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Cognitive control mediates age-related changes in flexible anticipatory processing during listening comprehension

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Abstract

Effective listening comprehension not only requires processing local linguistic input, but also necessitates incorporating contextual cues available in the global communicative environment. Local sentence processing can be facilitated by pre-activation of likely upcoming linguistic input, or predictive processing. Recent evidence suggests that young adults can flexibly adapt local predictive processes based on cues provided by the global communicative environment, such as the reliability of specific speakers. Whether older comprehenders can also flexibly adapt to global contextual cues is currently unknown. Moreover, it is unclear whether the underlying mechanisms supporting local predictive processing differ from those supporting adaptation to global contextual cues. Critically, it is unclear whether these mechanisms change as a function of typical aging. We examined the flexibility of prediction in young and older adults by presenting sentences from speakers whose utterances were typically more or less predictable (i.e., reliable speakers who produced expected words 80% of the time, versus unreliable speakers who produced expected words 20% of the time). For young listeners, global speaker reliability cues modulated neural effects of local predictability on the N400. In contrast, older adults, on average, did not show global modulation of local processing. Importantly, however, cognitive control (i.e., Stroop interference effects) mediated age-related reductions in sensitivity to the reliability of the speaker. Both young and older adults with high cognitive control showed greater N400 effects of predictability during sentences produced by a reliable speaker, suggesting that cognitive control is required to regulate the strength of top-down predictions based on global contextual information. Critically, cognitive control predicted sensitivity to global speaker-specific information but not local predictability cues, suggesting that predictive processing in local sentence contexts may

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be supported by separable neural mechanisms from adaptation of prediction as a function of global context. These results have important implications for interpreting age-related change in predictive processing, and for drawing more generalized conclusions regarding domain-general versus language-specific accounts of prediction.

1. Introduction

Accumulating evidence across cognitive domains points to the ubiquity of prediction, or probability-driven anticipation for likely events (Clark, 2013). For example, in the field of language comprehension, it is now widely accepted that comprehenders can use local contextual (e.g., sentential) information to anticipate upcoming linguistic input, allowing comprehenders to generate specific predictions[1] for upcoming words ((Altmann and Mirkovic, 2009; Brothers et al., 2015; Elman, 1991; Kuperberg and Jaeger, 2016; Van Berkum et al., 2005) but see (Huettig and Mani, 2016; Klimovich-Gray et al., 2019; Nieuwland, 2019)). When predictions are accurate, top-down pre-activation can reduce the neural activity required for lexical access when the word is ultimately encountered. The advantage of predictive processing is therefore clear: pre-activation can reduce the neural and cognitive resources needed for processing upcoming words in sentences, allowing for faster and more efficient local contextual processing.

In real-world communication, however, sentences are rarely presented in isolation. Instead, they are often embedded in extended or global communicative contexts with varying statistical properties. Predictive strategies may become more or less effective across language environments as a function of global contextual cues (Fine et al., 2010; Huettig, 2015; Kuperberg and Jaeger, 2016; Lupyan and Clark, 2015). Recent electrophysiological evidence suggests that comprehenders can *regulate* the strength of top-down sentence-level predictions based on the global regularity or reliability of contextual cues. For example, in global contexts with high levels of prediction error, young adults can decrease the strength of their local lexical-semantic predictions (Brothers et al., 2017; Brothers et al., 2019; Delaney-Busch et al., 2019).

The mechanisms underlying flexible adaptation of predictive processing are still poorly understood. Specifically, it is unclear whether processes employed during local processing resemble those underlying adaptation to global contextual environments. Further, it is unknown whether reliance on local or global contextual information differs between healthy young adults and populations with known reductions in neural and cognitive resources, such as older adults.

Adaptation to global contextual cues may be especially difficult in populations such as older adults due to diminished cognitive control (reviewed in (Payne and Silcox, 2019; Peelle, 2019; Pichora-Fuller, 2003)). Older adults tend to have more difficulty regulating their behavior in novel or rapidly changing environments, such as in tasks involving

[1]Accounts differ about the specificity of predictions that are generated, i.e., whether individuals predict one most likely word or multiple potential words in a probabilistic or Bayesian fashion (Kuperberg and Jaeger, 2016; Levy, 2008; Van Petten and Luka, 2012). The current study cannot address this debate as we only examined activity to the highest likelihood completion (i.e., we did not examine graded predictability effects across multiple moderate-to-high likelihood completions).

implicit learning (Howard and Howard, 2013), the inhibition of automatic or preponent responses (Hasher and Zacks, 1988; Kramer et al., 1994; Ortega et al., 2012), and during task switching or selective attention (i.e., attention to relevant stimuli and inhibition of irrelevant stimuli) (Hull et al., 2008). Previous studies have demonstrated that cognitive control is integral to the representation, maintenance, and updating of contextual information during language processing in clinical and neuro-typical populations, including older adults (Boudewyn et al., 2012a; Boudewyn et al., 2012c; Hsu and Novick, 2016; January et al., 2009; Swaab et al., 2013). Context updating relies on the regulation of top-down feedback, which is critical for flexible adaptation to relevant cues in the environment. This process can be influenced by statistical regularities in the global context (Brothers et. al, 2017; 2019). Thus, sensitivity to global contextual cues may be mediated by availability of cognitive control.

Whether local, sentence-level predictive processing requires recruitment of executive resources, such as cognitive control, is less clear. A prominent *domain-general* account posits that comprehenders rely on domain-general executive resources when generating local predictions, because pre-activation of specific words is a neurally effortful process (Federmeier et al., 2020; Nozari et al., 2016), which can be especially costly when prediction is less beneficial, e.g., in environments with high prediction error (Brothers and Kuperberg, 2021; Kuperberg and Jaeger, 2016). Age-related reductions in cognitive control have been suggested to explain why, despite preserved or even improved vocabulary knowledge in healthy aging, electrophysiological studies have found age-related reductions in neural facilitation to predictable words in local contexts, e.g., in individual sentences (Dave et al., 2018b; Federmeier et al., 2002; Federmeier and Kutas, 2005; Kutas and Iragui, 1998; Payne and Federmeier, 2018; Wlotko et al., 2012).

An alternate account suggests that sentence-level prediction may not require executive resources, but can rely on language-specific brain networks that are distinct from those underlying domain-general executive processes (Diachek et al., 2020; Ryskin et al., 2020). According to this *language-specific* account, while flexible adaptation to global cues relies on non-linguistic cognitive control, the local effects of contextual constraint depend on stored lexico-semantic knowledge. Recent evidence from neuroimaging (Kroczek and Gunter, 2020) provides support for a language-specific account of prediction. In this study, syntactic complexity of individual sentences correlated with activity in frontal-temporal language network regions, while global cues about speaker-specific use of syntax (i.e., more or less complex sentence structures) were associated with increased activation across brain regions in the frontal-parietal executive function network. Whether this dissociation is influenced by distinctions between lexical-semantic and syntactic functional networks is not yet known.

