## Title

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# Cognitive control and language ability contribute to online reading comprehension: Implications for older adult bilinguals

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## Abstract

**Aims:** Previous research has indicated that young adults form predictions for the meaning of upcoming words when contexts are highly constrained. This can lead to processing benefits when expectations are met, but also costs, as indicated by a late, frontally distributed and positive event-related potential (ERP), when an unexpected word is encountered. This effect has been associated with the conflict that arises for prediction errors, as well as attempts to suppress a previously formed prediction. However, individual differences have been found for young adult bilingual and older adult monolingual readers, whereby only those who exhibited better language regulation and executive function skill showed this pattern. The goal of the current study was to investigate how these executive functions influence comprehension skill and behavior for elderly bilinguals.

**Approach:** We asked whether older adult monolinguals and bilinguals were capable of generating predictions online, and whether cognitive control and language regulation ability were related to the magnitude of prediction costs.

**Data and Analysis:** Participants ($N = 27$) read sentences while their electroencephalogram was recorded, and completed a battery of language and cognitive performance tasks.

**Findings:** While older adult monolinguals showed some sensitivity to prediction error, older adult bilinguals produced greater prediction costs, an effect that was significantly correlated with both age and control ability.

**Originality:** This study is the first to show ERP evidence that bilinguals are capable of forming predictions during comprehension in older adulthood.

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The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Significance:** These results have important implications for the ways in which bilingualism may influence comprehension across the lifespan. While healthy aging has been proposed to lead to declines in executive function these declines may be mitigated for bilinguals, who have a wealth of experience in negotiating language-related conflict.

**Keywords**

Bilingualism; cognitive control; comprehension; aging; event-related potentials

## Introduction

A critical question in language science is whether experience in managing the use of multiple languages has an effect on cognition and neuroplasticity across the lifespan. Some have proposed that extended bilingual language experience has positive consequences for executive function and even health outcomes (Alladi et al., 2015; Bak, Vega-Mendoza, & Sorace, 2014; Gold, Kim, Johnson, Kryscio, & Smith, 2013). These effects are typically found in early development or later in life when older adults are undergoing cognitive decline (Baum & Titone, 2014; Bialystok, 2017). For young adults, however, results are often mixed, which some have taken as evidence that no positive consequences for bilingualism exist (de Bruin, Treccani, & Della Sala, 2015; García-Pentón, García, Costello, Duñabeitia, & Carreiras, 2016; Valian, 2015; but see Bialystok, Kroll, Green, MacWhinney, & Craik, 2015), or that they are only likely to occur under special circumstances (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009). In addition, the manner in which these changes in executive function might occur, and the degree to which this pertains to all bilinguals, is a topic of active debate.

The most detailed account of the consequences that bilingualism might have for cognition is the Adaptive Control Hypothesis (Abutalebi & Green, 2007; Green & Abutalebi, 2013). According to this hypothesis, the ways that bilinguals engage the two languages can impose differential demands on the executive function system and the neurocircuitry that supports it. This includes attending to the appropriate language in a conversational setting, monitoring for changes in speaker identity and potential language switching requirements, and continuously suppressing some or all of the language not in use. It is this last behavior, the suppression of the non-target language, which has been highlighted as being uniquely difficult for bilinguals (Van Assche, Duyck, & Gollan, 2013). However, without this ability, bilingual language production and comprehension would result in severe cross-language interference and multiple speech production and processing errors, which is not the case in daily bilingual language use. This suggests that bilinguals are adept at appropriately regulating the unintended language. Accordingly, language regulation is a potential locus for the positive consequences of bilingualism, where the ability to exercise control over language has been hypothesized to transfer to control in other domains.

### Executive control in comprehension

Most research on the consequences of bilingualism focuses on the recruitment of executive functions during production, but not comprehension.[1] Language comprehension is rife with opportunities for the employment of these cognitive skills, and multiple studies have shown that executive function ability, cognitive control in particular, predicts performance in online language comprehension, for both monolinguals and bilinguals. In a series of studies, Novick, Hussey, Teubner-Rhodes, Harbison, and Bunting (2014; Teubner-Rhodes et al., 2016) tested whether working memory and control ability predicted readers' ability to resolve syntactic ambiguities online. Their results showed that better inhibitory control predicted better comprehension, that bilinguals were more successful at performing a version of the control task that involved greater conflict, and that training in this task resulted in improved comprehension performance.

Whereas this previous work investigated how the use of control during comprehension may be common across monolinguals and bilinguals, others have turned to the unique nature of bilingual comprehension. When reading or listening, bilinguals are required to attend to the target language in question. However, the non-target language is also active (Van Hell & Tanner, 2012), and can influence processing of the target language at multiple stages. The most notable instance of this is the case of words that either share meaning and form across both languages (i.e., cognates) or share their form, but not their meaning (i.e., interlingual homographs). When cross-language overlap converges, as is the case for cognates, processing benefits occur. When there is cross-language divergence and conflict, as is the case for homographs, there are processing costs. However, during bilingual language use, parallel activation is constantly in flux. As a result, while the suppression of the non-target language is often regarded as the standard for successful production and comprehension (i.e., due to a reduction in cross-language interference), this may not necessarily be true in naturalistic settings. For example, a bilingual reader, who has successfully down-regulated the activation of the non-target language, may not experience much of a processing benefit when encountering cognates. Thus, while non-target language suppression can support target language processing in some respects, it can also reduce the cross-language benefits often available to bilinguals.

