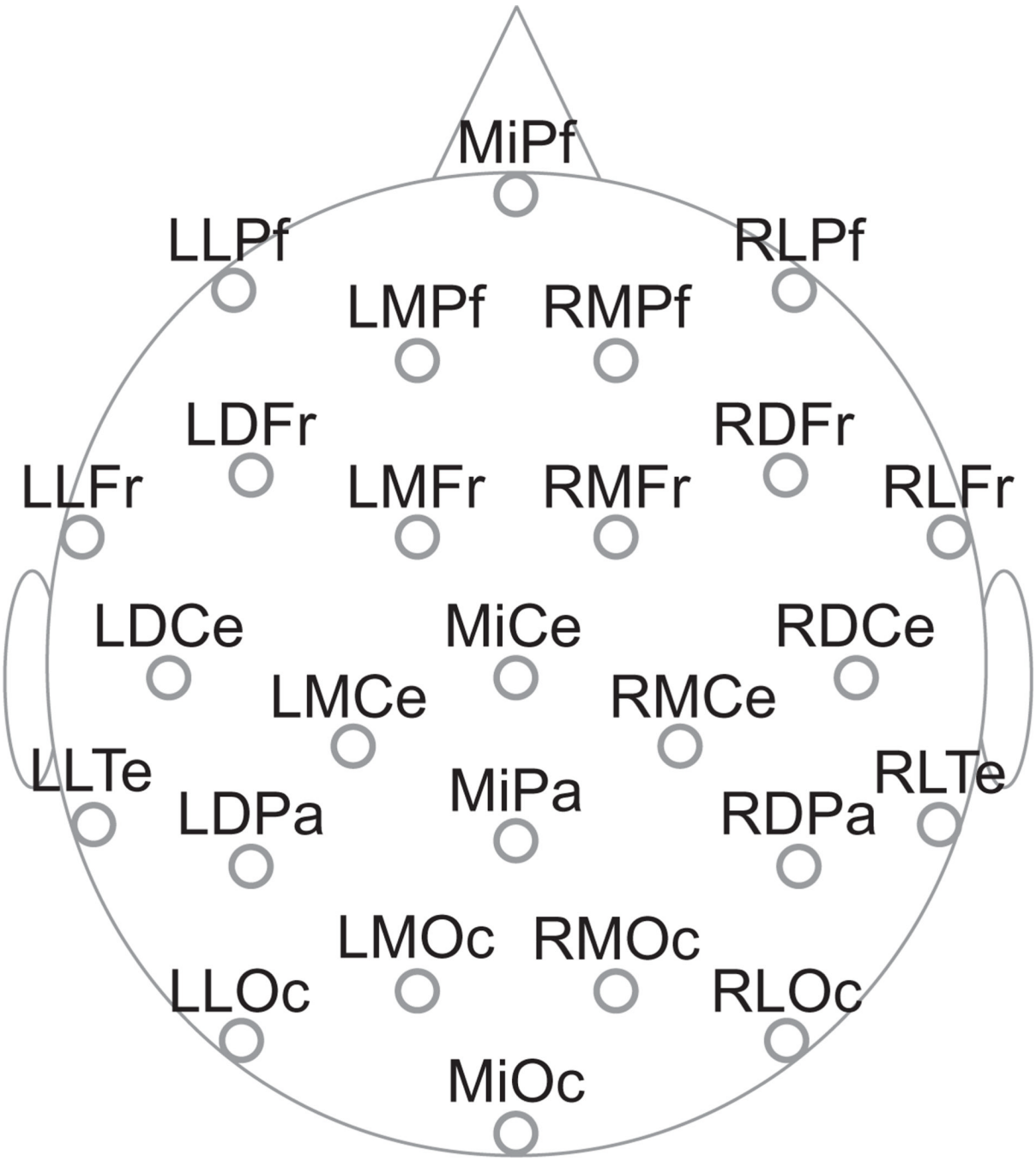

Fig. 1.
Schematic showing the array of 26 scalp electrodes from which ERPs were recorded.