We investigated the effects of age-related changes in cognitive control on local and global predictive processing using the paradigm employed in Brothers et al. (2019). In this paradigm, *filler* sentences were introduced to manipulate the global validity of predictive cues, i.e., the likelihood of encountering a prediction error across two different speakers.[2] One speaker reliably produced sentence endings that were predictable given the prior sentence context (e.g., *Jack forgot about the cookies baking in the oven*), while the other typically generated sentence endings that were unlikely to be predicted (e.g., *Jack forgot about the cookies baking in the house*). We refer to these speakers as the reliable and unreliable speaker, respectively.

We subsequently examined whether speaker reliability influenced local anticipatory processing in a smaller subset of *critical* sentences. Critical sentence trials contained a critical word that was either highly predictable (e.g., *In 1967, NASA wanted to land a man on the moon before the Russians did*) or unexpected yet plausible (e.g., *I had heard that they wanted to go to the moon before the Russians did*). In this way, differences due to local predictability could be assessed within each speaker-specific context. Predictability effects were measured as neural activity recorded via electroencephalography (EEG) to predictable versus unpredictable critical words (e.g., *moon*). We expected to see a reduction in brain activity peaking around 400ms following onset of the predictable word: the N400. The N400 is a well-characterized event-related potential (ERP) component, which has been shown to be sensitive to the difficulty of lexico-semantic processing in younger and older adults (reviewed in (Federmeier, 2007; Kutas and Federmeier, 2011)).

Brothers et al. (2019) demonstrated that, in young adults, typical effects of local contextual predictability on the N400 are influenced by the global environment (speaker-specific reliability). These findings are consistent with models of predictive processing that propose a flexible architecture (Huettig, 2015; Lupyan & Clark, 2015; Kuperberg & Jaeger, 2016), and show that listeners can adapt their prediction mechanisms during natural sentence comprehension. We expected to replicate the results of Brothers et al. (2019) in the current study, and further aim to address whether this flexible adaptation is reliant on the availability of cognitive control in young and older adults.

Both domain-general and language-specific accounts predict that older adults and individuals with lower cognitive control would be less likely to show flexible adaptation to global context cues. However, a domain-general account would predict that cognitive control scores should correlate with effects of both local sentence context and global communicative context on the N400. In contrast, a language-specific account of predictive processing would predict that cognitive control should not correlate with local neural effects associated with predictive processing, but should correlate with effects of adaptation to global contextual cues. Critically, to differentiate between these predictions of domain-general and language-specific accounts, we collected response times to congruent and incongruent color-meaning conditions of the Stroop task (Stroop, 1935), a gold-standard metric of inhibitory cognitive control (detailed in Methods).

Stroop task performance depends on the ability to utilize a global, task-specific cue to regulate behavior at the local level. We used this measure to determine the extent to which cognitive control predicts sensitivity to local (predictability) and global (speaker reliability) cues in order to differentiate between domain-general and language-specific prediction

[2]A parallel literature suggests pragmatic information about speakers (e.g., gender, age) can influence neural activity during sentence comprehension (Lattner and Friederici, 2003; Molinaro et al., 2016; Van Berkum et al., 2008). In the current study, speakers were randomly assigned to the ‘reliable’ or ‘unreliable’ condition by manipulating predictability in an independent set of filler sentences. Therefore, any speaker-specific information had to be learned by participants during the experimental session.

accounts, and in doing so, further our understanding of how predictive processing changes with age and declines in cognitive control.

2. Results

2.1. Behavioral results

During the experiment, participants responded to true/false comprehension questions about preceding sentences in order to gauge listening comprehension. Listeners performed very well on the comprehension task (mean = 91.4% in young adults, 91.7% in older adults), with no significant differences emerging as a function of speaker reliability for either young adults ($t(39) = 1.45$, $p = 0.16$) or older adults ($t(39) = 0.63$, $p = 0.47$). This implies that both young and older adults were attentive and alert during sentence presentation across speaker contexts.

A post-experiment debriefing indicated that neither young adults nor older adults were generally aware of the study manipulation (number of participants who identified the speaker reliability manipulation: 2 young adults, 1 older adult). When we explained the speaker reliability manipulation to participants and asked them to identify the reliable speaker, young and older adults were typically successful in determining the correct speaker (mean speaker identification accuracy: 75.0% in young adults, 72.5% in older adults). Age group did not significant affect reliable speaker identification ($t(78) = 0.25$, $p = 0.80$). Participant confidence in their speaker selection was not above chance (median speaker identification confidence: 4 out of 7 in both young and older adults) and did not vary significantly as a function of age (Mann-Whitney U = 611, $Z_{40} = 1.72$, $p = 0.09$).

2.2. ERP results

2.2.1. N400 predictability contrast for filler sentences in both age groups—

We first examined ERPs time-locked to sentence-final words for filler trials. In order to examine the effects of local predictability cues, we compared sentence-final words for filler sentences spoken by the reliable speaker, which were always predictable given the preceding context, with sentence final words for filler sentences spoken by the unreliable speaker, which were always unexpected. We therefore anticipated that these items would yield the typical effects of contextual predictability on the N400 component, i.e., reduced neural activity in the 300–600ms time window for expected versus unexpected words.

Figure 1 shows N400 effects of predictability in the filler sentences in young and older adult listeners. In the 300–600ms time window, robust effects of predictability were observed in young adults ($t(39) = 7.70$, $p_{corr} < 0.001$, $d = 1.47$) and older adults ($t(39) = 7.90$, $p_{corr} < 0.001$, $d = 1.35$) over the centro-posterior cluster of electrodes for which the N400 effect is maximal. Consistent with previous ERP studies conducted with older adults (Dave et al., 2018b; DeLong et al., 2012; Federmeier and Kutas, 2005; Kutas and Iragui, 1998; Wlotko and Federmeier, 2012; Wlotko et al., 2012), N400 effects of predictability measured during filler trials were significantly reduced in older relative to younger adults (age by predictability interaction: $F(1, 78) = 5.29$, $p = 0.02$). Therefore, while both young and older adult listeners show expected N400 effects associated with predictive processing, this effect was reduced in older adults.

2.2.2. Young – but not older – adults show speaker-specific adaptation in critical sentences—

We subsequently analyzed ERPs for critical sentence trials (Figure 2) to examine if speaker reliability modulated sentence-level prediction. Sentence-medial critical word trials varied in predictability (predictable, unpredictable) for a subset of sentences counterbalanced across speaker (reliable, unreliable). The speaker reliability factor was created by manipulating the number of filler sentences that were predictable (i.e., all filler sentences were predictable in the reliable speaker condition and unpredictable in the unreliable condition). Importantly, the same set of critical sentences was used in both the reliable and unreliable speaker conditions (for more details, please see Methods).

A 2 (predictability) × 2 (speaker reliability) × 2 (age) repeated-measures mixed-effects ANOVA (rANOVA) on mean ERP amplitudes in the canonical N400 time window (300–600ms) revealed a significant three-way interaction between age group and speaker reliability on the N400 effect of predictability ($F(1, 78) = 6.30$, $p = 0.01$). These results also included a significant main effect of age on the amplitude of the N400 ($F(1, 78) = 6.13$, $p = 0.01$), indicating that N400 amplitudes across conditions were reduced for older adults, independent of experimental condition. The three-way interaction paired with the expected main effect of aging on N400 amplitudes supported our *a priori* statistical follow-up analyses for each age group separately.

