Published in final edited form as:
Cognition. 2018 July ; 176: 87–106. doi:10.1016/j.cognition.2018.03.001.

Cognitive Control Ability Mediates Prediction Costs in Monolinguals and Bilinguals

Megan Zirnstein[1], **Janet G. van Hell**[2], and **Judith F. Kroll**[1,2]

[1]Department of Psychology, University of California, Riverside

[2]Center for Language Science, Department of Psychology, Pennsylvania State University

Abstract

In this study, we examined the role that cognitive control and language regulation ability play in mediating readers' susceptibility to prediction error costs when reading in the native language (L1) or a second language (L2). Twenty-four English monolinguals (Experiment 1) and 28 Chinese-English bilinguals (Experiment 2) read sentences in English while their EEG was recorded. The sentences varied in the predictability of an upcoming expected word and in whether that prediction was confirmed. Monolinguals showed sensitivity to sentence contexts in which expectations were not met (i.e., when unexpected words were encountered) in the form of a late, frontally-distributed positivity, but for bilinguals this effect was more complex. For both groups, performance on the prediction task was modulated by individual differences on the AX-CPT, a measure of inhibitory control. However, the bilinguals' reading performance in the L2 was affected not only by inhibitory control, but also by their performance on an L1 verbal fluency task that indexed language regulation and production capability, related to their language dominance and immersion context. Bilinguals with better regulation of the L1 generated a larger frontal positivity in response to unexpected words in the L2, an effect that was attenuated by inhibitory control ability. In contrast, bilinguals with lower regulatory ability generated a larger, late negativity, which was also mediated by control. These findings suggest that the ability to regulate the native language when immersed in a second language environment can influence mechanisms underlying the prediction process when reading in the L2. In addition, cognitive control ability, specifically inhibitory control, appears to mediate the difficulty readers incur when predictions are disconfirmed, not only in the native language, but also for proficient bilinguals reading in the L2. We argue that the mechanisms engaged during prediction in the L1 and L2 are fundamentally the same, and that what differs for bilinguals are the additional demands imposed by their language experience and language use.

Keywords

prediction; cognitive control; bilingualism; verbal fluency; language regulation

---

Address Correspondence to: Megan Zirnstein, Department of Psychology, 900 University Ave., University of California, Riverside, Riverside, CA 92521, megan.zirnstein@ucr.edu.

Introduction

Prediction errors, and their neurological and behavioral repercussions, have been the focus of recent research across multiple cognitive domains, including attention, perception, action, learning, social motivation, and decision-making (for reviews, see Bubic, von Cramon, & Schubotz, 2010; Den Ouden, Kok, & de Lange, 2012). Prediction itself has been proposed to be a hallmark of the human cognitive experience, especially the ability to efficiently adapt when conflicts or errors arise to contradict an individual's expectations. Prediction errors can take many forms, and their magnitude often depends upon how frequently errors have occurred, how rewarding it is to adapt to these errors, and whether an individual is personally motivated to do so. An additional concern is whether it is likely that predictions have been generated and how strong those predictions may be, as any error experienced as a result of a disconfirmed prediction should be proportionate to the strength of the prediction that had previously been formed. In this paper, we present evidence from two experiments in the language domain that attempt to elucidate aspects of prediction that are common across multiple cognitive domains: (1) when predictions are likely to be generated, and (2) what mechanism(s) may attenuate prediction errors and potentially contribute to later adaptation. We do this by utilizing two groups of readers: monolinguals reading in their native language (L1) and bilinguals reading in their highly proficient, but second language (L2).

Prediction in Language Processing

In the language domain, readers and listeners use contextual information to generate expectations about the meaning of upcoming words, an effect that has been demonstrated quite extensively in both sentence and discourse processing (see Federmeier, 2007; Van Berkum, 2008, for reviews). For example, sentences like (1) that are more highly semantically constraining tend to result in processing benefits for high cloze or expected target words (e.g., disease) when compared to sentences like (2) that are less semantically constraining.