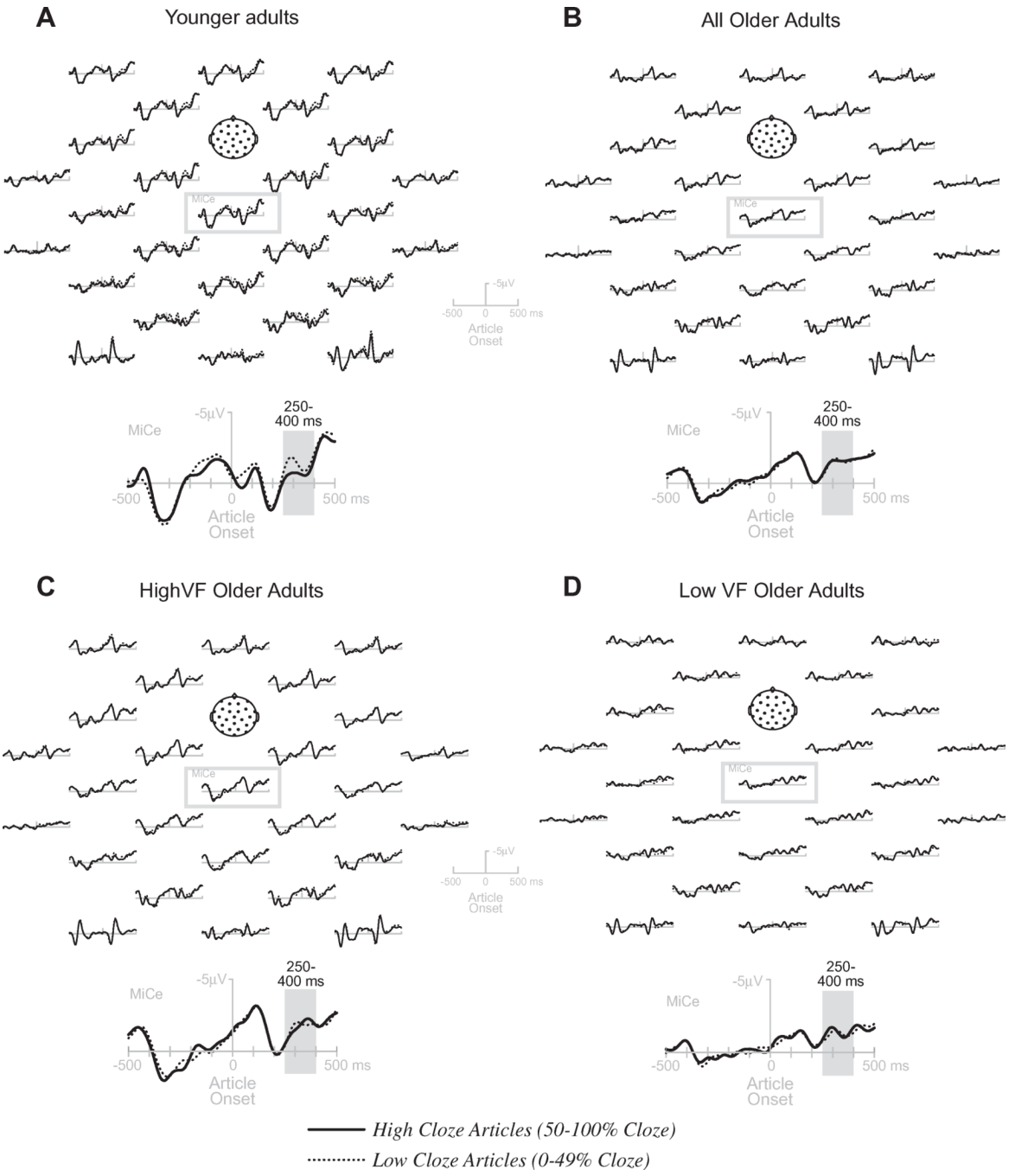

Fig. 2.

High versus low cloze target articles for (A) younger adults, (B) all older adults, (C) high VF older adults, and (D) low VF older adults. ERPs over 26 channels, with vertex channel enlarged. The article N400 time window (250–400 ms) used for regression analyses is highlighted. No statistical tests were performed on these categorically sorted data.