2.2.2.1. Young adults: In a new sample of young adults, we replicated the findings of Brothers et al. (2019). Namely, significant effects of predictability emerged when young adults listened to the reliable ($t(39) = 8.03$, $p_{corr} < 0.001$, $d = 1.72$) and the unreliable speaker ($t(39) = 5.26$, $p_{corr} < 0.001$, $d = 0.95$), but the N400 predictability effect was approximately 1.5 times larger when listening to the reliable versus the unreliable speaker ($F(1, 39) = 4.95$, $p = 0.03$, $\eta^2 = 0.11$) (Figure 2).

We performed additional analyses to examine whether the speaker reliability manipulation affected processing for predictable or unpredictable critical words. Unpredictable critical words were not affected by the speaker reliability manipulation, and similar N400 amplitudes were found for both speaker conditions ($t(39) = 0.48$, $p_{corr} = 0.98$, $d = 0.09$). The speaker manipulation modulated N400 amplitudes for predictable words; a reduced N400 was found to predictable words in the reliable speaker condition ($t(39) = 2.25$, $p_{corr} = 0.05$, $d = 0.50$). This finding (Figure 3) suggests that the global effects of speaker reliability primarily increased benefits for predictable words in constraining contexts, with younger listeners generating stronger lexical predictions in the context of a reliable speaker.

2.2.2.2. Older adults: We performed the same analyses on EEG data collected from older adults (Figure 2). As in young adults, an N400 predictability effect was found for both the reliable ($t(39) = 6.66$, $p_{corr} < 0.001$, $d = 1.30$) and the unreliable speaker conditions ($t(39) = 6.52$, $p_{corr} < 0.001$, $d = 1.41$). However, we observed no significant interaction between predictability and speaker reliability in older listeners ($F(1, 39) = 1.45$, $p = 0.24$, $\eta^2 = 0.04$). When directly comparing individual conditions, speaker reliability did not meaningfully influence N400 amplitudes to predictable critical words ($t(39) = 0.79$, $p_{corr} = 0.86$, $d = 0.15$). N400 activity was marginally greater for unpredictable items spoken by the unreliable relative to the reliable speaker, although this difference was not statistically significant after Bonferroni correction ($t(39) = 2.23$, $p_{corr} = 0.07$, $d = 0.42$).

Cumulatively, these results indicate that older adults were, on average, less responsive to global reliability of predictive cues than young adults. Critically, the results of the debriefing questionnaire indicated that young adults were not more likely than older adults to be aware of the speaker reliability manipulation, or more accurate or confident when identifying which speaker was more reliable. Considered alongside the neural findings, these debriefing results suggest that age-related differences in the effects of speaker reliability on processing predictable words are unlikely to result from differences in conscious comprehension strategies.

2.2.2.3. Individual differences in global versus local predictive processing: We conducted an additional analysis to determine whether individual differences in the magnitude of the global *speaker-specific adaptation effect* were correlated with individual differences in local predictability effects on the N400. The global adaptation effect was calculated across critical sentences as the difference between the N400 effect to high versus low cloze critical words spoken by the unreliable speaker and the N400 effect to high versus low cloze critical words spoken by the reliable speakers. The local predictability effect was calculated between high versus low cloze endings for filler sentences. The magnitude of the adaptation effect in critical sentences did not correlate with the N400 main effect of predictability for filler trials in young adults ($r(39) = 0.04$, $t(39) = 0.25$, $p = 0.81$) or older adults ($r(39) = 0.12$, $t(39) = 0.75$, $p = 0.46$). This result suggests that establishment and use of speaker-specific predictability cues is unlikely to engage the same cognitive or neural sources as lexical-semantic predictability in local sentence contexts.

2.2.3. Age-related reductions in speaker-specific adaptation mediated by cognitive control—

We subsequently determined whether typical age-related declines in cognitive control (as measured by Stroop interference effect response times; detailed in Methods) could explain age-related deficits in global *speaker-specific adaptation*.

2.2.3.1. Mediation of speaker-specific adaptation effect by cognitive control: As above, we calculated the speaker-specific adaptation effect as the difference between the N400 effect to high versus low cloze critical words spoken by the reliable versus unreliable speaker. We examined correlations between speaker-specific adaptation effects and individual differences in chronological age and cognitive control. Significant correlations were found between age and speaker-specific adaptation effects ($r(78) = 0.25$, $t(78) = 2.51$, $p = 0.01$), between age and cognitive control ($r(78) = 0.48$, $t(78) = 4.99$, $p < 0.001$), and between cognitive control and speaker-specific adaptation effects ($r(78) = 0.45$, $t(78) = -3.49$, $p < 0.001$) (Figure 4A).

Using nonparametric bootstrapping methods (Bollen and Stine, 1990; Tingley et al., 2014), we tested whether cognitive control acts as a mediating variable, explaining age-related differences in speaker-specific adaptation. Unstandardized indirect effects were estimated for 1,000 bootstrapped simulations, yielding a statistically significant indirect effect of 0.90 (95% confidence interval: 0.08–2.08, $p = 0.03$). As seen in Figure 4B, cognitive control fully mediated age-related reductions in speaker-specific adaptation. After including cognitive control in the model, the effect of age on speaker-specific adaptation was no longer significant ($p = 0.71$). 73.5% of the effect of age on speaker-specific adaptation was explained by individual variability in cognitive control.

We also performed correlational analyses between cognitive control and the N400 predictability effect in *filler* sentences. Cognitive control scores were not correlated with N400 effects of predictability on filler trials, for either young ($r(39) = 0.20$, $t(39) = 1.26$, $p = 0.22$) or older listeners ($r(39) = 0.15$, $t(39) = 0.94$, $p = 0.36$), or when both groups were combined ($r(78) = 0.03$, $t(78) = 0.27$, $p = 0.79$). This finding implies that cognitive control scores do not predict local effects of contextual constraint. Rather, cognitive control appears to selectively influence the modulatory global effects of speaker reliability.

2.2.3.2. Individual variability in effects of cognitive control on global prediction: We conducted exploratory analyses to determine whether the effects of cognitive control on speaker-specific adaptation reflected changes in processing sentences spoken by the reliable or unreliable speaker.

Across both age groups, cognitive control scores significantly predicted the N400 effect for sentences spoken by reliable speakers ($r(79) = 0.43$, $t(43) = -4.21$, $p < 0.001$). Higher cognitive control performance (i.e., lower Stroop interference effect times) predicted larger N400 effects of predictability in young adults ($r(39) = -0.33$, $t(39) = -2.18$, $p = 0.04$) and marginally correlated with N400 effects in older adults ($r(39) = -0.30$, $t(39) = 1.97$, $p = 0.055$) (Figure 5A). Interestingly, across both age groups, cognitive control scores also predicted the N400 effect for sentences produced by the unreliable speaker ($r(79) = 0.30$, $t(79) = 2.76$, $p = 0.007$). These effects were primarily driven by smaller N400 effects in older adults with low cognitive control ($r(39) = 0.43$, $t(39) = 2.95$, $p = 0.005$), as there were no significant effects in young adults ($r(39) = 0.21$, $t(39) = 1.31$, $p = 0.20$) (Figure 5B). Therefore, both young and older adults with high cognitive control showed greater N400 effects of predictability during sentences in the reliable-speaker condition, and older adults additionally showed reduced N400 effects of predictability during sentences in the unreliable-speaker condition.

