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Age-related differences in processing event knowledge during real-time language comprehension

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Abstract

To understand language, we use knowledge about everyday events to create rich internal (situation) models. Although knowledge increases with age, fluid cognitive abilities tend to decline, potentially making it more difficult to access that knowledge. Here, we asked how aging affects the ability to use event knowledge during real-time language comprehension. We recorded event-related brain potentials as younger and older adults read vignettes about everyday events. Both groups showed facilitation on the N400 (a neuroelectric marker of semantic processing) for words that fit the context. However, only younger adults showed facilitated N400s to anomalous but event-related words compared to unrelated anomalies. Among older adults (aged 53-80), there was a negative correlation between age and N400 effects of event-relatedness. We conclude that real-time access to event knowledge during language comprehension may shift across the course of the adult lifespan such that older adults restrict activation to the most immediately relevant content.

Keywords: cognitive aging, event knowledge, language comprehension, event-related brain potentials

Introduction

Imagine you are hiking up a mountain. It is a beautiful day, the birds are singing, and the smell of pine trees is delightful. What else do you see in your mind's eye? When asked to paint a mental picture of a hiking event, people often bring to mind images of boots, poles, and backpacks, as well as trees, skies, and so on. Most people do not have trouble imagining these things, but there is likely to be considerable variability in exactly what people bring to mind, and with what time-course, as they understand language about everyday events.

Metusalem and colleagues (2012) capitalized on the exquisite temporal resolution of event-related brain potentials (ERPs), which reflect neuroelectric activity synchronized to events of interest, to investigate the nature of the information people rapidly bring to mind as they read sentences describing everyday events like hiking, birthday parties, football games, and so on. More specifically, they examined N400 potentials to words that varied in their relationship to sentences describing common events. N400s are negative-going ERPs peaking ~400 ms after the onset of a meaningful stimulus, like a word. They are present any time the brain attempts to link potentially meaningful sensory input to knowledge and are facilitated (smaller in amplitude) when some of the semantics normally evoked by that input has already been made active, for example by supportive context information (Federmeier, 2021; Kutas & Federmeier, 2000, 2011); N400 modulations do not require conscious awareness, as they are observed during attentional lapses (Rolke et al., 2001) and sleep (Ibáñez et al., 2006). N400s are therefore a useful tool for examining the nature of information that becomes active in semantic memory as people understand language, in real time.

Metusalem et al. first asked a group of young adults to "paint a mental picture" of common events and list five people/places/things likely to be present. They used these data to generate language materials (three-sentence vignettes) in which a critical word was either a contextually supported word, an unrelated and anomalous word, or an event-related (but linguistically anomalous) word (taken from the paint-a-mental-picture task)—for example, in a vignette about going to the library, the final sentence read, '*I was shocked to find out I owed a huge…*' and continued with '*fine*' (supported), '*tire*' (anomalous and unrelated) or '*book*' (anomalous but related to the event). A second group of young adults read these vignettes while their EEG was recorded. Unsurprisingly, N400 amplitudes elicited by the final word were largest for the anomalous/unrelated words and small for the supported words. Critically, anomalous but event-related words showed an intermediate amplitude, being reduced compared to the unrelated anomalous words. The authors interpreted this as evidence that their participants could rapidly infer rich situation models (e.g., Zwaan & Radvansky, 1998) from linguistic input, suggesting that event knowledge not only drove linguistic expectations but also facilitated access to event-related knowledge even when it was linguistically inappropriate.

Many studies using similar "related-anomaly" paradigms have shown that young adults can immediately activate and maintain a rich array of knowledge of people, places, things as they process sentences (Kutas & Hillyard, 1984; Paczynski & Kuperberg, 2012; Rabs et al., 2022; Troyer & Kutas, 2020). They also seem to pre-activate, in a more punctate fashion, sensory/perceptual and semantic features of likely upcoming input that is predictable from context (Amsel et al., 2015; Federmeier & Kutas, 1999; Rommers et al., 2013). These processes are likely to occur at least somewhat outside of conscious awareness and reflect the structure of information stored in semantic long-term memory (Kutas & Federmeier, 2000).