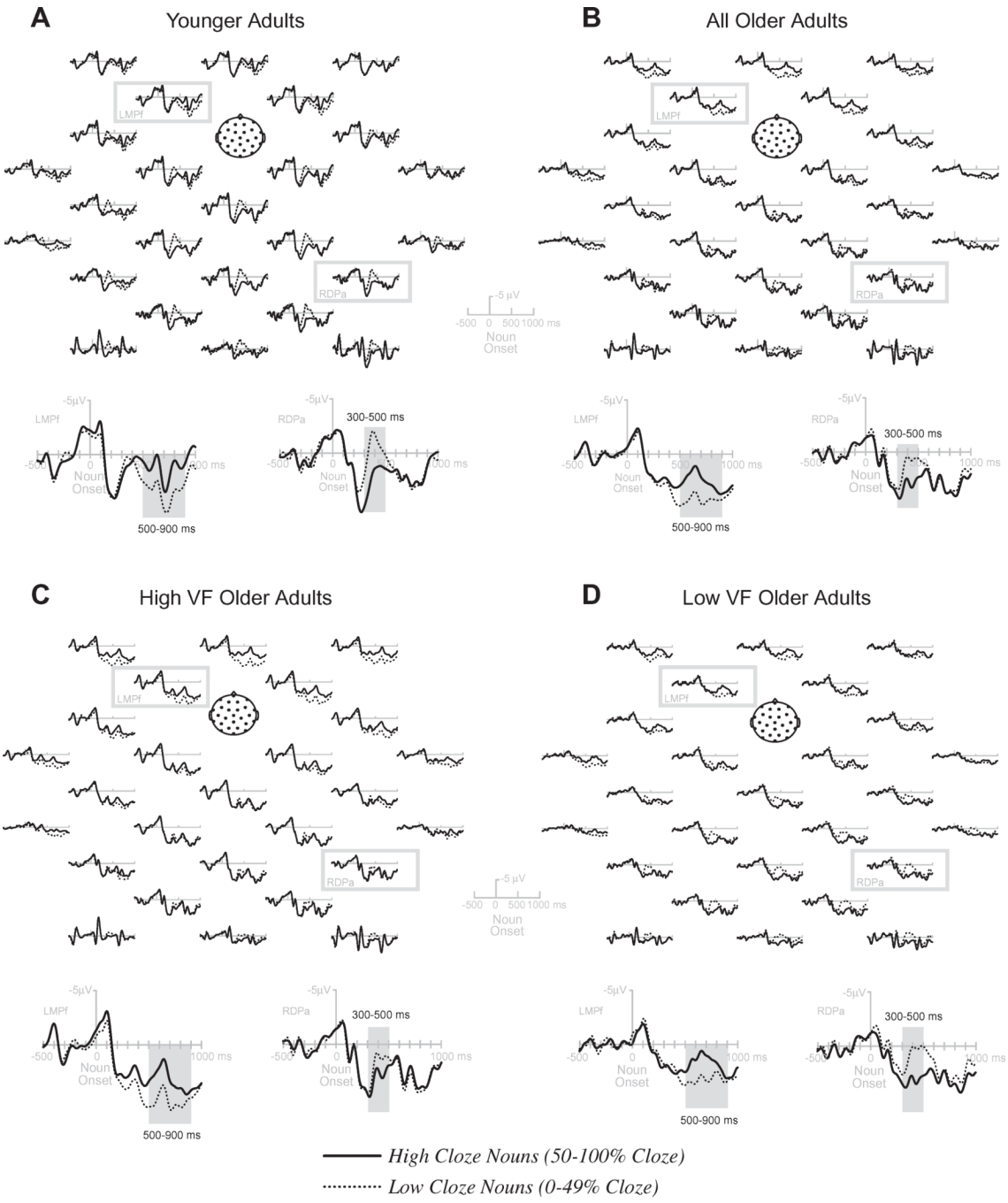

Fig. 3.

High versus low cloze target nouns for (A) younger adults, (B) all older adults, (C) high VF older adults, and (D) low VF older adults. ERPs over 26 channels with anterior and posterior electrodes enlarged. Noun N400 (300–500 ms) and late positivity (500–900 ms) time windows used for regression analyses are highlighted. No statistical tests were performed on these categorically sorted data.