3. Discussion

The current study examined the mechanisms by which young and older listeners can adjust to new communicative environments, i.e., whether anticipatory processing was affected by different levels of prediction error. Using a recently developed experimental paradigm (Brothers et al., 2019), we manipulated the both the local predictability of words in sentences and the global reliability of prediction based on speaker-specific cues. We examined the effects of local context by measuring the N400 to high versus low cloze sentence-final words in filler sentences. In these sentences, predictable words elicited reduced N400 responses over centro-parietal electrode sites relative to unpredicted sentence endings in both age groups. This finding suggests that both young and older adults are sensitive to local contextual constraints, which allows for the prediction of upcoming linguistic content.

Importantly, the magnitude of predictability effects varied as a function of the global communicative context in young adults. In the context of a reliable speaker, listeners showed greater N400 facilitation for contextually predictable words in a subset of critical sentences, resulting in a significant interaction of predictability and speaker reliability in the N400 time window. This replicates the results in young adults studied in Brothers et al. (2019). In contrast, older listeners – on average – did not show a speaker-specific adaptation effect. Instead, older adults showed robust main effects of local, sentence-level predictability that did not differ significantly as a function of the global communicative context.

We hypothesized that flexible adjustment of predictive processing in response to speaker-specific cues requires effective use of cognitive control to modulate the influence of top-down feedback on local lexical predictions. Indeed, both young and older adults with higher cognitive control showed greater sensitivity to the speaker reliability manipulation, with enhanced predictability effects when listening to the reliable speaker. Moreover, individual differences in cognitive control fully mediated age-related reductions in speaker-specific adaptation. These results have important implications for interpreting age-related changes in predictive processing, as well as implications for more general conclusions regarding the influence of domain-general cognitive control mechanisms on the effects of global and local predictive cues.

3.1. Support for a language-specific account of predictive processing

A subset of predictive processing accounts postulates that comprehenders can recruit a feed-forward expectancy-induced mechanism to generate predictions based on *both* pre-existing semantic knowledge *and* global information regarding the precision/reliability of contextual cues in the current language environment (e.g., predictability established via speaker reliability) (Brothers et al., 2015; Brothers et al., 2017; Brothers et al., 2019; Huettig, 2015; Lupyan and Clark, 2015). This active expectancy mechanism would thus necessarily rely on contextual information encoded at both local and global levels. Interestingly, for young adults, the magnitude of local predictability effects on sentence-final words in the filler sentences did not predict the magnitude of global speaker-specific adaptation effects in critical sentences. Likewise, despite age-related reductions in both local predictability and global speaker-specific adaptation effects, we observed no correlation in the magnitude of these two effects among older listeners. These findings suggest *dissociable* sensitivity to local versus global contextual information, consistent with the recruitment of dissociable cognitive and neural sources.

We believe these findings are inconsistent with the predictions of domain-general accounts that suggest cognitive control affects both local predictive processing and the top-down effects of the global context on predictive processing. These accounts[3] suggest that

[3]Similar theories of executive support for linguistic prediction suggest predictions are maintained and accessed via structures implicated in working memory (e.g., (Lau et al., 2013)). We focus here on theories specific to inhibitory control in line with testable hypotheses given the current dataset.

successful sentence-level prediction requires effective use of cognitive control (Gernsbacher, 1991; Hasher et al., 1991; Nozari et al., 2016). Stroop interference effect response times were *not* predictive of local N400 predictability effects, and this was the case for both young and older adult listeners, despite well-established age-related slowing on the Stroop task (MacLeod, 1991; Stroop, 1935). As such, this measure of cognitive control did not explain neural effects of local predictability. In contrast, Stroop performance was a valuable predictor of the tendency for older adults to show a young-like response pattern for speaker-specific adaptation, i.e., for their use of global cues to regulate top-down, anticipatory processing. Thus, a parsimonious interpretation of this dissociation is not necessarily critical for generating sentence-level lexico-semantic predictions. Instead, cognitive control may be required to *regulate* the strength of top-down predictions based on global contextual information. Significantly, this interpretation is age-invariant, given similar patterns of high versus low cognitive control in both age groups. These results are also consistent with findings of Boudewyn et al. and Swaab et al. (Boudewyn et al., 2012a; Boudewyn et al., 2012c; Swaab et al., 2013), who showed that poor cognitive control in neurotypical adults and individuals with schizophrenia affected global effects of discourse congruence, but not local effects of semantic relations between adjacent words.

In seeming contrast to the current results, several previous studies have found links between measures of cognitive control and neural activity associated with local sentence-level predictions (Ye and Zhou, 2008; Zirnstein et al., 2018). In these studies, cognitive control performance did not correlate with neural activity during the N400 time window, but rather with later brain activity typically described as the post-N400 positivity (PNP) or P600 (Kuperberg, 2007; Van Petten and Luka, 2012). While the magnitude of N400 activity is thought to reflect the robustness of lexical-semantic pre-activation, post-N400 positivity is associated with updating or reanalysis of ongoing discourse representation when presented with conflicting, unpredicted words (Brothers et al., 2015; Van Petten and Luka, 2012). Some neurocognitive models have therefore suggested distinct processes underlying neural activity in N400 and post-N400 windows (Kolk and Chwilla, 2007; Novick et al., 2005; Regel et al., 2014; Ryskin et al., 2020). Because N400 activity relies predominantly on stored language-specific knowledge, it may primarily engage the language network. In contrast, cognitive control and language networks may interact during the later updating and reanalysis stage, which requires conflict detection, monitoring, and resolution (i.e., error detection forms of cognitive control, ((Ye and Zhou, 2008; Zirnstein et al., 2018) but see (Kuperberg, 2007)).

These results support the idea that prediction mechanisms that specifically affect pre-activation of local linguistic representations can run in parallel with prediction mechanisms that are affected by global probabilistic cues. Recent large-scale neuroimaging meta-analyses and neurostimulation studies inform this language-specific hypothesis by showing that language-selective frontal-temporal networks engaging core aspects of sentence comprehension (including prediction of upcoming words and structures) can run parallel to domain-general networks implicated in executive functions (Dave et al., 2020; Diachek et al., 2020; Shain et al., 2020). As in Kroczek and Gunter (2020), we found that domain-general resources were correlated with dynamic sensitivity to speaker contexts, but not to sensitivity to sentence-level contextual information.