Pivneva, Mercier, and Titone (2014) investigated this interplay during a reading comprehension task that involved sentences with embedded French-English cognates (e.g., piano) and homographs (e.g., chat). They took into account whether bilinguals were high in proficiency, and therefore likely to have greater parallel activation, and their ability to suppress conflicting information, as indexed by their performance on multiple cognitive control measures. Bilinguals with greater cross-language proficiency experienced the greatest cognate benefits, while those with better control ability were less susceptible to homograph interference. These findings introduce an added level of complexity for bilingual comprehension: it is not only a matter of understanding the problem that cross-language competition presents, but also how bilinguals attempt to resolve that competition online. In particular, it is important to understand how an individual's language and cognitive profile may collectively contribute to baseline parallel language activation states and subsequent ability to regulate those states.

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[1] However, see work by Blumenfeld, Schroeder, Bobb, Freeman and Marian (2016) and Martín, Macizo, and Bajo (2010) for evidence that bilinguals are adept at utilizing inhibitory control during single word comprehension.

The approaches we have outlined are useful in highlighting what aspects of language experience are critical for bilingual comprehension, and can help further our understanding of how executive functions may be impacted by a lifetime of bilingual experience. When considering how bilingual comprehension might unfold and what repercussions it may have for long-term changes in cognitive ability, several key issues arise. Firstly, it is important to note the degree of parallel activation likely to be experienced during testing. This can take into account degree of proficiency or dominance, but also age of acquisition, immersion context, and, especially for older adults, the trajectory of language use and loss. Secondly, if cross-language interference is likely to occur, domain-general executive functions appear to be at play at multiple levels. At one level, the non-target language itself may be regulated, so that it does not unduly interfere with target language processing.[2] This regulatory ability can, in turn, be influenced by language dominance and the immersion context itself, as suppression of a less proficient or non-immersed language is likely to be less effortful. Finally, at another level, other features of the target language may require the recruitment of cognitive control, in a manner that should be experienced to some degree by any individual proficient in that language, regardless of their bilingual status. This could be a conflict experienced as a result of a syntactic ambiguity or the repercussion of other sentence processes, such as prediction.

## Prediction in comprehension

When reading or listening, comprehenders generate predictions for the meaning of upcoming words, especially in contexts that are highly semantically constraining. This process can produce processing benefits when a word with the expected meaning is encountered (Van Berkum, 2008). However, when expectations are not met, and a less expected word is presented, processing costs occur. This can be realized in the event-related potentials (ERPs) time-locked to the unexpected word, including a late, frontally distributed positivity. Peaking at around 500–800 milliseconds, this ERP effect has been related to the efforts that comprehenders undergo when plausible language input conflicts with a prediction that has been generated (e.g., DeLong, Groppe, Urbach, & Kutas, 2012; Federmeier, Wlotko, DeOchoa-Dewald, & Kutas, 2007; Federmeier et al., 2010). These costs could be due to attempts to update expectations for future reading (Kuperberg & Jaeger, 2016) or attempts to revise or suppress a mis-prediction that has come in conflict with a presented word.

Whether prediction error costs are the result of updating preferences for future prediction processes, the result of mediating conflict, or some combination thereof, it appears likely that cognitive control ability may support recovery from prediction error, and thus lead to attenuated ERP effects. This hypothesis was investigated in a recent study by Zirnstein, van Hell, and Kroll (in press), in which young adult monolinguals and bilinguals were asked to read sentences while their electroencephalogram (EEG) was recorded. The critical comparison (see Example 1) involved sentences of high semantic constraint with embedded target words that were either expected (i.e., <u>tip</u>) or unexpected (i.e., *ten*).

**1.** They paid for their meal, but forgot to leave a <u>tip</u>/*ten* for the waitress.

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[2] See Green (2017) for recent discussion about the potential limits of bilingual language suppression in the context of L2 use.

ERPs time-locked to these target words revealed an effect of unexpectedness in frontal electrode sites, such that less expected words elicited a larger frontally distributed positivity from 500 to 700 ms when compared to expected words. This pattern was found not only for young adult monolingual readers, but also for bilingual readers who had exhibited skill in regulating the non-target language. Specifically, young adult bilinguals in this study were reading in their less-dominant second language (L2), but were also immersed in an L2 context that required regulation of the first language (L1). Their ability to subsequently de-regulate and use the L1 was measured using a verbal fluency task. Previous research (Linck, Kroll, & Sunderman, 2009) has shown that these same immersion conditions can lead to a reduction in L1 verbal fluency, due to immersion-related difficulties with language regulation. Likewise, for the young adult bilinguals in the study by Zirnstein and colleagues (in press), better performance in L1 fluency (i.e., better language regulation) significantly predicted the magnitude of prediction error cost in the ERPs. Once such a prediction error had occurred, better performance on a domain-general executive control task subsequently mediated the magnitude of this cost, in both monolinguals and bilinguals.

These findings suggest that L2 prediction relies, at least in part, on the ability to free up cognitive resources by regulating the demands that parallel language activation imposes. Previous research with older adult monolinguals (Federmeier, Kutas, & Schul, 2010) also supports the idea that executive function ability, and perhaps the availability of cognitive resources, is key to understanding whether prediction is likely to occur in populations whose language processing is under constraint. In their study, only elderly monolinguals with better performance on a semantic category fluency task were capable of generating predictions and experiencing subsequent ERP costs due to unexpectedness. Although the ability to predict the meaning of upcoming words appears quite prevalent in the processing behavior of young adults, the ability to engage in the same, resource-demanding processing behaviors in older adulthood appears to rely heavily on executive functions that are known to decline with age (Brickman et al., 2005).