Less is known about the time-course with which older adults access knowledge during language comprehension. By definition, older adults have more experience—with

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language and with the world—than younger adults, and they therefore are likely to possess a great deal more knowledge. Although fluid abilities relating to working memory start to decline even in middle adulthood, so-called "crystallized" abilities, like vocabulary skills, are maintained throughout most of the adult lifespan in healthy aging (Park & Gutchess, 2006). However, older adults often experience some difficulty in rapidly accessing their knowledge, as evidenced by increased numbers of "tip-of-the-tongue" states during language production (Burke et al., 1991). Moreover, a great deal of evidence from ERP studies suggests that older adults are less likely than younger adults to engage in active prediction during language comprehension (reviewed in Payne & Silcox, 2019), although having greater verbal fluency and a larger vocabulary are associated with more evidence of prediction among older adults (Federmeier et al., 2002; Federmeier & Kutas, 2019).

A recent study probed whether possessing expert-like knowledge of a fictional world would allow older adults to rapidly bring to mind people/places/things related to the events described in sentences (Troyer, Stine-Morrow, & Federmeier, 2024). As previously shown in young adults (Troyer & Kutas, 2020), older adults showed immediate effects of sentential context on N400 brain potentials, and the size of these effects for sentences about the fictional world were graded according to knowledge levels. However, unlike in young adults, there was no relationship between knowledge levels of the fictional world and the size of the related anomaly N400 effect (related vs. unrelated anomalous words). The authors interpreted these results as suggesting that older adults may judiciously engage in precise activation of only the most relevant knowledge as linguistic input unfolds, potentially due to a combination of age-related declines in fluid ability and more mature / organized semantic networks.

The Troyer et al. study was limited to examining knowledge activation during sentences describing a fictional world, one which the older adults could not have encountered until middle adulthood. By contrast, most studies have examined more common language, which would have been learned much earlier in life and with which individuals would have much more experience. It is an open question whether older adults might immediately access event-related knowledge when understanding language about common, everyday events. In the present study, we therefore used the Metusalem et al. paradigm to examine the activation of event-related, but linguistically anomalous, knowledge as older adults read sentences for comprehension, word by word. We also directly replicated the original Metusalem et al. findings in a group of young adults.

Methods

Participants

24 young adults (ages 18-22; 15 female) and 30 older adults (ages 53-80; 23 female) participated in the study for course credit or cash. A power analysis on the Metusalem et al. (2012) data suggested that 24 young subjects would provide more than 80% power to detect the related anomaly effect over the six-electrode N400 ROI we analyze in the present study. We then increased the sample size for older adults (who sometimes show smaller effect sizes), matching to the 30 (young adult) subjects used in Metusalem et al. (2012).

Materials

72 three-sentence vignettes taken from Metusalem et al. (2012) described generalized events. The third sentence included a sentence-medial critical word that was either Expected (the best completion), Related (to the general event being described, but linguistically anomalous), or Unrelated (and anomalous); e.g., '*The climb up Mount Whitney is beautiful but very challenging. Manny and Julia were tired but looking forward to what they knew awaited them at the top. Finally, they rounded the last bend and were awed by the magnificent [view (E) / boots (R) / scissors (U)] of Owens Valley below.*'

Experimental procedures

After consenting to the experiment, participants completed demographic questionnaires. They then completed measures of print exposure (the Author and Magazine Recognition Tests; Acheson, Wells, and MacDonald, 2008) and verbal fluency (based on Benton, Hamsher, & Sivan, 1983). Older adults additionally completed the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), which was used to ensure that participants scored at or above a threshold score of 25.

During the EEG session, participants silently read the vignettes for comprehension and were then asked a yes/no comprehension question about each. This question had the same correct answer across conditions (e.g., for the hiking example above, the question was, '*Did Manny and Julia go hiking down by the river?*'). Participants first read the first two sentences, which were presented in their entirety on the screen. Then, they pressed a button to advance to the next sentence, which was presented one word at a time (200 ms on, 300 ms off). These words flashed in the center of the screen just above a stationary red cross-hair that indicated to participants to reduce eye movements and blinking during the final sentence.

ERP recording and data analysis

The electroencephalogram (EEG) was recorded from 26 Ag/AgCl electrodes arranged geodesically in an ElectroCap. Impedances were kept below 5 KΩ. Additional electrodes were placed adjacent to and under the eyes to monitor blinks and eye movements and on the left mastoid (online reference) and right mastoid; data were referenced offline to an average of left and right mastoids. EEG was recorded using BrainVision's BrainAmp DC with a bandpass of .02-250 Hz and a sampling rate of 1000 Hz. Trials with artifacts (e.g.,