3.2. Age-related changes in sensitivity to global environments

There may be several potential explanations for older adults showing reduced sensitivity to global speaker-specific reliability information. One possibility is that older adults were less able to acquire new statistical information about the two speakers, either due to deficits in implicit learning (Howard and Howard, 2013) or a preference to attend to local (versus global) contextual information (Wlotko et al., 2012). Although a distinct possibility, this account does not explain why younger and older adults were equally confident when identifying the reliable and unreliable speaker in the debrief questionnaire, after they had been made aware of the speaker reliability manipulation. Alternately, older adults may have stronger predictive priors relative to young adults, derived from a lifetime of experience with reliable sources (Payne et al., 2012; Peelle, 2019). Strong priors may have generated cognitive inertia, preventing older adults from rapidly adapting to new information (Dagerman et al., 2006; Payne and Federmeier, 2018).

Finally, it is also possible that both young and older listeners generated lexical-semantic predictions rapidly and automatically, but younger listeners were better equipped to *inhibit* these predictions in the context of an unreliable speaker. Specifically, in the unreliable speaker context, younger listeners may have activated and then subsequently suppressed lexical-semantic predictions, which were unlikely to facilitate upcoming comprehension. In contrast, older adults may have failed to inhibit predictions rapidly enough to influence processing of critical words. This inhibition failure account (Hasher et al., 1991) could also explain why individual differences in cognitive control strongly predicted differences in speaker-specific adaptation. Notably, these differences are unlikely to result from conscious shifts in processing strategies, as the results of the post-test debrief indicated that young and older adult confidence in speaker reliability identification was approximately at chance. Instead, it is more likely that the availability of cognitive control modulated whether comprehenders could implicitly adjust their inherent or schematic lexical prediction strategies to meet global contextual information. In future studies, it will be important to distinguish the roles of implicit processing and inhibition in speaker-specific adaptation, including whether older adults show similar adaptation deficits in other linguistic domains (e.g., at the level of phonology or syntactic structures (Kaan and Chun, 2018; Norris et al., 2003)).

3.3. Examining age-related changes in cognitive control

Normative aging can alter the pattern of brain activity observed during the Stroop task (Langenecker et al., 2004; Milham et al., 2002). In addition to expected decreases in responsivity in typical frontal-parietal network regions (e.g., dorsolateral prefrontal cortex, superior parietal lobule, precuneus), older adults with reduced cognitive control exhibit broader activation of ventral visual and anterior inferior prefrontal cortices, likely indicating reduced ability to inhibit task-irrelevant information (Langenecker et al., 2004; Milham et al., 2002). These changes occur despite age-related increases in sensitivity of the prediction error detection hub in the anterior cingulate cortex (Cera et al., 2019; Milham et al., 2002). This pattern recapitulates a larger literature showing age-related variability in functional localization in conjunction with generalized de-differentiation of brain networks (Koen and Rugg, 2019; Tomasi and Volkow, 2012), and may provide a neural correlate to the aforementioned inhibition failure account for older adults with low cognitive control (cf. (Martin et al., 2020)).

Additionally, while Stroop task performance is a well-established measure of cognitive control, poorer performance in older adults is known to conflate response inhibition with generalized slowing (Bugg et al., 2007; Manard et al., 2014; Tam et al., 2015). Likewise, in addition to proposed age-related shifts from top-down to bottom-up processing, age-related reductions in the N400 are also tied to inefficient synaptic transmission (Dave et al., 2018a; Li et al., 2001) reduced processing speed (Caplan and Waters, 2005; Salthouse, 1996), and decline in auditory and visual acuity (for review, see (Payne and Silcox, 2019)). Mediation of age-related changes in speaker-specific adaptation by cognitive control may provide only an indirect explanation by reflecting common consequences of generalized slowing. Although we believe that this explanation is unlikely, given that similar correlations did not emerge for cognitive control and N400 amplitudes during filler sentences, this possibility should be tested directly in future research.

3.4. Conclusions

This study joins a growing body of experiments illustrating the importance of examining individual differences in cognitive resources when evaluating effects of context on language processing (Boudewyn et al., 2013; Boudewyn et al., 2015; Huettig and Janse, 2016; Nakano et al., 2010; Van Petten et al., 1997), especially in aging populations (Dave et al., 2018b; DeLong et al., 2012; Federmeier et al., 2002; Federmeier et al., 2010; Gunter et al., 1995; Janse and Jesse, 2014; Stites et al., 2013). The present findings demonstrate that both young and older adults can use information from the global communicative context to regulate anticipatory processing, but these effects depend on the availability of sufficient cognitive control. Critically, these results complement recent neuroimaging research by providing compelling neural evidence that local predictive processing can be conducted in parallel with domain-general processing. Importantly, the domain-general network interacts with the language network when establishing global reliability of predictive cues. Given the pragmatic value associated with assigning specific information to different speakers, maintenance of both domain-general and language network function is critical to sustaining comprehension across the lifespan.

4. Materials and methods

4.1. Participants

Data were collected from 40 young adults (29 females; mean age: 20.2; range: 18 to 26) and 40 older adults (26 females; mean age: 69.1 years; range: 60 to 80). All participants identified as native English speakers with normal or corrected-to-normal vision. All participants indicated via self-report that they had normal hearing, and did not require the use of corrective aids. Participants reported that they had no history of psychiatric or neurological disorders, neural trauma, or ongoing use of prescription medications for neurological conditions. Young and older adults provided written informed consent to a protocol approved by the Institutional Review Board at the University of California, Davis. Young adults were all undergraduate students who received course credit for study participation, while older adults were recruited broadly from Yolo and Sacramento counties in California and received payment for study participation. Data from five additional young adults and two additional older adults were excluded from analyses due to excessive artefacts in EEG recordings.

4.2. Experimental stimuli

During each session, participants listened to 330 sentences divided equally across two different speakers (165 sentences per speaker). The manipulation employed across these sentences was identical to that used in Brothers et al. (2019, which contains additional details regarding offline norming and sentence recording parameters).

Two sets of sentence trials were generated: filler trials and critical trials. Filler sentences were used to establish the reliability of each speaker. All filler trials had highly constraining contexts (e.g., *Jack forgot about the cookies baking in the…*). For the reliable speaker, filler sentences always ended with the highest predictability completion (e.g., *oven*), with an average expectancy of 95% (range: 80–100%). In contrast, for the unreliable speaker, filler sentences always ended with an unexpected but plausible completion (e.g., *house*), with an average expectancy of less than 1% (range: 0–6%). 202 filler trials were generated, with 101 presented during each session for each speaker.

Critical trials manipulated predictability of a sentence-medial critical word, and were used to assess whether the filler trials influenced the benefits of local contextual constraint on lexical processing. First, 128 words were selected as critical words. For each word, a constraining and non-constraining sentence context were generated, such that the critical word was either highly predictable (e.g., *In 1967, NASA wanted to land a man on the moon…*) or unexpected but plausible given the preceding context (e.g., *I had heard that they wanted to go to the moon…*) (predictable word cloze mean: 95%, range: 70–100%; unpredictable word cloze mean: <1%, range: 0–2%). A short continuation followed the critical word, such that each critical word was always sentence-medial (e.g., *…before the Russians did*). Of the 128 critical trials, 64 sentences (32 predictable, 32 unpredictable) were presented during each session for each speaker.