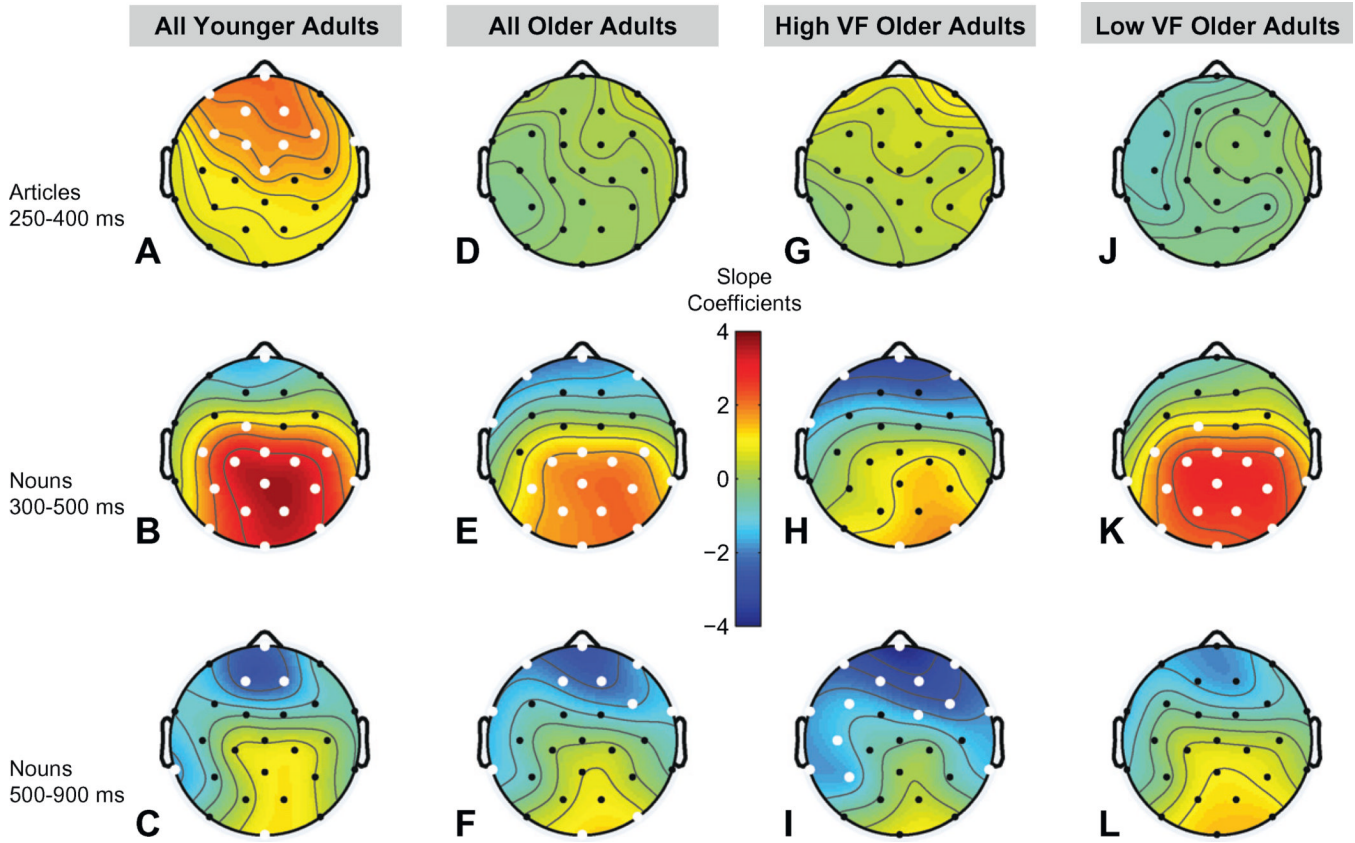

Fig. 4.

Twenty-six channel topographic scalp maps of mean slope coefficients from cloze probability/ERP mean amplitude repeated measures regression analyses for young adults, all older adults, high VF older adults, and low VF older adults (respectively) over the following time windows: target article N400 (A, D, G, J), target noun N400 (B, E, H, K), and target noun late positivity (C, F, I, L) time windows. Red shading indicates more negative ERP responses with decreasing cloze. Blue shading indicates increasing ERP positivity with decreasing cloze. Correlations with significant p-values are indicated by white electrodes. Though not depicted in this figure, regression coefficients plotted as t-scores (the mean coefficient divided by the standard error of the mean) exhibit similar statistically significant distributional patterns.