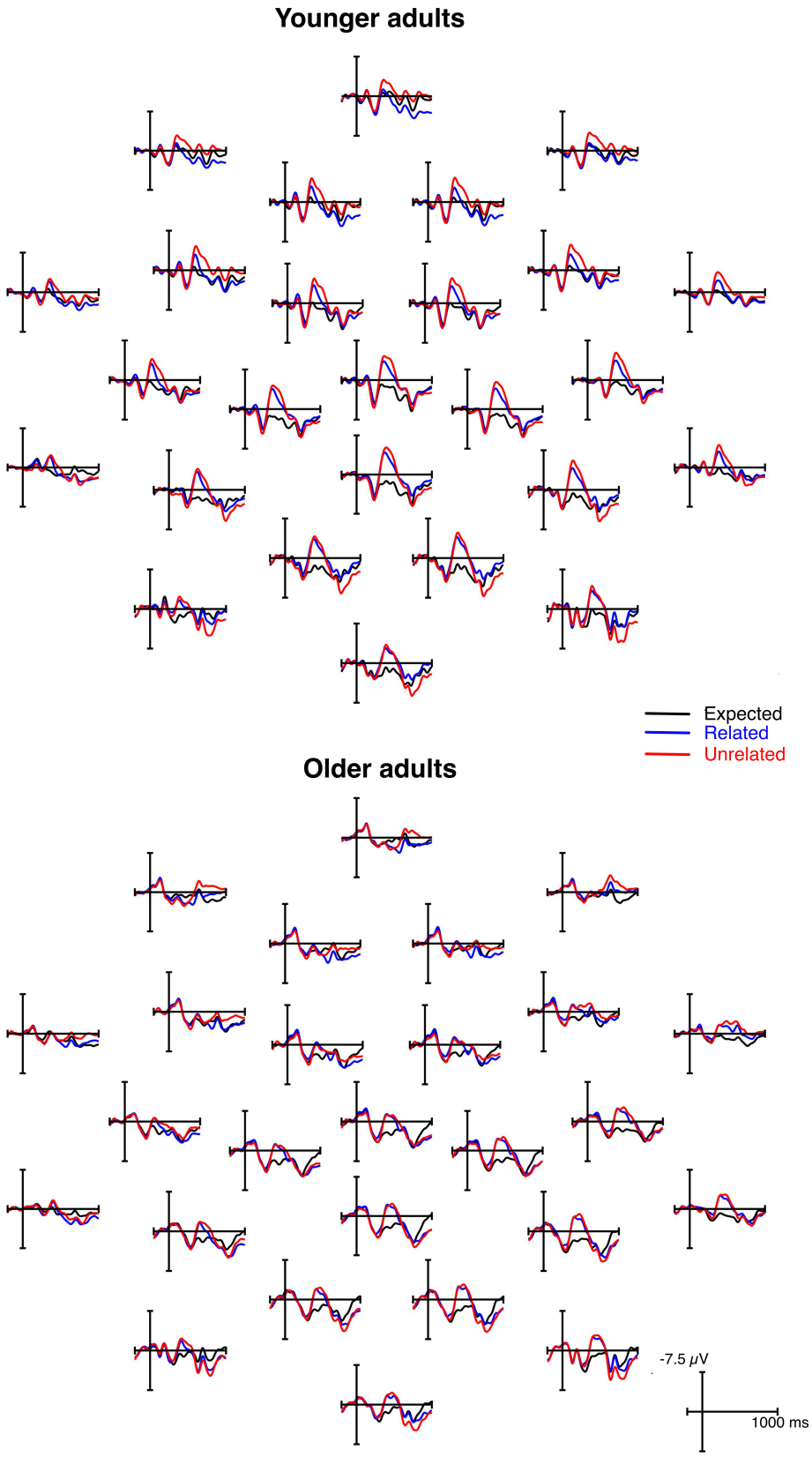


Figure 1. Grand-averaged ERPs to critical words for younger (top) and older (bottom) adults. Note that negative is plotted up.

excessive muscle activity, eye movements or blinks, or skin potentials) were removed prior to data analysis, affecting 4.83% of the data for younger adults and 8.16% of the data for older adults.

We present grand-averaged ERPs to sentence-final words across all scalp electrodes for younger and older adults, separately. For statistical analyses, we focused on an N400 (300-500 ms) ROI, including 6 electrode sites where N400 effects are typically largest (LMCe, RMCe, MiCe, MiPa, LDPa, and RDPa), and an LPC (600-900 ms) ROI, with 5 electrode sites where LPCs are typically most prominent (LLOc, RLOc, LMOc, RMOc, and MiOc). We used repeated measures ANOVA for most analyses; for individual difference analyses, we used linear mixed-effects models with random intercepts for subjects.