(1) The woman was born with a rare *disease*.

(2) The woman had discovered a rare *disease*.

This benefit is often indexed by a reduction in the amplitude of the N400 event-related potential (ERP), which is widely regarded as an electrophysiological index of lexico-semantic activation (Federmeier & Kutas, 1999; Kutas & Hillyard, 1984; Van Berkum, Hagoort, & Brown, 1999; Van Petten, 1993; for a review, see Swaab, Ledoux, Camblin, & Boudewyn, 2011). Previous research has suggested that these effects are the result of readers being able to take advantage of the highly constraining context in such a way that semantic features of the expected target word were active before it was actually encountered in the sentence. However, it can be difficult to disentangle whether modulation of the N400 ERP effect is due to prior prediction, later lexical access and/or semantic integration, or some combination of these processes (except in cases where these EEG effects are tied to situations in which prediction is likely to have occurred, e.g., Brothers, Swaab, & Traxler, 2015, or when these effects manifest in prior discourse, e.g., van Berkum, 2012).

In addition to these processing benefits, several studies have also reported that readers incur costs when the predictions that they have generated are not verified later in the sentence (e.g., DeLong, Groppe, Urbach, & Kutas, 2012; Federmeier, McLennan, De Ochoa, & Kutas, 2002; 2007; 2010). In contrast to sentences like (1), comprehenders who encounter sentences like (3) tend to generate a larger, frontally-distributed positivity between 500 and 900 milliseconds after the onset of an unexpected, though plausible, target word (i.e., *gift*).

(3) The woman was born with a rare *gift*.

Importantly, this late, frontally-distributed positivity is an effect that typically manifests in cases where plausible violations of a prediction have occurred, making it a useful index of the repercussions of prediction processes. In the language domain, it has largely been found in work involving the processing of unexpected words in highly predictable or constraining contexts (e.g., with jokes; Coulson & Wu, 2005), and is often interpreted as a repercussion of comprehenders having to revise or suppress a previously generated prediction (e.g., Federmeier et al., 2007; or discourse representation, e.g., Brothers, Swaab, & Traxler, 2015). The ability to predict upcoming words and to quickly recover when predictions are disconfirmed (i.e., to adapt quickly to a situation where a meaningful conflict occurs) could, therefore, result in a reduction in processing load and free up cognitive resources for other tasks. A question that remains, then, is to what extent constraints on cognitive resources may affect prediction generation and recovery. One way to further examine this is to investigate possible changes in the prediction process when readers are engaged in a highly resource-demanding task, such as reading in the L2. Contexts that increase cognitive demand in language processing are also likely to affect the prediction process. As such, we might expect that reading and predicting in an L2 will mimic the same processes when individuals read under conditions with increased cognitive load.

Prediction in a Second Language

Bilinguals may provide a unique opportunity for understanding the way cognitive resources are engaged during online processing. When bilinguals read or speak in one of their languages, the language not in use is also active (e.g., Van Hell & Tanner, 2012). As a result, information from the non-target language often affects performance (especially in the L2; see Kroll & Dussias, 2013). This can involve cross-language conflict (e.g., with interlingual homographs or homophones, and for competing syntactic parsing preferences) or overlap, when the two languages converge in a manner that supports processing (e.g., with cognate words or parsing preferences shared across both languages). Efficiently regulating this cross-language activation, to allow for appropriate cross-language support and suppress irrelevant cross-language interference, is a necessary part of successful communication and comprehension for bilinguals. Due to these constraints, highly proficient L2 comprehension may provide a unique opportunity for understanding how cognitive resources are engaged during online prediction, in a way that may not as easily be revealed through the very skilled, native reading of monolinguals.