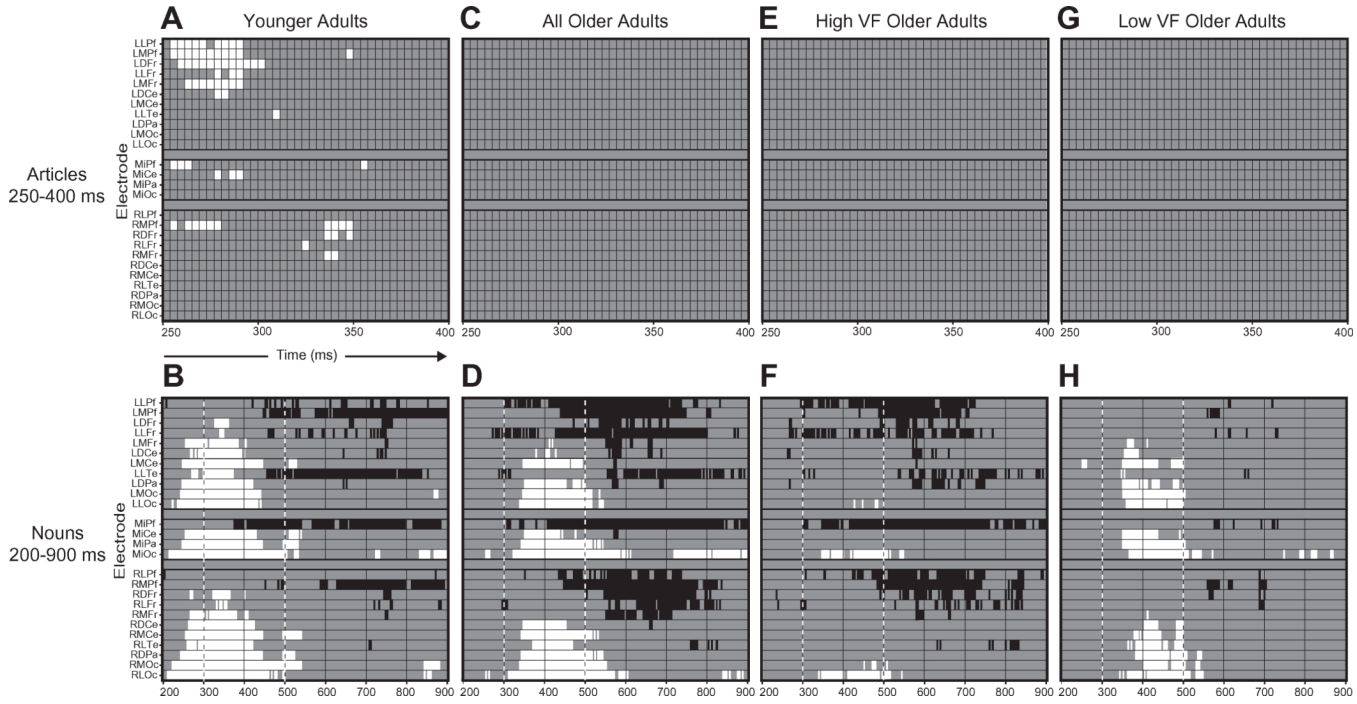

Fig. 5.

Raster plots of slope coefficients that significantly differed from zero, from mass univariate regression tests. Results are plotted in 4 ms increments for articles and nouns (respectively) for the following participant groups: younger adults (A and B), all older adults (C and D), high VF older adults (E and F), and low VF older adults (G and H). Left scalp electrodes are depicted uppermost, midline scalp electrodes in the center, and right scalp electrodes in the lower portion of each panel. Significant positive correlations (i.e., more negative amplitude ERPs with decreasing cloze) are represented in white and negative ones (increasing ERP positivity with decreasing cloze) in black.