The cloze probabilities described above were obtained across three groups of 60 young adults (reported in Brothers et al., 2019). To assess whether these cloze probabilities would replicate in older adults, additional cloze norms were collected in 100 older adults (mean age: 64.7 years; range: 56 to 77; recruited and compensated via Amazon Mechanical Turk). The results of this norming study in older adults replicated the findings for young adults: For filler sentences, high cloze completions had an average expectancy of 94% (range: 78–100%), while unexpected completions had an average expectancy of 0.6% (range: 0–2%). For critical sentences, high cloze versus low cloze continuations had average cloze probabilities of 94% and 0.6%, respectively (predicable word cloze range: 72–100%; unpredictable word cloze range: 0–5%).

The experiment used a 2 × 2 within-subjects design, manipulating the predictability of each critical word (predictable, unpredictable) and the global reliability of each speaker (reliable, unreliable). Sentence materials were counterbalanced across 8 lists, which varied whether each critical word appeared in a constraining or non-constraining sentence context, whether each filler sentence was spoken by the reliable or unreliable speaker, and whether the male or female speaker was the reliable speaker. Critical and filler trials were pseudo-randomly intermixed in each session, with at least one filler sentence appearing between critical sentences.

In total, 165 sentences were presented for each speaker in a single experimental session. For sentences spoken by the reliable speaker, 133 of all filler and critical trials included a predictable continuation (i.e., 80.6% of trials included a highly predictable word given preceding context). For sentences spoken by the unreliable speaker, only 32 included a highly predictable continuation (i.e., 19.4% of trials). Trials were split evenly into 4 blocks. For half of the participants, blocks 1 and 4 were spoken by the reliable speaker and blocks 2 and 3 were spoken by the unreliable speaker. The reverse was true in the other half of participants.

4.3. Procedure

Participants wore over-ear Beyer dynamic headphones while electroencephalography (EEG) was recorded. Each trial was preceded by a centrally-presented fixation cross on a computer screen, followed by a 500ms delay. Following 25% of trials, participants provided button-press responses to a true/false comprehension question about the preceding sentence in order to ensure they were listening attentively. Participants were not informed of the speaker reliability manipulation, and they were only asked to listen attentively in order to answer comprehension questions. Prior to beginning the experiment, audio volume was individually adjusted for comfort and clarity.

Immediately after the EEG experiment, participants answered questions about their knowledge of the experimental manipulations. During this debriefing questionnaire, experimenters asked participants to describe what they believed to be the purpose of the study. Experimenters then explained the speaker reliability manipulation, and asked participants which speaker had been the “reliable” speaker and to rate their confidence in this judgment on a scale of 1 (no confidence) to 7 (high confidence).

After the listening comprehension study, participants performed an automated manual Stroop task (PsyToolKit (Stoet, 2017)). The Stroop task (Stroop, 1935) is a well-established measure of cognitive control. Participants were instructed to respond via button-press to the color, and not the meaning, of visually presented words. They were given a maximum of 2s to respond to each of 120 word trials. Word meaning and color were either congruous (e.g., RED printed in the color red) or incongruous (RED printed in the color blue). Performance was measured as the difference in response time for accurate responses to congruous versus incongruous trials (the Stroop interference effect). Stroop effects were within typical ranges for both young adults (mean = 150.2ms, SD = 103.9ms) and older adults (mean = 250.6ms, SD = 72.9ms) (MacLeod, 1991), with no significant difference in variance between age groups (Levene’s test for homogeneity: $F(1, 78) = 0.64$, $p = 0.43$). Split-half reliability was calculated by random reordering of test items, and resulted in a Spearman-Brown internal consistency estimate of 0.69. Stroop effects were significantly larger in older adults ($t(78) = 4.99$, $p < 0.001$), likely resulting from effects of aging on response times as well as specific reductions in cognitive control (e.g., modeled in (Bugg et al., 2007)). Stroop effect response times were normalized across all participants via Z-scoring for follow-up analyses.

4.4. EEG recording and pre-processing

While participants were seated in an electrically shielded and sound attenuated booth, EEG was recorded using SCAN (Compumedics Neuroscan), with subsequent processing and analysis performed using Matlab-R2020b (The MathWorks, Natick, MA) with EEGLAB toolbox and ERPlab plugins. EEG was recorded from 29 tin electrodes mounted in an elastic cap (ElectroCap International), with additional electrodes attached below and on the outer canthi of the eyes in order to capture blinks and other eye movements. All channels were initially referenced to an electrode placed over the right mastoid and re-referenced offline to the average of left and right mastoids.

Electrode impedances were kept below 5kΩ. The EEG signal was amplified with a Synamps Model 8050 Amplifier (bandpass cutoffs: 0.05 – 100Hz) and was continuously digitized at a sampling rate of 250Hz. After recording, independent components analysis was used to decompose EEG responses into subcomponents with fixed scalp distributions and independent time courses. Next, eye blink components were removed, and single-trial waveforms were screened for amplifier blocking, muscle artifacts, and horizontal eye movements (on average, <5% of trials in each condition were removed because of subject generated artefacts). Event-related potentials (ERPs) were generated for average EEG activity for reliable speaker filler trials and unreliable speaker filler trials. For critical trials, we calculated separate ERP averages as a function of contextual predictability (predictable, unpredictable) and speaker reliability (reliable, unreliable). Based on a previous study using the same paradigm (Brothers et al., 2019), we restricted our analyses to ERP responses in the N400 time-window (300–600ms) over central and posterior electrode sites (CP1, CP2, CZ, C3, C4, Pz, P3, P4, O1, O2, POz). For each participant, we calculated mean ERP amplitudes in each condition within this spatiotemporal region of interest. A 300–600ms time-window was used, rather than the 300–500ms time-window typically used in studies of reading comprehension, because the duration of the spoken word input is more variable, and thus the N400 maximum is reached at a later point in time (e.g., (Boudewyn et al., 2012b; Brothers et al., 2019)).

4.5. Analysis plan

All statistical analyses were performed and all plots were generated using R-4.0.2. For sentence endings in filler trials, we performed a 2 × 2 repeated-measures mixed-effects ANOVA (rANOVA) for predictability (within-subjects: high, low) × age (between-subjects: young, older).

For critical words in critical sentence trials, we performed 2 × 2 × 2 mixed-effects rANOVAs for predictability (within-subjects: high, low) × speaker reliability (within-subjects: reliable, unreliable) × age (between-subjects: young, older). We also conducted follow-up 2 × 2 (predictability × speaker reliability) within-subjects rANOVAS separated by each age group. All within-subjects rANOVAs are reported alongside partial eta squared for effect sizes.

All significant results in rANOVAs were followed up by t-tests with Bonferroni corrections (indicated as p_{corr}) with Cohen's d reported for effect sizes. For mediation analyses, we tested indirect effects using causal mediation analyses with nonparametric bootstrapping methods with 1,000 permuted estimates (Bollen and Stine, 1990; Tingley et al., 2014).