Several studies have now shown that young adults are capable of rapidly forming expectations when reading or listening for comprehension in their native language. If the ability to predict the meaning of upcoming words is a hallmark of skilled comprehension in young adulthood, then predicting in the L2 may be a natural part of attaining high L2 proficiency. To our knowledge, only a few published studies have investigated prediction during L2 comprehension (Foucart, Martin, Moreno, & Costa, 2014; Foucart et al., 2015; Kaan, Kirkham, & Wijnen, 2016; Martin et al., 2013; but see the following for work on the effect of contextual constraint on L2 sentence processes: Lagrou et al., 2013; Schwartz & Kroll, 2006; Titone et al., 2011; Van Assche et al., 2011; Van Hell & De Groot, 2008). Martin and colleagues (2013) had Spanish-English bilinguals (reading in the L2, English) and English monolinguals read highly semantically constraining sentences with either expected or unexpected sentence-final nouns. For example, in (4), *singer* is expected and *artist* is unexpected. This in turn changes the expectancy of the preceding article, with “a” being more expected because it would precede *singer*, and “an” being less expected because it would precede *artist*, at least for readers who are actively predicting the expected word.

(4) She has a nice voice and always wanted to be (a *singer*/an *artist*).

The authors aimed to identify effects of prediction or prediction costs prior to the expected or unexpected target word. For monolinguals, as expected, N400 responses to the article preceding an unexpected noun were larger than for the article preceding the expected noun, suggesting that native readers were predicting not only the meaning of the final word, but also its orthographic form (i.e., whether it began with a vowel or a consonant). Monolinguals also produced a larger frontal positivity to the articles preceding the unexpected nouns, reflecting early difficulty with encountering a prediction error. This effect was not found for bilinguals, however, who only showed a larger N400 effect for unexpected words. Based on these results, the authors suggested that L2 processing may occur too slowly in the L2 (Frenck-Mestre & Pynte, 1997) for predictions to either be generated or for preactivation to occur rapidly enough for prediction costs to be incurred. However, the L2 readers in this study were still capable of taking advantage of semantic information in prior context (leading to changes in N400 amplitude for expected and unexpected nouns), suggesting a reasonably high level of L2 proficiency.

Bilinguals may be less likely or less able to engage in language processing in the L2 on par with native speakers of that language (Clahsen & Felser, 2006), possibly due to the constraints and/or cognitive demands that L2 processing imposes (Hasegawa, Carpenter, & Just, 2002; McDonald, 2006). Based on the results from the study by Martin and colleagues (2013), this may also be the case for semantic prediction in the L2. However, a recent ERP study demonstrated that, when bilinguals’ two languages are more closely related (e.g., for Spanish and French), both early and late acquirers of an L2 are capable of anticipating upcoming words (Foucart et al., 2014). In this study, Spanish monolinguals, early Spanish-Catalan bilinguals, and late French-Spanish bilinguals read highly constraining sentences in Spanish that either had an expected or unexpected target word embedded later in the sentence. As a critical distinction from Martin et al. (2013), target words differed in their gender, such that the gender marking of a preceding article either matched or did not match the expected word. Surprisingly, for the bilinguals as well as the monolinguals, larger N400 effects were elicited on the preceding article when the gender did not match the expected word, and both N400 and frontal positive effects were elicited for unexpected targets. Taken together, the data from these past studies indicate variability in whether bilingual, L2 readers are likely to exhibit ERP effects related to the anticipation of upcoming language input. In particular, it seems that the elicitation of the frontal positivity in response to a prediction error may depend strongly on the nature of the manipulation of expectedness in each study (i.e., whether successful prediction relies on semantic or syntactic knowledge; see Kaan et al., 2016), and the relationship between a bilingual reader's L1 and L2.