## Current study

The results from this prior work reveal two potential properties of comprehension that are highly relevant for bilinguals: (1) when processing in one language, regulating the parallel activation of the non-target language can support comprehension; and (2) once this is in place, aspects of executive function that support comprehension ability across both monolinguals and bilinguals can be observed. What is unknown is to what extent these behaviors might work in coordination to support comprehension for bilingual older adults. While monolingual older adults are less likely to engage in prediction processes (Wlotko & Federmeier, 2012; Wlotko, Federmeier, & Kutas, 2012), the persistence of other executive functions (i.e., verbal fluency) may be in place to support prediction generation (DeLong et al., 2012; Federmeier et al., 2010) in a manner that is not typical for the population at large. These findings are similar to what Zirnstein and colleagues (in press) found with younger adult bilinguals, suggesting a potential overlap between seemingly disparate language processing contexts.

Age-related cognitive decline appears to be an important factor in determining whether older adults engage in prediction strategies during reading. Some research has suggested that executive functioning, in particular inhibitory control ability, tends to decline with age (e.g., Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988), which supports the idea that older adult monolinguals may have difficulty supporting comprehension strategies that are highly resource demanding. However, very little is known about the neural changes that occur as a result of age-related cognitive decline (Burke & Graham, 2012), or how these changes may specifically be delayed as a result of multiple language use. As such, older adult bilinguals are an ideal group for testing the potential consequences of bilingualism for executive control and comprehension. The goal of the current study is to investigate how prediction processes might unfold for readers who have benefited from a lifetime of experience in regulating the use of more than one language.

## Methods

### Participants

Twenty-seven older adults (aged 61–83 years; M = 69.81, SD = 6.25; 16 female), with an average educational background of 16.89 years (SD = 2.61) participated in the study. Participants were recruited from the community in the wider Toronto area in Ontario, Canada, and were categorized as bilingual ($N = 12$) or monolingual ($N = 15$) according to their language background. Bilingual and monolingual groups were matched in age ($F(1,25) = .474$, $p = .498$) and education ($F(1,25) = .404$, $p = .531$). All participants were required to be highly proficient in English, right-handed, have corrected or corrected-to-normal vision, and have no prior history of neurological or reading disorders. They were compensated 16 Canadian dollars per hour for taking part in the study.

Participants completed the mini-mental state exam (MMSE; Folstein, Folstein, & McHugh, 1975), and scored 27 or higher (30 maximum) in order to be included in the study. Monolinguals and bilinguals did not differ in their scores (M = 28.96, SD = 1.16; $F(1,25) = .171$, $p = .682$). Participants also completed Raven's Progressive matrices (Raven, Raven, & Court, 2000), a measure of inductive reasoning, in order to estimate general cognitive functioning, which also did not differ between groups (M = 76.68%, SD = 11.85; $F(1,25) = .778$, $p = .387$).

Participants completed a language history questionnaire at the beginning of the study. On a scale of 1–7 (1 being very poor and 7 being very high), monolinguals rated their ability to read, write, speak, and comprehend their L1 (English) at an average of 6.73 (SD = 0.59), which was not different from how bilinguals rated their English ability (M = 6.81, SD = 0.44; $F(1,25) = .148$, $p = .704$). Bilingual participants reported knowing a wide range of languages or dialects other than English (range: 2–5, M = 3.42, SD = 1.24; including Cantonese, Dutch, French, German, Hokkien, Hindi/Urdu, Italian, Japanese, Malay, Polish, Sindhi, Sinhalese, Spanish, Ukrainian, and Yiddish). Self-reported proficiency in their most dominant language other than English (M = 4.85, SD = 2.40) was significantly lower than their English ratings ($t(11) = 2.917$, $p = .014$). In addition, while some reported knowledge of a third, fourth, and even fifth language, none were able to successfully complete the verbal fluency task for these other languages.

There was, accordingly, a great deal of diversity in the language backgrounds of the bilingual participants, which included English native speakers with advanced L2 experience (*N* = 3), balanced bilinguals (in terms of proficiency and use at time of testing; *N* = 6), and bilinguals whose dominance had shifted from their original L1 to their later-acquired, yet now more dominant L2 (*N* = 3). Although it is not within the scope of the current study to compare across these sub-types of the bilingual experience, it is important to note that all were included in the sample, and that our measures of language ability (i.e., verbal fluency) were designed to quantify the potential consequences of this variability.

## Materials

### Sentence stimuli.—

Materials consisted of 120 critical items and 40 filler sentences with low semantic constraint, all in English (see Zirnstein et al., in press, for a detailed description). Of the critical items, participants saw 40 high constraint sentences with expected target words, 40 high constraint sentences with unexpected target words, and 40 low constraint sentences with neutral target words. Sentence contexts were matched in length. Target words were embedded within the sentence and matched on length and frequency (SUBTLEXus; Brysbaert & New, 2009). Cloze probabilities (provided by 38 native English speakers who did not take part in the main study) significantly differed between the high and low constraint contexts (high: .68–1.00; low: .10–47). Mean association strength between targets and all content words in the context (Edinburgh Associative Thesaurus; Wilson, 1988) was kept at or below .01 for all conditions. All materials were constructed to avoid strong collocations between the target and words in prior context (e.g., “The man proposed to her by getting on bended… *knee*”). Two words prior to and following the targets were kept the same across conditions. Items and conditions were counter-balanced across lists.