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Highlights:

- Older adults generate reduced N400s to local predictability manipulations
- Older adults show less flexible adaptation of N400s to variable global contexts
- Cognitive control mediates age-related reductions in global contextual adaptation
- But does not explain age-related changes in sentence context effects on the N400
- Prediction recruits distinct resources from domain-general processing

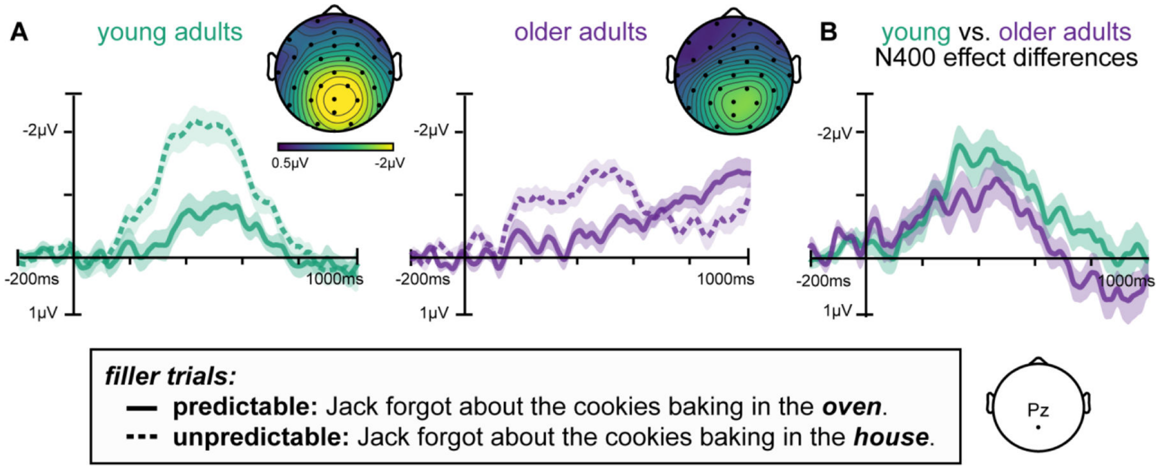

Figure 1. Age-related reductions in local predictability effects in filler sentences.

A. Grand-average event-related potentials to predictable and unpredictable sentence-final words in the filler sentences. Waveforms are plotted separately for young adults (green) and older adults (purple) at a representative midline posterior electrode site (Pz, displayed at bottom right), with shading indicating standard error from the group mean. Graphs are plotted alongside topographic distribution of the predictability effect (300–600ms), which showed the same typical centro-parietal distribution for young and older adults. **B**. Differences between ERP activity during unpredictable minus predictable critical words are plotted for both age groups. All ERPs were low-pass filtered at 10Hz for display purposes.

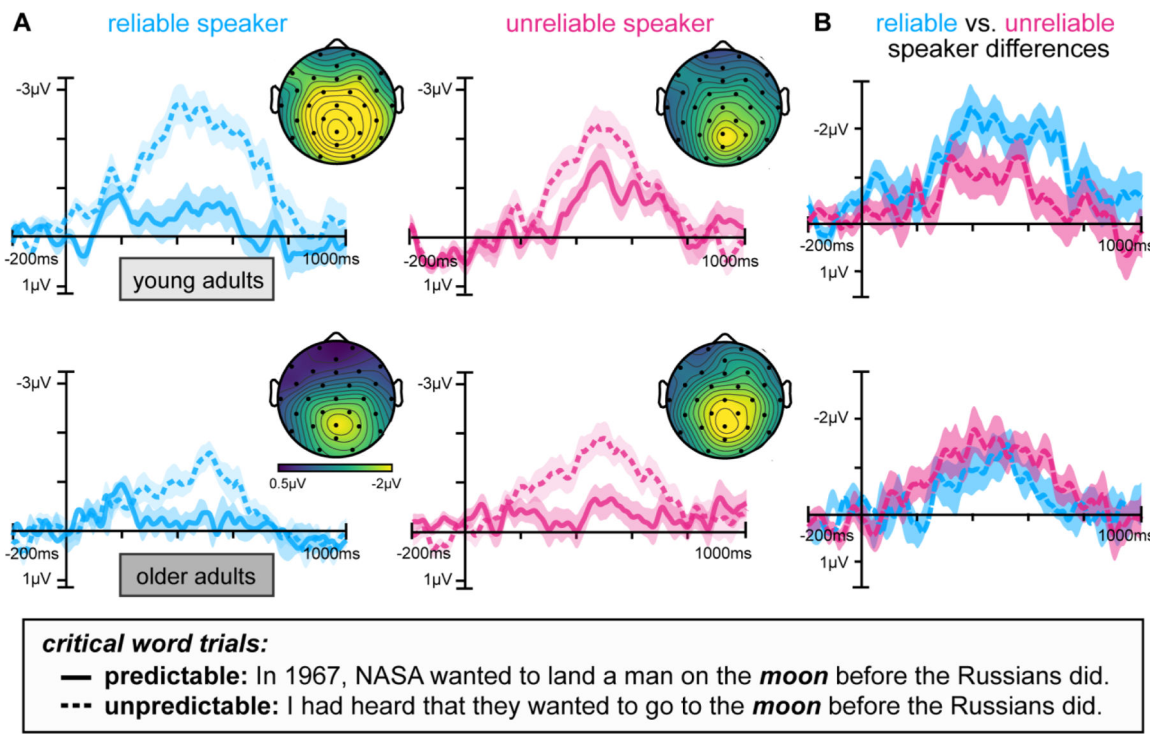

Figure 2. Effects of global context (speaker reliability) on sentence-level predictions in critical sentences.

A. Grand-average event-related potentials to predictable and unpredictable critical words for young adults (top) and older adults (bottom). Waveforms are plotted separately for sentences spoken by reliable (blue) and unreliable (pink) speakers at a representative electrode (Pz), with shading indicating standard error from the group mean. Graphs are plotted alongside the topographic distribution of differences between predictability conditions in the 300–600ms time window, which all show the typical centro-parietal effect distributions. **B**. Differences between ERP activity for unpredictable minus predictable critical words are plotted for both speaker conditions, separately for young and older study participants.

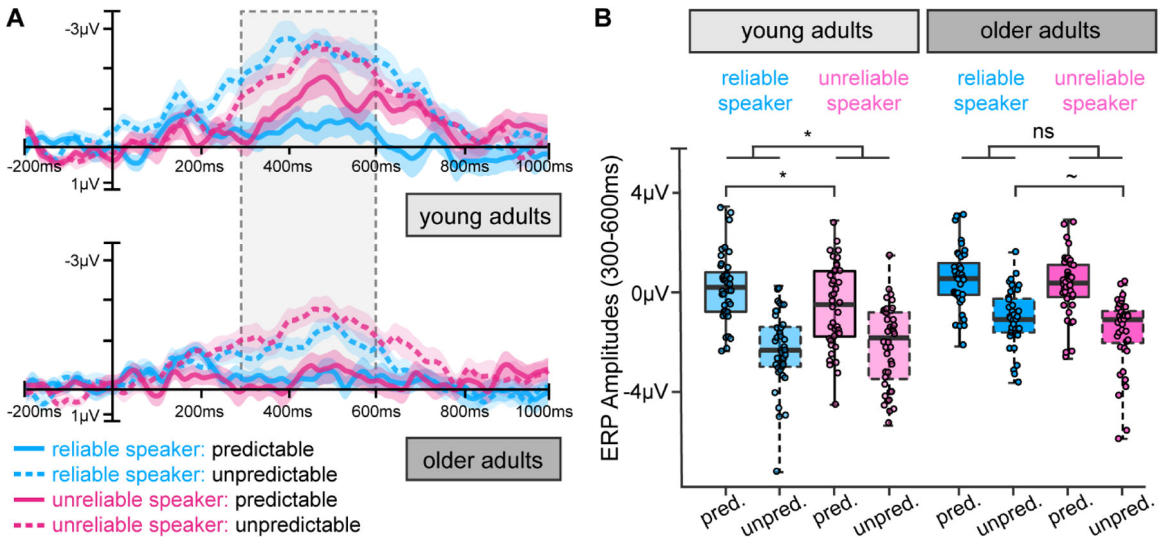

Figure 3. Age-related differences in speaker-specific adaptation effect in critical sentences.