In this and other work, it is often assumed that the absence of the frontal positive effect indicates that prediction did not occur. Indeed, it has been argued that prediction itself is not a necessary tool for comprehension (Huettig & Mani, 2016; but see Hintz, Meyer, & Huettig, 2016, for evidence that prediction can aid comprehension), as readers and listeners can instead opt for a less resource-demanding strategy, such as passively waiting to integrate upcoming words as they are presented. However, some readers may be more successful than others in overcoming the difficulty associated with encountering a prediction error. If the magnitude of the frontal positive effect is not only a repercussion of having predicted language input, but also reflects cognitive efforts related to resolving conflict between a previously generated prediction and the word actually encountered (e.g., Federmeier, Kutas, & Schul, 2010; DeLong et al., 2012), then an absence of such an effect could indicate greater success in mediating that conflict. Readers who are capable of quickly and ably resolving this type of conflict may, then, reduce cognitive load and make resources available for other processes, such as continuing to anticipate upcoming input. This process could be especially helpful during language processing, especially for bilingual L2 readers, but also during tasks in other cognitive domains that draw upon prediction processes.

There is now a wealth of research on bilingualism showing that the experience associated with acquiring and attaining proficiency in the L2 may in large part rely on an individual's ability to mediate language-related conflict (see Baum & Titone, 2014, and Bialystok, Craik, & Luk, 2012, for reviews). Bilinguals have been shown to be quite successful in regulating cross-language activation when one of their two languages competes for selection or similarly interferes with production or comprehension (see Kroll & Dussias, 2013, for a review). This is thought to be a natural consequence of the, at least momentary, parallel activation of a bilingual's two languages at all levels of language processing (e.g., van Hell & Tanner, 2012), be it lexical access, word production, or selecting amongst competing syntactic structures. Several studies now suggest that a lifetime of experience with regulating cross-language interactions can incur changes in cognitive control ability for elderly bilinguals who are undergoing cognitive decline (Bak, Nissan, Allerhand, & Deary, 2014; Gold, Kim, Johnson, Kryscio, & Smith, 2013). The potential influence of bilingual language regulation on domain general cognitive control, however, appears to occur over a long timecourse. What is much less understood is how the regulation of a bilingual's two languages and their current domain general cognitive control ability can be utilized in coordination to support comprehension online. In young adult bilinguals, who have yet to engage in decades of language use and regulation, it may be possible to reveal an interaction between domain general executive function and language experience or skill when engaged in the demanding task of reading and predicting in the L2 (and see Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009, for evidence that cognitive benefits for young adult bilinguals on executive function tasks may be more likely to be seen under conditions that impose demands on cognitive resources).

Current Study

Both prediction and L2 comprehension may be sufficiently cognitively demanding as to reveal a more complex relationship between executive function skill and language processing ability than would typically be observed in standard comprehension paradigms. The goal of the current study was to test the degree to which cognitive control ability, specifically inhibitory control, mediates the costs associated with prediction errors in native as well as proficient, non-native reading.

For bilinguals, the ability to overcome prediction error may not only rely on inhibitory control, but also on the ability to regulate cross-language activation. When it comes to tasks performed in the less dominant L2, bilinguals often have to exert great effort to regulate the activation of the more dominant L1. Recent studies of bilingual production have shown that, to plan speech in the L2, even highly proficient bilinguals appear to modulate the more dominant L1 (e.g., Meuter & Allport, 1999; Misra, Guo, Bobb, & Kroll, 2012; Van Assche, Duyck, & Gollan, 2013). In these types of tasks, participants are first asked to speak in the less dominant L2. When the L1 is spoken following the L2, participants experience difficulty with speech planning in correspondence with the degree of L1 inhibition that had occurred during the previous L2 block. This occurs even after an extended opportunity to use the L1, and shows difficulty with regulating the demands of both languages and efficiently de-regulating the L1 when appropriate. This is reflected in both the amount of verbal output and in the presence of an increased N200 component in the ERP record in the later L1 block that requires de-regulation. These effects are, surprisingly, evident even during very short language-switching tasks in an experimental setting.