### Cognitive task battery.—

Participants completed multiple tasks designed to assess individual differences in cognitive function, including a Semantic Category Verbal Fluency task (Luo, Luk, & Bialystok, 2010; Rohrer, Wixted, Salmon, & Butters, 1995), an Operation Span task (Turner & Engle, 1989; Unsworth, Heitz, Schrock, & Engle, 2005), and the distractor version of the AX Continuous Performance task (AX-CPT; Braver et al., 2001).

In the fluency task, participants viewed four semantic categories in each proficient language (English for monolinguals; English and one other language for bilinguals), and named as many tokens as possible within 30 seconds for each category. The total number of correct tokens was used as the performance score for this task.

In the Operation Span task, participants viewed randomized trials that included sets of paired simple mathematical equations and letters. Sets could increase from three to seven. For each paired math question and letter, participants first saw the equation, clicked a mouse, and then saw a number with a true or false button. They were asked to indicate whether the number matched the solution to the previous equation. Following this, a letter appeared. The participants’ goal was to memorize the series of letters in the set, in the correct order, while continuing to solve math problems, and to recall the series of letters at the end of the set.

The total number of correctly recalled letters, across all sets, was used as the performance measure for this task.

In the AX-CPT, participants viewed 10 practice and 100 critical trials. In each trial, a series of five letters was presented, one at a time, at the center of the screen, starting with a red-letter cue, followed by three white-letter distractors, and ending with a red-letter probe. Participants were asked to press one button in response to every letter, but to change their response at the end of the sequence if the two red letters (the cue and probe) were A followed by X. AX trials took up 70% of the total trials, while three other cue-probe conditions took one third of the remaining 30% (AY, BX, and BY). AY trials were designed to be difficult if participants were highly expecting an X probe, thus resulting in longer reaction times (RTs) and more errors to the Y probe. BX trials were intended to tax participants who failed to maintain the goal of the task, and thus took longer to reject or mistakenly accepted the X probe. Control BY trials reflected performance when neither the cue nor the probe was manipulated.

## Procedure

Participants came in to the lab for two sessions. In the first session, they completed the language history questionnaire, MMSE, and reading task (during which their EEG was recorded). In the second session, they completed the cognitive task battery.

**Reading task.—**Participants were tested individually in a room separate from the experimenter. Sentence stimuli were presented on a computer screen approximately 100 cm from the participant, using E-prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Participants were instructed to relax and restrict motor movement and muscle tension while the sentences were being displayed. At the start of each trial, a blank screen appeared for 1000 ms, followed by a fixation cross and each word in the sentence, which were presented via rapid serial visual presentation (RSVP), with a 400 ms presentation duration and 200 ms inter-stimulus interval (ISI) blank screen. After the final word, a blank screen was presented for 750 ms. After each sentence, a prompt appeared, either instructing the participant to press a button to continue, or with a true or false statement about the prior sentence.

**EEG recording and data analysis.—**Continuous EEG was recorded from 64 active Ag/AgCl electrodes (Biosemi Active Two system, Amsterdam, the Netherlands), with a sampling rate of 512 Hz and at a bandwidth of .01–100 Hz, while referenced to the common mode sense (CMS) electrode, and with the driven right leg (DRL) electrode acting as the common ground. Six additional electrodes were placed on the left and right mastoids (for later off-line algebraic re-referencing), as well as on the outer canthi of each eye and above and below the left eye. Impedances were kept below 20 kΩ.

EEG pre-processing was conducted in EEGLAB (Delorme & Makeig, 2004) and ERPLAB (erpinfo.org/erplab) toolboxes for MATLAB. Prior to off-line averaging, all single trial waveforms were screened for amplifier blocking, muscle artifacts, horizontal eye movements, and blinks across 1200 ms epochs starting 200 ms before the onset of the critical target words. For nine participants, blink artifacts were corrected in the continuous

EEG using Infomax ICA decomposition in EEGLAB. EEG was re-referenced off-line to the average of the left and right mastoids. One thousand millisecond epochs were extracted at the onset of critical words, with 200 ms pre-stimulus baselines. Grand average ERPs were filtered (0.1–25 Hz), and statistical analyses were conducted on these data.

Repeated measures analyses of variance (ANOVAs) were conducted on a subset of electrodes ($N = 15$) to compare within-participant factors of Unexpectedness (Expected, Unexpected), Anteriority (Frontal, Central, Posterior), and Electrode (with 5 levels), along with a between-participants factor of group (monolingual, bilingual). Electrode subsets were determined a priori, with five electrode sites for frontal (F3, Fz, F4, FC1, and FC2), central (C3, Cz, C4, CP1, and CP2), and posterior regions (P3, Pz, P4, O1, and O2). Analyses were conducted on the mean amplitude across three time windows of interest: 300–500, 500–700, and 700–900 ms. Planned contrasts were conducted on the high constraint sentence conditions containing expected or unexpected target words.[3] Greenhouse–Geisser corrected $p$-values were used for all analyses with more than 2 degrees of freedom in the numerator.

## Results and discussion

Below, we report the results for ERPs and the behavioral task battery, with language groups compared to one another, followed by individual difference analyses within each language group separately. For group comparisons within task, monolingual and bilingual performance appeared to be very similar. However, when differences in age, verbal fluency, working memory, and cognitive control ability are taken into account, we observed distinct effects of bilingualism on comprehension.

### ERPs

No significant interactions with group (monolingual versus bilingual) were found in the ERP analyses. The following results, therefore, focus on effects of Unexpectedness (high constraint expected versus high constraint unexpected), Anteriority (frontal, central, posterior electrode regions), and electrode (with five levels within each region). As can be seen in Figure 1, older adults exhibited a frontally distributed positivity in response to unexpected words. The onset of this effect was earlier than anticipated (around 350 ms), and the effect lasted throughout the epoch in some channels (e.g., Fz).