A. Grand-average event-related potentials to critical words, plotted as a function of speaker reliability (reliable, unreliable) and predictability (predictable, unpredictable) for young and older adults. ERPs are plotted for a representative electrode, Pz, with shading indicating standard error from the group mean. **B**. Amplitudes for event-related potentials (in microvolts) plotted for the same conditions described in 3A. Amplitudes were averaged over a cluster of centro-posterior electrode sites that were used in all statistical analyses (see Methods) in the 300–600ms window indicated in grey in Figure 3A. Medians and 1^{st} and 3^{rd} quartiles are indicated with horizontal lines. For young adults, a significant interaction between speaker reliability and predictability was driven by modulation of the N400 amplitude in the related conditions; a reduced N400 was found to related words in the reliable speaker condition. There was no significant interaction in older adults. * $p < 0.05$, ~ $p = 0.07$

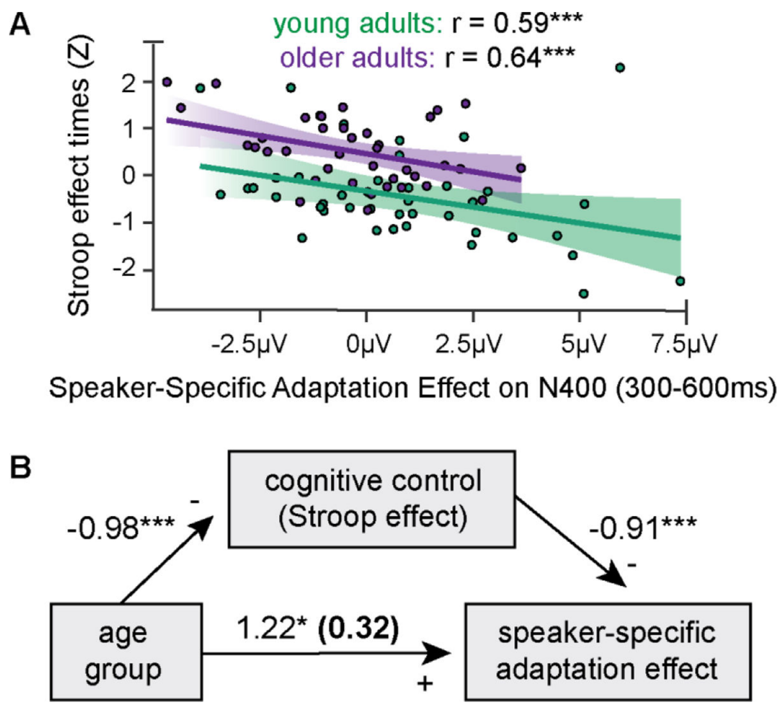

Figure 4. Cognitive control mediates age-related reductions in speaker-specific adaptation.

A. Speaker-specific adaptation effects on the N400 correlated with Stroop effect response times in both age groups. Positive values on the x-axis represent a larger N400 adaptation effect (i.e., we reversed the typical low-minus-high cloze N400 subtraction to ease figure interpretation). Negative z-values on the y-axis reflect smaller Stroop interference effects (i.e., better performance). For both age groups, greater adaptation effects correlated with better Stroop performance. Age-specific correlations are plotted with regression lines including confidence intervals. **B**. Speaker-specific adaptation effects were reduced in older adults, but cognitive control fully mediated these age-related deficits. Numerical values on connector lines in the model indicate the path coefficient between each pair of variables, displayed alongside +/− signs/arrows and asterisks indicating the direction and significance of each effect, respectively. The bolded numerical value indicates the non-significant direct effect of age group on speaker-specific adaptation after controlling for cognitive control. *** $p < 0.001$, * $p < 0.05$

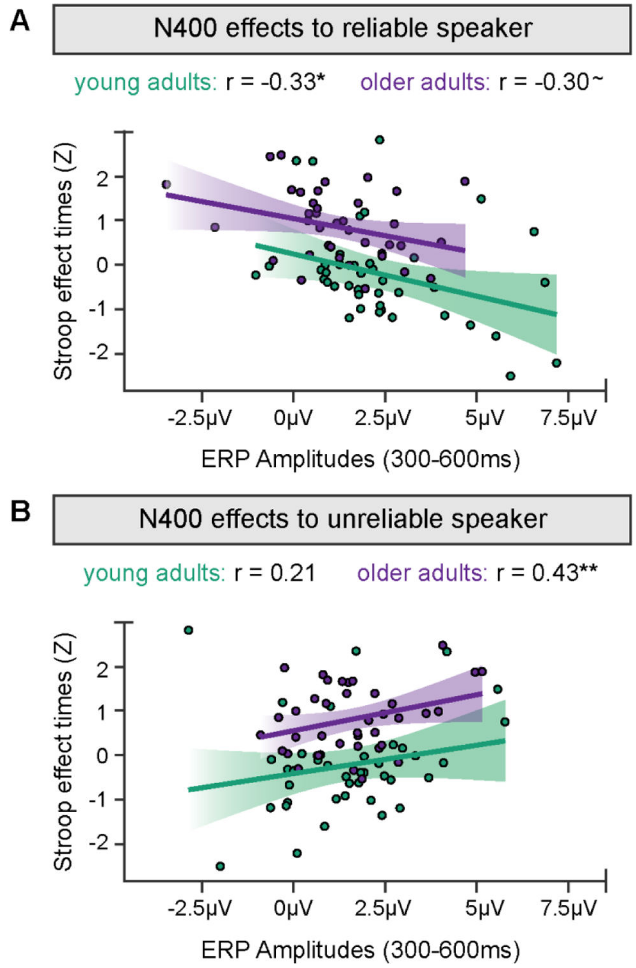

Figure 5. Cognitive control modulates processing of sentences spoken by the reliable speaker.
N400 effects on words spoken by the reliable speaker (**A**) and unreliable speaker (**B**) correlated with Stroop interference effects in both age groups. Cognitive control affected processing of sentences spoken by the reliable speaker in both age groups, and processing of sentences spoken by the unreliable speaker in older adults. Age-specific correlations are plotted with regression lines including confidence intervals. ** $p < 0.01$, * $p < 0.05$, ~ $p = 0.055$