Results

Behavioral assessments

Summary statistics for verbal fluency, print exposure, and MoCA scores (older adults only) are provided in Table 1.

Table 1. Mean, standard deviation (SD), and range for measures of individual differences for young vs. older adults.

	Young adults			Older adults		
	Mean	SD	Range	Mean	SD	Range
Print exposure						
ART	9.88	5.97	[3-24]	36.73	(15.28)	[11-61]
MRT	4.38	5.23	[-1-21]	23.40	(6.28)	[11-36]
Combined	14.25	10.72	[3-44]	60.13	(19.21)	[27-95]
Verbal fluency						
Letter	38.58	(8.17)	[24-55]	49.93	(13.22)	[23-74]
Category	69.58	(10.72)	[46-87]	77.62	(15.53)	[53-110]
Combined	108.16	(17.22)	[70-138]	127.55	(25.73)	[82-183]
MoCA				28.13	(1.31)	[25-30]

ERPs

Grand-averaged ERPs to critical words are plotted separately for younger and older adults in Figure 1.

Young adults. We expected to replicate the finding from Metusalem et al. (2012) that young adults would exhibit graded effects of event knowledge on N400 amplitudes, with the largest amplitudes elicited by unrelated words, smaller amplitudes by related words, and smallest amplitudes by expected words (best completions). Figure 2 demonstrates that this is exactly the pattern we found. Ending type had a significant effect on N400 amplitudes ($F(2, 46) = 39.86$, $p < .0001$). Planned paired t-tests revealed both effects of contextual support (Expected < Unrelated; $t(23) = 7.00$, $p < .0001$) and event-relatedness (Related < Unrelated; $t(23) = 2.32$, $p < .05$) on N400 amplitudes.

In addition, we analyzed the late positive complex, a part of the ERP that was not analyzed in the original Metusalem et al. study. We found that ending type had a significant effect on LPC amplitude ($F(2, 46) = 6.06$, $p < .01$). Paired t-tests revealed that this was driven by enhanced LPCs for Unrelated compared to either the Related ($t(23) = -3.63$, $p < .01$) or Expected ($t(23) = -2.21$, $p < .05$) words.

Older adults. Among older adults, a repeated measures ANOVA revealed a significant effect of ending type on N400 amplitudes ($F(2, 58 = 29.20$, $p < .0001$). Consistent with the existing literature, older adults showed an effect of contextual support on N400 amplitudes (Expected < Unrelated; $t(29) = 5.96$, $p < .0001$). However, there was no evidence for a related anomaly effect (Related vs. Unrelated; $t(29) = 0.26$, $p = .80$) (Figure 2) Thus, older adults did not seem to activate and maintain broader event-related knowledge as they read the sentences.

We also observed a significant effect of ending type on LPCs ($F(2, 58) = 8.70$, $p < .001$). Unrelated words elicited larger positivities than Related words ($t(29) = -2.82$, $p < .01$), which in turn elicited larger positivities than Expected words ($t(29) = -2.15$, $p < .05$).

Thus, although older adults did not show a related anomaly effect in the N400 time period, we did observe an effect of related anomaly during the post-N400 late positivity time window, demonstrating that older adults did ultimately appreciate the difference between event-related and event-unrelated words, in less than a second.

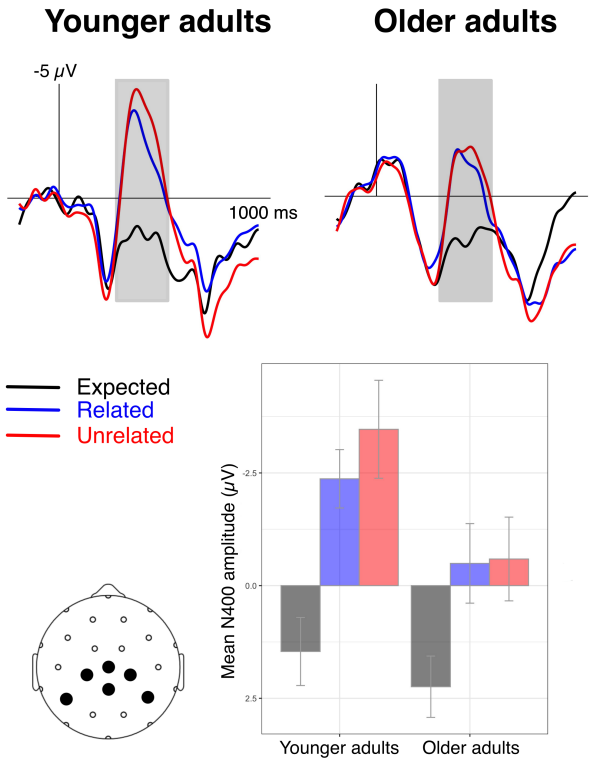


Figure 2. ERPs to critical words are plotted for younger adults (top left) and older adults (top right) averaged across the six electrodes for our centro-parietal ROI (as illustrated on the bottom left). Mean N400 amplitude in this ROI is plotted in the bottom right.