While the previous example demonstrates how bilinguals are called to regulate cross-language activation in an experimental setting, similar effects are also found naturalistically. Studies of immersion in an L2 context (such as at a university or during travel to another country) reveal a similar reduction in the accessibility of the L1 (e.g., Baus, Costa, & Carreiras, 2013; Linck, Kroll, & Sunderman, 2009) that may reflect the adaptation of the native language to the increased exposure and usage of the L2. Linck and colleagues found that L2 learners who were immersed in the L2 in a study abroad program produced fewer exemplars in the L1 in a semantic verbal fluency task than learners restricted to classroom study in their home environment. At the same time, the immersed learners produced more exemplars in the L2 than the classroom learners. These immersion data and the previous experimental data both demonstrate the interplay between environmentally-induced down-regulation of the dominant L1, the concurrent increase in activation and accessibility of the less dominant L2, and later repercussions for these changes, such as difficulty with de-regulating the L1, either due to task shifts or L2 immersion. Although complex, all of these behaviors are critical for examining L2 processing performance in bilinguals.

It is important to note that parallel language activation for bilinguals can lead to both benefits and costs. Depending upon the relative activation of each language, cross-language convergence and divergence can lead to varying degrees of processing support or interference. The goal for a bilingual comprehender is to strike a balance in language co-activation that is most optimal for the current situation, and shift or regulate that balance when circumstances call for such a change. Rather than viewing bilingual language regulation as merely the suppression or inhibition of the unintended language, it may instead be viewed as a more complex coordination of executive functions necessary to shift language co-activation to more appropriately suit the processing environment. The notion that language regulation may be partially independent from domain general inhibitory control has recently been tested by Prior and colleagues (2017; but see Giezen, Blumenfeld, Shook, Marian, & Emmorey, 2015). In their study, different script bilinguals were given language processing tasks that tapped in to this language regulatory process, for example by inducing cross-language interference, as well as domain general tasks of inhibitory control. The authors found no relationship between the management of cross-language interactions and domain general inhibition, suggesting that these mechanisms may be partially independent from one another.[1] Thus, while bilingual language regulation may recruit domain-general suppression or inhibition skill, conceptually this skilled behavior (and therefore any task that can be argued to successfully tap into this process) reflects the ability to coordinate multiple cognitive control processes, rather than skill on a single dimension of cognitive control. Language regulation, and its relationship to domain-general inhibitory control, can therefore be viewed as partially, but not wholly overlapping.

One of the goals of the current study is to investigate the degree to which prediction in the L2 is influenced both by L2 ability and this regulatory process that bilinguals must undergo in order to comprehend input in one of their languages. Due to the complex relationship between regulation and proficiency in bilingual language use, we utilized a semantic category, verbal fluency task to assess language proficiency and regulatory ability. In this type of task, participants must produce exemplars in a pre-determined semantic category under a time limit, thus taxing both an individual’s vocabulary as well as their ability to maintain task demands by not repeating items and only naming items appropriately within category boundaries. As we have discussed previously, for bilinguals naming items in one language, while currently immersed in an environment that supports another language, regulation is required for successful performance to occur. Thus, fluency tasks can tap both proficiency in a language, as well as a bilingual’s ability to regulate their languages. In the current study, bilinguals were asked to name items in the L2, while currently immersed in an L2 environment. Having already down-regulated the dominant L1 to accommodate the L2 in their daily life, L2 verbal fluency is more likely to reflect relative proficiency in the L2, as no change or shift in activation is required between an L2 immersion context and a verbal fluency task in the same language. In contrast, while fluency performance in the L1 will also reflect whether bilinguals have maintained proficiency in their first and dominant language (e.g., L1 fluency should always be greater than that for the L2 in an L1-dominant bilingual group), the modulation of L1 verbal fluency is more likely to indicate how successful bilingual speakers were at appropriately up-regulating activation of the L1 in a task that requires such a shift. This change in relative activation has previously been demonstrated to be most effortful when in an environment that encourages and supports active use of the L2.[2]

---

[1] However, as we discussed previously, the relationship between domain general inhibition and bilingual regulatory skill may shift across the lifespan, as has been suggested by multiple studies of language and cognitive skill for elderly bilinguals (Bak et al., 2014; Gold et al., 2013).