**Three hundred to five hundred.—**There was a significant interaction between Unexpectedness and Anteriority ($F(2,50) = 11.488$, $p < .001$), as well as an interaction between Unexpectedness and Electrode ($F(4,100) = 3.435$, $p = .021$). Follow-up analyses were conducted on each electrode region separately (frontal, central, and posterior), but no significant effects were found for these independent regions. Interactions with Unexpectedness were primarily driven by changes in polarity across electrode regions from a small positivity in frontal sites to a negativity in posterior sites (see Figure 2).

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[3] Analyses were also conducted to establish the effect of Constraint (high versus low, with expected versus neutral targets), which indicated significant effects in the 300–500 window (main effect of Constraint ($F(1,26) = 9.916$, $p = .004$); and Constraint by Electrode interaction ($F(4,104) = 3.156$, $p = .025$)), with neutral targets producing a larger and more centro-posterior N400 effect than expected targets (see Figure 1).

#### Five hundred to seven hundred.—

We expected to see an effect of Unexpectedness if older adult participants had been engaging in prediction processes and subsequently experienced difficulty with prediction error. There was indeed an interaction between Unexpectedness and Anteriority in this time window ($F(2,50) = 10.113$, $p = .002$). A subsequent main effect of Unexpectedness was observed for the frontal region ($F(1,25) = 4.529$, $p = .043$), while no effects were found independently for the central or posterior regions. Figure 2 shows the magnitude of this frontally distributed positivity in response to unexpected words. Although no group interactions were observed, the magnitude of these prediction error costs may have been driven by bilinguals.

#### Seven hundred to nine hundred.—

Previous work on prediction error ERP costs has sometimes indicated a delayed effect in later time windows, especially for bilingual readers (e.g., Zirnstein et al., in press). We observed a significant interaction in this late time window between Unexpectedness and Anteriority ($F(2,50) = 5.216$, $p = .009$). A main effect of Unexpectedness was found for the frontal region ($F(1,25) = 4.940$, $p = .036$), while no effects were found in the central or posterior regions. Prediction error costs in this late time window appear to be a continuation of the frontal positivity observed from 500 to 700 ms (see Figure 2).

### Cognitive tasks

#### Semantic category fluency.—

Monolinguals and bilinguals performed similarly on the verbal fluency task when naming words in English ($F(1,25) = .067$, $p = .798$), with monolinguals producing 45.87 tokens on average (SD = 8.30) and bilinguals producing 44.83 (SD = 12.44). This is likely a reflection of the English-supporting immersion context in which participants had been living for many years, as well as the impact this context had on bilinguals' language dominance. Bilingual participants also completed the task with a separate set of semantic categories in the language they were most fluent in other than English. Performance in this language was lower (M = 34.42, SD = 22.89), but also more variable than for English (difference between languages: M = 20.42, SD = 18.55), and was therefore not significantly different ($t(11) = 1.945$, $p = .078$). English fluency was taken as a measure of proficiency in the immersed language, while fluency in the other language was taken as a measure of continued bilingual language maintenance and use.

#### Operation span.—

Bilingual participants (M = 51.58, SD = 15.36) outperformed monolinguals (M = 42.13, SD = 16.52) in the total number of letters correctly recalled on the span task. However, this varied widely among participants, and was not significant in a group comparison ($F(1,25) = 2.320$, $p = .140$).

#### AX-CPT.—

A repeated measures ANOVA was conducted to assess the degree to which the within-participants factor of condition (AY, BX, and BY) interacted with group (monolingual, bilingual), for both RTs to correct trials and proportion of errors. While no significant interactions with group were found ($F$s $< 1.00$, $p$s $> .05$), there was a significant effect of condition for both RTs ($F(2,48) = 50.891$, $p < .001$) and errors ($F(2,48) = 5.152$, $p = .009$). Planned contrasts (comparing conditions AY and BX to the control condition BY) revealed a significant effect for AY in both RTs ($F(1,24) = 53.215$, $p < .001$) and errors

($F(1,24) = 15.810$, $p = .001$), as well as a significant effect for BX RTs ($F(1,24) = 5.765$, p = .024) and errors ($F(1,24) = 9.264$, $p = .006$). While the AY condition was the most difficult in terms of RT, the BX condition produced more errors (see Figures 3 and 4).

An additional analysis was performed to determine whether monolinguals and bilinguals may have differed in the strategies they used when approaching task rules. Some participants may have biased themselves toward maintaining the goal of the task (preparing for X probes, following A cues), resulting in longer RTs and more errors to AY trials. Other participants, however, may have attempted to balance their attention toward the task goal and the possibility of needing to inhibit responses. Previous researchers have calculated this bias, or Behavioral Shift Index (BSI; Paxton, Barch, Storandt, & Braver, 2006), using the following formula: (AY – BX) / (AY + BX). We calculated BSI composite scores (with $z$-scored RTs and errors). A more positive score on this index implies an over-reliance on goal maintenance, with subsequent difficulty inhibiting responses in AY trials. Values closer to zero imply a more balanced approach between maintaining the task goal and correctly inhibiting incorrect responses. Both monolinguals (M = .21, SD = 2.03) and bilinguals (M = .74, SD = 3.36) exhibited BSI indices above zero, but did not differ significantly from one another ($F(1,25) = .257$, $p = .617$).