ERPs and individual differences

The present findings support prior claims that younger adults engage in broad knowledge activation during comprehension such that linguistically anomalous but event-related knowledge is facilitated during real-time semantic access, reflected in N400 amplitudes. In contrast, older adults as a group do not seem to engage in this kind of wide-ranging knowledge activation and/or maintenance. However, there is a great deal of variation in fluid processing, knowledge, and other language-related variables among older adults, which may be related to the ability to maintain activation of multiple event-related entities during comprehension of a sentence or discourse. We therefore examined whether our measures of verbal fluency (a measure of fluid verbal ability that also taps into knowledge) and print exposure (a measure of crystallized knowledge) might relate to the size of the contextual support and related anomaly effects in the N400 and LPC time periods. We also examined these relationships among younger adults for completeness.

Young adults. To test the influence of individual differences on N400 effects of contextual support and related anomaly, respectively, we conducted nested model comparison. In these comparisons, the full model included individual predictors of condition, age, verbal fluency, and print exposure (ART/MRT) as well as two-way interactions between condition and each of the individual difference measures. We conducted separate comparisons for both N400 and LPC measures of contextual support and related anomaly, respectively. For all comparisons, the simpler model was preferred (all ps > .05), suggesting that the individual differences we measured did not significantly modulate any of the ERP effects among young adults.

Table 2. Effects of individual differences on N400 effects of related anomaly among older adults. The interaction of age and condition (Related vs. Unrelated) was a significant predictor of N400 amplitude. (VF=Verbal Fluency; PE=Print Exposure)

	Estimate	SE	df	*t*-value	p-value
Intercept	-0.60	0.49	24	-1.23	0.23
Condition	0.22	0.19	24	1.14	0.27
Age	-0.15	0.62	24	-0.24	0.81
VF	0.19	0.52	24	0.37	0.72
PE	0.27	0.47	24	0.57	0.57
MoCA	0.36	0.52	24	0.68	0.50
Condition:Age	0.73	0.24	24	3.00	0.01
Condition:VF	-0.17	0.21	24	-0.83	0.41
Condition:PE	-0.06	0.18	24	-0.30	0.77
Condition:MoCA	0.02	0.21	24	0.08	0.93

Older adults. We conducted similar analyses to test whether individual differences may have modulated any of our ERP effects among older adults. The only difference was that we additionally included the MoCA score, which was collected only for older adults. We were particularly interested in whether measured individual differences might reveal that some of the older adults did show a related anomaly effect, especially given previous results that factors related to fluid abilities, like verbal fluency measures, relate to real-time ERP indices of prediction (e.g., Federmeier et al., 2002).

For N400 effects of related anomaly, but not for any other effects (i.e., N400 effects of contextual support or any LPC effects), nested model comparison revealed that the more complex model that incorporated individual differences was preferred ($p < .05$). Inspection of this model revealed a significant interaction effect of condition (Related vs. Unrelated) and age (Table 2).

We followed up on this relationship by conducting simple correlations between age and the size of the related anomaly N400 effect among older adults. This revealed a significant negative correlation ($r = -.48$, $p < .05$), such that as age increased, the size of the related anomaly effect decreased (Figure 3).

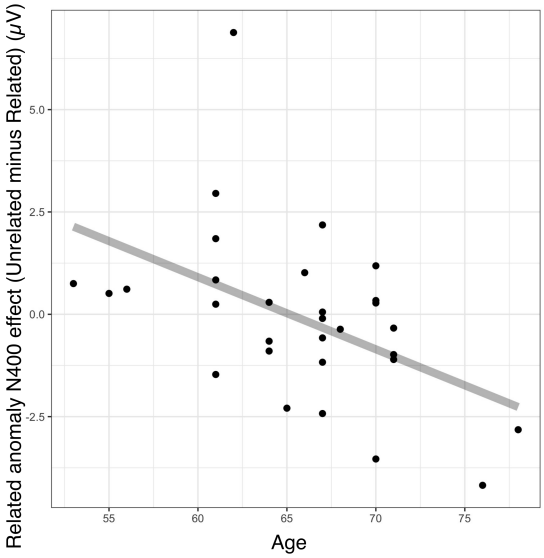


Figure 3. Each individual older adult's N400 related anomaly effect plotted against their age.