[2] It is important to note that the Chinese-English bilingual participants recruited in this study may be more likely than other bilingual and cultural groups to maintain their L1 dominance in such a strong L2 immersion environment. This has repercussions for how the

Although the regulation of the L1 and L2 for bilinguals draws upon an individual's ability to flexibly dis-inhibit when appropriate, a host of executive functions are employed to achieve this skilled behavior, including selective attention, conflict-monitoring, and task-switching. However, there is no current and comprehensive characterization of how these executive functions are engaged in coordination to successfully regulate between two or more languages. One theory, the Adaptive Control Hypothesis, proposes that linguistic and social environments can differentially impose demands on these executive or control mechanisms for bilingual speakers (e.g., see Green & Abutalebi, 2013, specifically with respect to the relationship between language- and code-switching and their repercussions for the neural underpinnings of the cognitive control network). While the controlled use and regulation of a bilingual's languages may draw upon multiple domain-general cognitive control mechanisms in order to support online language processing, we attempt to articulate the partially independent contributions of these skills by distinguishing between (1) this regulatory process for the native and dominant language and (2) the more domain-general mechanism of inhibitory control that may characterize prediction error recovery across multiple cognitive domains and, therefore, in monolingual and bilingual speakers alike. Prior research (e.g., Hsu & Novick, 2016; Pivneva, Mercier, & Titone, 2014; Prior et al., 2017; Teubner-Rhodes, et al., 2016), has suggested partially independent contributions of these two factors during online bilingual reading, especially in the L2. Although bilingual language use has been hypothesized to draw upon a broad range of domain general cognitive processes, the ability to recruit these processes in coordination to support online bilingual language use, and domain-general skill on one subdomain of cognitive control (i.e., inhibition) may be more distinct. This further highlights the need to account for both bilingual language skill and cognitive control ability when modeling the performance of bilingual readers and speakers.

In the present study, we had monolingual, native speakers of English (Experiment 1) and bilingual, non-native, but highly proficient speakers of English (i.e., Chinese-English bilinguals; Experiment 2) read sentences in English while their EEG was recorded. Sentence contexts varied in their semantic constraint, and we compared ERPs time-locked to expected or unexpected target words embedded within these sentences. Our goals were to investigate individual differences in how non-native readers engage in prediction processes, and to look at changes in cognitive control ability and its influence on costs associated with prediction error. Several previous studies have utilized linear and multiple regression techniques to assess individual variability in ERP effects at the sentence and discourse level (see Boudewyn, Long, & Swaab, 2012; 2013; Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Federmeier, Kutas, & Schul, 2010; Laszlo & Federmeier, 2011; Nakano, Saron, & Swaab, 2010). Of particular note is a study by Federmeier and colleagues (2010; see also DeLong et al., 2012), in which native language verbal fluency performance was shown to significantly predict whether older adult monolinguals experienced difficulty with prediction errors in the form of a frontally-distributed positive ERP response. Those older adults who produced a greater number of tokens in a semantic category fluency task patterned with young adults

---

L1 fluency task can be utilized to measure language regulation in bilinguals. Bilingual populations that are more likely to engage in code-switching, who are not able to maintain L1 dominance in an L2 immersion context, or who are in other immersion environments, may not demonstrate the same characteristics on this fluency measure.

and generated a frontal positivity, while those who performed more poorly on the task (i.e., produced fewer tokens) did not. For older adults, better performance on this type of fluency task relies on proficiency, but also the ability to regulate task demands, which has been shown to decline with age (Clark, et al., 2009). This suggests that, when constraints are imposed on native language processing, even as a result of the natural aging process, L1 fluency may be a strong predictor in determining whether readers have sufficient resources necessary to overcome those constraints and generate predictions online. As L1 fluency performance for bilinguals in an L2 immersion context may also reflect regulatory skill, young adult bilinguals who outperform their peers on this type of task may also be more likely to demonstrate sensitivity to prediction error. Therefore, a second aim of the present experiments was to investigate how cognitive control (measured by an executive function task) and language regulation and L2 proficiency (measured by verbal fluency in the L1 and the L2, respectively) interactively contribute to the magnitude of prediction costs.