**Correlations between ERP effects and cognitive performance.—**A clear finding from the ERP analyses is that older adults appear to be quite successful at engaging in prediction processes during online reading, at least enough to experience subsequent costs when those predictions are not verified. This finding is somewhat in conflict with results from previous studies (DeLong et al., 2012; Federmeier et al., 2010), which have found these effects only for older adult monolinguals with higher executive function ability (i.e., verbal fluency). Group differences in our study, however, were not observed either in the ERP analyses or in the individual analyses for verbal fluency, working memory, or performance on the AX-CPT. Despite this, the magnitude of the frontal positivity seen in the grand average waveforms (Figure 1), and the subtle trend for bilingual older adults to show a larger effect in this region from 500 to 700 ms (see Figure 2), suggests that a more complex pattern between bilingual status and reading strategy may be at play. We therefore conducted a series of correlational analyses to assess the relationship between age and cognitive ability, and the magnitude of prediction error costs in the ERP results.

For monolinguals, age, English verbal fluency, and performance on the AX-CPT (as indexed by the BSI) did not significantly correlate with the magnitude of prediction error cost, in any time window or electrode region. Working memory performance did correlate with the effect of Unexpectedness, but only in the 700–900 ms time window and only in posterior electrodes ($r = .460$, $p = .042$). Working memory ability may have determined the extent to which elderly monolinguals were capable of maintaining previously generated predictions over time (i.e., as new words in the sentence were presented), thus leading to greater prediction error costs.

For bilinguals, however, two prominent effects were revealed. Firstly, age significantly and negatively correlated with the magnitude of prediction error costs in frontal electrode sites in the 300–500 ($r = -.562$, $p = .029$) and 500–700 ms time windows ($r = -.543$, $p =$

.034). As age increased, the magnitude of prediction error costs decreased. The presence of this ERP effect, although technically a cost, is also an indication that readers were able to generate predictions during online comprehension, an ability that appears to decline more dramatically with age for elderly bilinguals, in comparison to monolinguals. Secondly, for bilinguals, a more balanced approach to the AX-CPT (leading to a BSI closer to zero) was associated with prediction error costs in frontal electrode sites that appeared earlier (from 300 to 500 ms: $r = -.506$, $p = .047$) and remained longer (from 700 to 900 ms: $r = -.508$, $p = .046$) in the ERP record than the typical 500–700 ms effect. Based on this finding, it is quite likely that elderly bilinguals with balanced cognitive control strategies drove the frontal positivity in the grand average ERPs to appear earlier and last longer than has been previously demonstrated in any published study of lexical prediction.

Together, these findings suggest that a younger group of older adult bilinguals were the most likely to engage in prediction during online comprehension. Older adult monolinguals, in contrast, did not show the same age benefit, and were only likely to have engaged in prediction if their working memory ability was sufficiently high. Bilinguals also showed evidence for the recruitment of executive control during comprehension in a way that monolinguals did not. Bilinguals who more strategically approached the executive control task experienced prediction error costs across a much longer time course than we expected. It is unclear whether the ability to balance between goal maintenance and inhibition in the executive control task is what drove older adult bilinguals to generate predictions in the first place, or whether it instead only determined the time course of prediction error costs in the ERPs. Regardless, these results indicate that older adult bilinguals are capable of engaging in prediction processes successfully during reading.

## General discussion

The current study provides the first evidence that older adult bilinguals can engage in the highly resource-demanding task of predicting during online comprehension. The relationship between executive functions hypothesized to decline due to healthy aging, namely working memory and cognitive control, and online prediction was not only complex, but also patterned somewhat differently between language groups. Whereas declines in working memory led to similar declines in prediction capability for monolinguals, bilinguals instead appeared to be more broadly capable of generating predictions. However, in the older age range, these qualitative group differences were not present. More research is needed to identify the exact mechanisms driving these findings, but this study suggests they are related to the ways that comprehension and executive function change throughout the aging process, which may be quite different for monolinguals and bilinguals.

Notably, the prediction effects observed in the current study mirror similar anticipatory processes found in perception for habitual code-switchers (e.g., Fricke, Kroll, & Dussias, 2016). While the current findings were isolated in the neurophysiological performance of a highly diverse group of elderly bilinguals, future work will need to establish a more direct link between the lifespan trajectory of bilingual language experience, including code-switching behaviors, and how this impacts the relationship between comprehension and executive function in older adulthood. In particular, it will be important to investigate the potential relationship between the cross-language anticipation of language or code-switches and within-language anticipatory processes, such as the prediction of specific words or meanings.

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Judith Kroll is a Distinguished Professor of Psychology at the University of California, Riverside, and Professor Emeritus of Psychology, Linguistics, and Women's Studies at The Pennsylvania State University. The research that she and her students conduct concerns the way that bilinguals juggle the presence of two languages in one mind and brain. Their work shows that bilingualism provides a tool for revealing the interplay between language and cognition that is otherwise obscure in speakers of one language alone. For more information, see https://bilingualismmindbrain.com/