Discussion

Our study investigated whether older adults would rapidly activate broad event knowledge as they understood language about everyday, common events, as has been demonstrated among younger adults (Metusalem et al., 2012) and replicated here. Our findings from N400 effects of related anomaly support the conclusion that older adults (on average) do not activate this information in such a way that it is made continuously available over the course of a sentence. These findings square well with a recent study finding that variation in domain knowledge among older adults does not (on average) make contextually related words more available as older adults understand language about a specific domain, as has been demonstrated among younger adults (Troyer et al., 2024).

These findings align with recent studies of age-related differences in the network structure of semantic knowledge (Cosgrove et al., 2023; Wulff, Hils, & Mata, 2022). In these

studies, older adults are shown to have more modular networks, with fewer connections between each node of the network (i.e., between each concept/word), compared to younger adults. Thus, one reason that older adults may not immediately activate large swaths of information is that their semantic networks have matured to a stage where only the most relevant knowledge (e.g., within a modularized "hub") is easily accessible at any given moment. Our findings suggest that these differences may extend to the real-time activation of event knowledge, such that older adults may not have immediate access to knowledge associated with everyday events like going on a hike or attending a birthday party.

However, among older adults, we also observed a significant relationship between N400 related anomaly effects and age. In our sample, there was a relatively large range of ages among our older adult group (53-80 years). This suggests that as individuals enter into older adulthood, they may encounter shifts in the organization of and/or ability to access semantic memory (i.e., long-term knowledge).

Our findings from LPC effects suggest that older adults do eventually engage in differential processing for related anomalies vs. words that are completely unrelated to the sentence context. In memory paradigms, LPC effects have been linked to an endogenous capture of attention that benefits memory (Polich, 2007). In language comprehension tasks, larger late (posterior) positive potentials have instead been observed to words that are anomalous in context, compared to those that are linguistically expected and/or plausible (e.g., DeLong, Quante, & Kutas, 2014). Recent work has suggested a link between these attention- and memory-related LPC effects and LPC effects during language comprehension, suggesting that linguistic anomalies may also involve endogenous attentional capture (Contier, Hoeger, & Rabovsky, 2024; Leckey & Federmeier, 2019). On this interpretation, our findings would suggest that, among older adults, contextually event-related words may still have some degree of privileged status during comprehension compared to unrelated words, such that unrelated words more strongly evoke attentional capture compared to related words.

It is worth noting that sentences in the present study described very common events, which seem likely to be well-learned by middle to later adulthood. It is possible that relatively novel, infrequent, or unusual events, such as those encountered in fantastical/fictional worlds, may engender ongoing learning even into older adulthood (cf. Stine-Morrow et al., 2024). Thus, it may be an effective strategy for older adults to deploy more fluid processing (possibly reflecting learning mechanisms) in cases where they stand to gain new knowledge or substantially augment existing knowledge. Supporting this idea, Troyer et al. (2024) found that for a subset of trials on which older adults could produce (i.e., recall from long-term memory) appropriate sentence completions, domain knowledge *did* influence the N400 response to anomalous but sentence-related words completing fictional "facts" about Harry Potter. Thus, it may be possible that with aging, some semantic networks remain more flexible and/or susceptible to learning processes during language comprehension compared to other ("over-learned") networks.

Taken together, the findings from the present study suggest the presence of age-related differences in how individuals access event knowledge as they attempt to understand words in sentences in real time such that older adults restrict activation to the most immediately relevant content. To date, few studies have involved a comprehensive investigation of how real-time access to semantic memory changes across the course of the entire adult lifespan. In one study, Kutas and Iragui (1998) investigated individuals across the adult lifespan (aged 20-80 years, binned in 10-year increments). They observed systematic changes in N400 congruity effects, being present but overall smaller and somewhat slower (longer-latency) as a function of age. However, to our knowledge, no prior studies have investigated real-time differences in access to broader, contextually related meaning across the full adult lifespan. In future work, we hope to study adults in middle age to examine the time-course of changes in semantic processing during language comprehension, including the ease with which adults at various stages of maturation readily learn from new information during language comprehension.

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