Based on previous work on L1 and L2 prediction, we expected that both monolinguals and bilinguals would exhibit evidence for prediction benefits in the form of a reduced N400 effect for expected target words in highly semantically constraining contexts, and that prediction costs would be evident in the form of a frontal positivity after the onset of an unexpected target word in the same context, at least for monolinguals reading in their native language. For bilinguals reading in their L2, we hypothesized that only those bilinguals with better proficiency in the L2 (i.e., higher L2 verbal fluency) would likely be able to generate predictions while reading in the L2 and, therefore, exhibit prediction costs in the form of the previously mentioned frontal positivity.

However, to what extent may these costs be attenuated in either group? Previous work on native reading has tied cognitive control and reading ability to successful sentence or discourse comprehension (see Boudewyn, Gordon, Long, Polse, & Swaab, 2012; Camblin, Gordon, & Swaab, 2007; Gernsbacher, 1996, 1997). Work by Gernsbacher and colleagues (Gernsbacher & Faust, 1991; Gernsbacher, Varner, & Faust, 1990), for example, has shown that skilled readers tend to more successfully suppress irrelevant contextual information during discourse processing (such as suppressing the irrelevant concept of an *ace* when reading the sentence *I dug with a spade*). It is possible, then, that the effort related to encountering a prediction error may be related to this type of suppression mechanism in comprehension. We therefore expect cognitive control ability, specifically inhibitory control (as assessed by the AX-CPT), to predict the magnitude of the frontal positive effect for monolinguals in Experiment 1. If, in Experiment 2, bilinguals with high L2 proficiency also generate a frontal positive effect, we expect to find a similar pattern. Specifically, for those bilinguals with better L2 proficiency, high domain-general inhibitory control ability should virtually eliminate prediction costs, as would be evident in a reduced frontal positive effect. An open question is whether regulation of cross-language activation, as indexed by L1 verbal fluency (for L1-dominant bilinguals in an L2 immersion context), will play a role in determining the presence of prediction costs in the L2.

A further question is whether L2 proficiency or language regulation skill in the L1 will more consistently reflect bilingual readers' ability to generate predictions online during L2 reading. While previous work with older adult monolinguals naturally only tested fluency performance in one language, bilingual readers are fluent in at least two languages. In addition, as noted above, performance on fluency tasks, for older adults and for bilinguals in certain language environments, can reflect more domain-general executive function skill, as better performance reflects successful regulation of task demands and goal maintenance (Henry, Crawford, & Phillips, 2004; Sandoval, Gollan, Ferreira, & Salmon, 2010), as well as the ability to regulate language co-activation if one is bilingual. For young adult bilinguals, L1 fluency performance may reflect regulatory skill that is necessary for successfully predicting upcoming words in the L2.

We expect that both L1 and L2 fluency performance may significantly impact bilingual readers' recovery from prediction error, but in different ways. If proficiency in the language being read is a strong indicator that a reader is likely to generate online predictions, then L2 proficiency, as indexed by the L2 fluency task, should interact with inhibitory control ability to impact the magnitude of prediction costs. If, however, the ability to effectively regulate the dominant, non-immersed language is the best indicator of successful L2 prediction, then bilinguals' fluency performance in their dominant L1, when bilingual participants must successfully de-regulate the non-immersed and more dominant language, should interact with control ability to impact L2 prediction costs.[3] Based on these predictions we set out to test the interaction between cognitive control ability and L1 and L2 fluency separately for our bilingual readers in Experiment 2. As we will see across Experiments 1 and 2, while inhibitory control ability may consistently mediate prediction error costs across L1 and L2 contexts, bilinguals may also require additional regulatory skill in order to successfully engage in L2 prediction. Perhaps counterintuitively, bilingual language regulation may lead to greater prediction error processing costs, while inhibitory control ability may subsequently reduce them.