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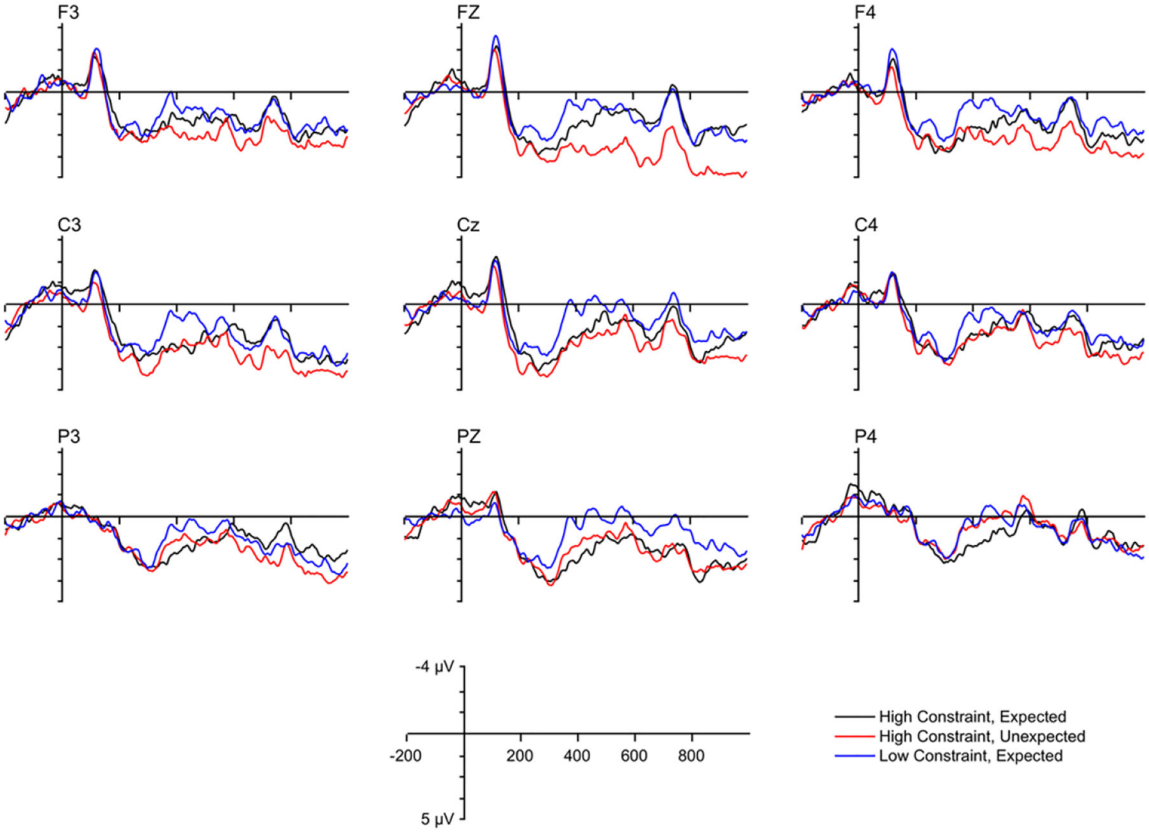

**Figure 1.**

Grand average event-related potential waveforms for the effect of Unexpectedness and Constraint, across nine representative electrodes.

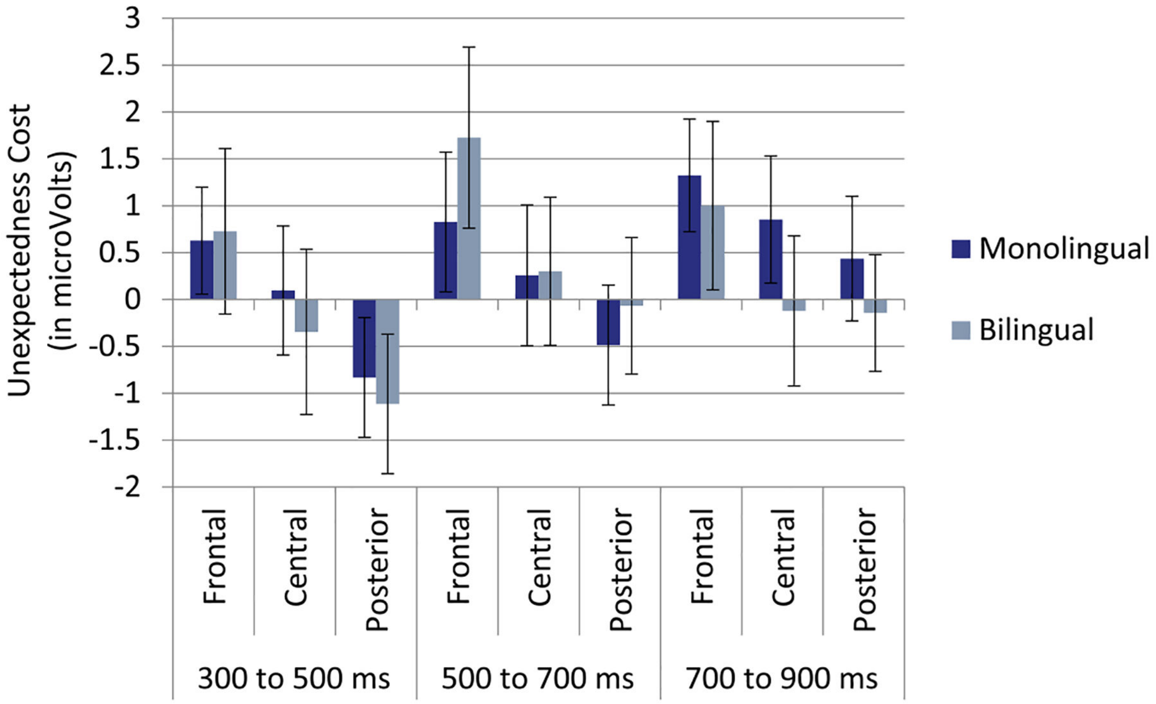

**Figure 2.**

Magnitude of the effect of Unexpectedness for monolinguals and bilinguals across all time windows and electrode regions.