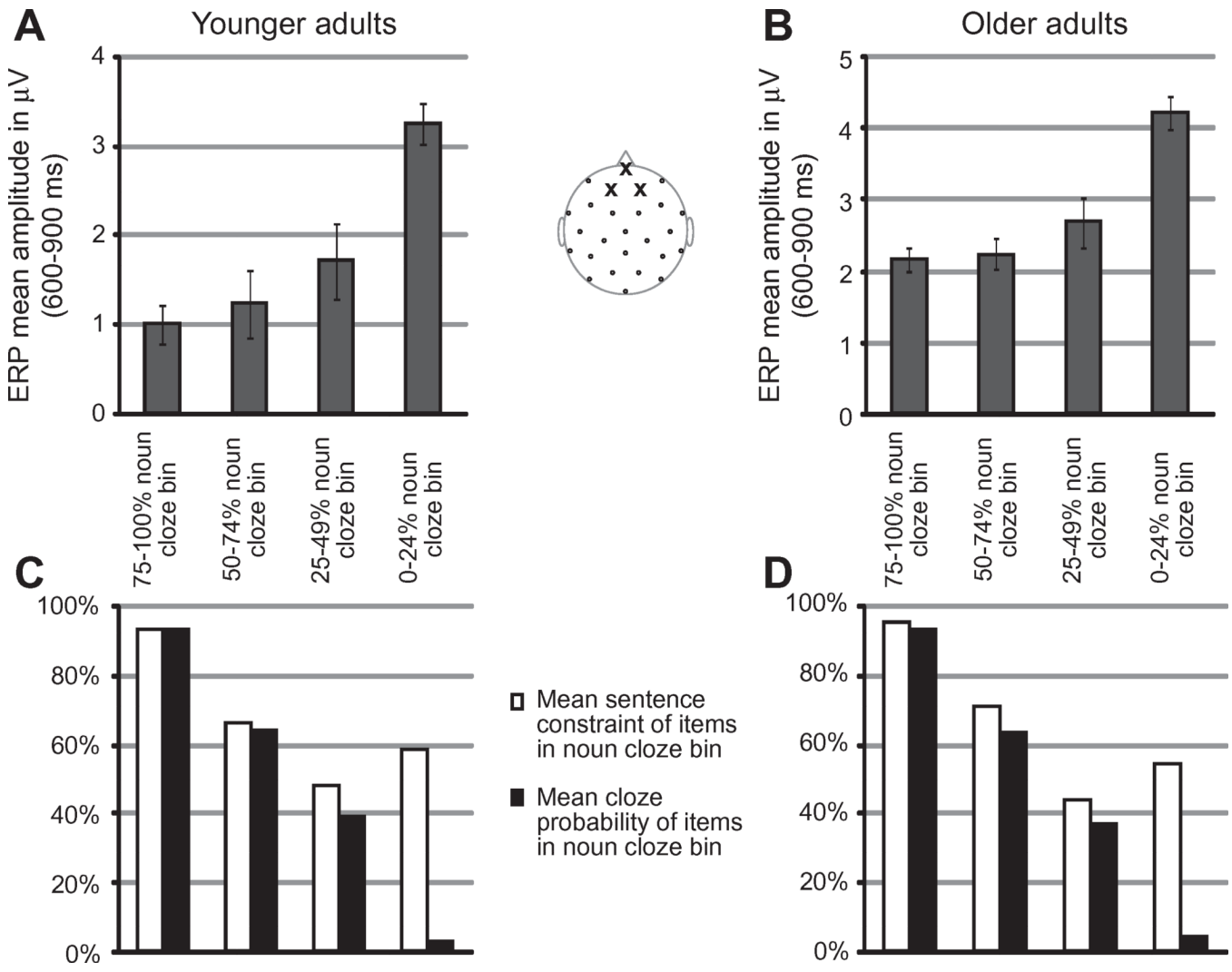

Fig. 6.

Top panels show ERP mean amplitude by graded noun cloze probability between 600 and 900 ms averaged over three prefrontal scalp sites, with both (A) younger and (B) older adults showing increased frontal positivity to low cloze nouns. Bottom panels show mean cloze probability and sentence constraint for each 25% noun cloze probability bin, again for (C) younger and (D) older adults. Noun cloze is calculated as the percentage of total norming respondents continuing truncated sentences (including pre-target articles) with the target noun as the first word. Sentence constraint is operationalized as the percentage of norming respondents supplying the most commonly provided noun for a given item (noun can be at any position within the response).

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Table 1

Representative experimental stimuli.

Sentence context	Target article + noun continuations	Comprehension question	Target article cloze		Target noun cloze (normed with *a/an* articles)	
			Older adults (%)	Younger adults (%)	Older adults (%)	Younger adults (%)
The highlight of Jack's trip to India was when he got to ride…through the streets.	*…a bicycle…*	*Did Jack travel to India?*	6	20	<1	<1
	…an elephant…		71	57	>99	52
The bakery did not accept credit cards so Peter would have to write…to the owner.	*…a check…*	*Did the bakery accept credit cards?*	>99	86	88	89
	…an apology…		<1	<1	<1	<1
Hannah wanted to live in a small town, but her husband preferred to live closer to…because of his job.	*…a city…*	*Did Hannah want to live in a small town?*	27	7	67	58
	…an airport…		<1	<1	18	12
When the representative retired in the middle of his term, the state was forces to hold…in his district.	*…a parade…*	*Did the representative serve out his full term?*	29	17	<1	<1
	…an election…		59	55	87	73

Table 2

Cloze probability norming summary.

Cloze probability statistics	Articles (160 total per age group)		Nouns (160 total per age group)	
	Older adults (%)	Younger adults (%)	Older adults (%)	Younger adults (%)
75% Quartile	67	70	88	92
Median	27	31	44	44
25% Quartile	<1	<1	<1	<1
Standard deviation	33	33	41	42
Range	<1–100	<1–96	<1–100	<1–100