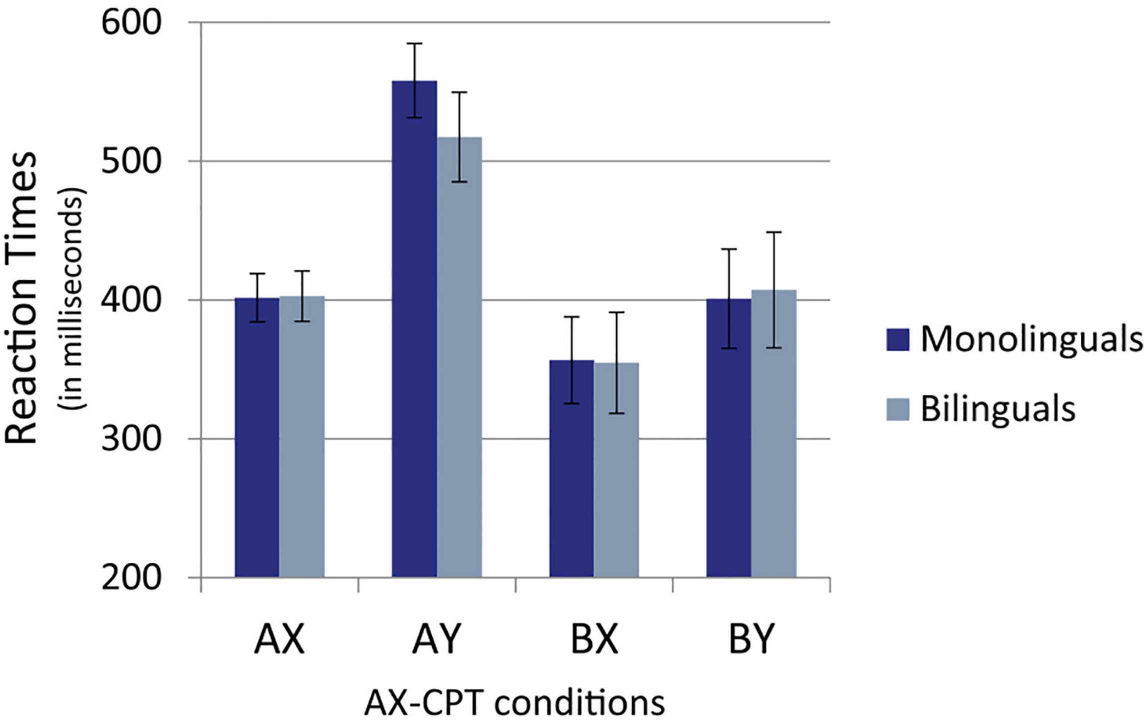

**Figure 3.**

Mean reaction time performance in milliseconds on the AX Continuous Performance task (AX-CPT).

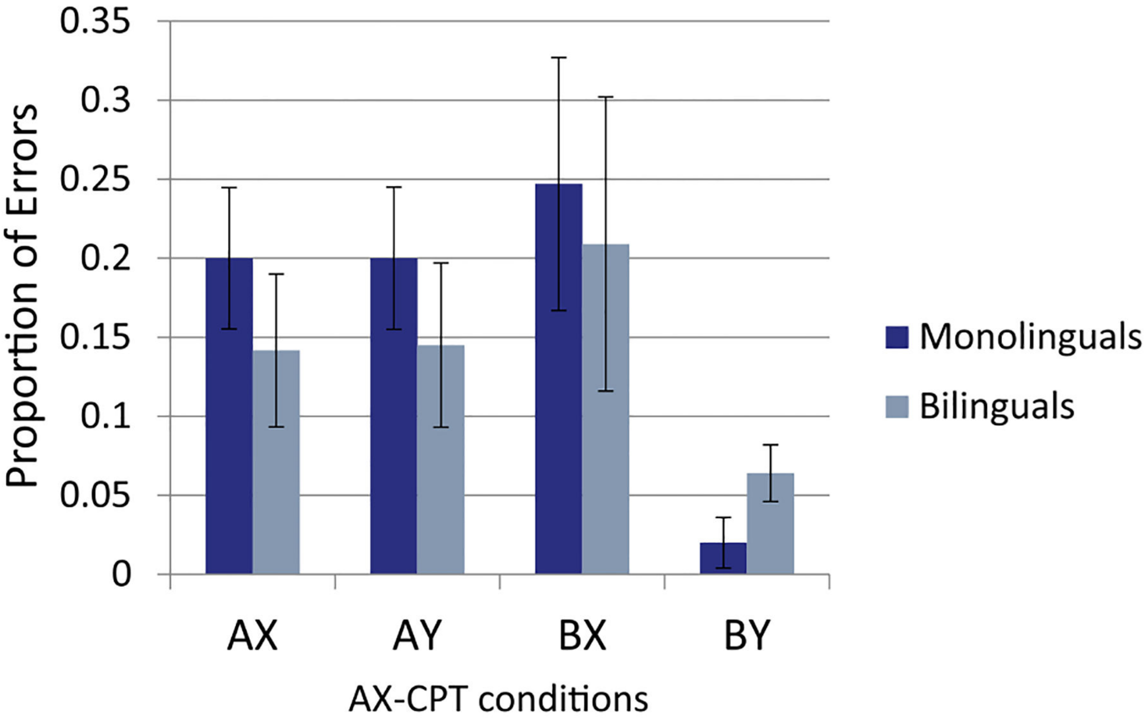

**Figure 4.**
Mean proportion of errors on the AX Continuous Performance task (AX-CPT).