Experiment 1: English Monolinguals

Method

Participants—Twenty-four monolingual speakers of English (15 female) with a mean age of 21.92 years (*SD* = 3.75) participated in this experiment. Twenty participants reported having some experience with a second language, with very low self-reported proficiency (*M* = 3.14, *SD* = 1.17; on a scale from 1 = no proficiency, to 10 = high proficiency) and no more than two years of experience with said language. All participants were right-handed, had normal to corrected-to-normal vision, and reported no prior history of neurological or reading disorders. Participants were given informed consent and compensated $10 or one course credit per hour for taking part in the study.

Sentence Materials—Sentence stimuli consisted of 120 critical sentences and 40 filler sentences (see Table 1 for examples). Of the 120 critical sentences, 40 were manipulated to be highly semantically constraining with an expected target word (High Constraint,

---

[3] This hypothesis assumes that greater L1 fluency should reflect better L1 de-regulation and, therefore, better bilingual cross-language regulatory ability. However, greater L1 fluency may instead reflect the presence of more non-target language interference during L2 reading. As such, L1 fluency and the magnitude of prediction costs could be positively or negatively correlated. The direction of this effect will indicate which process underlies successful L2 prediction: more cross-language regulation (positive correlation) or less non-target language interference (negative correlation).

Expected), 40 were highly constraining with an unexpected but plausible target word (High Constraint, Unexpected), and the remaining 40 were designed to be of low semantic constraint for the same target word as in the first condition (Low Constraint, Neutral). At minimum, two words prior to and following the target word remained constant across all conditions. In order to preserve an even distribution of high and low contextual constraint across all items, the 40 filler sentences were all low in semantic constraint (e.g., “He realized that he needed a plan in order to make a living”). Sentences were presented in three counterbalanced lists. Sentence condition was rotated across lists, so that each participant only viewed one version of each sentence. Each list consisted of 8 trial blocks, with 20 pseudo-randomized trials per block (5 trials per critical condition, 5 filler sentences).

Sentence stems (i.e., the portion of the sentence leading up to, but not including the target word) were, on average, 8 words long in both the high and low constraint conditions, and were normed for cloze probability by 38 native, English-speaking participants who did not participate in the main study. For cloze norming, stimuli were divided into two lists of 120 sentence stems (half high constraint and half low constraint, with condition counter-balanced across lists). Seventeen participants viewed each list and were asked to provide the best possible one-word ending for each sentence stem. High constraint sentence stems had a cloze probability of .92 for the expected completion (i.e., the expected target), with a range of .68 to 1.00. Low constraint sentence stems had a cloze probability of .29 for the best completion (i.e., any word most frequently provided in the norming responses, with a range of .10 to .47). As such, there was no overlap in cloze probability between high and low constraint conditions, and our cloze probability values matched those used in prior studies of sentential constraint and prediction (e.g., Federmeier et al., 2007).

Expected and unexpected target words were matched in length ($M = 4$ letters, in each condition). Lexical frequency of the targets was assessed using the SUBTLEXus database (Brysbaert & New, 2009). Expected targets were overall less frequent ($M = 131.22$, $SD = 286.89$) than unexpected targets ($M = 167.58$, $SD = 322.05$), but this difference was not statistically significant ($F(1,239) = 0.85$, $MSE = 93011.91$, $p = .36$). As our goal was to avoid cases in which expected target words were significantly more frequent than unexpected target words, and the difference in frequency was in opposite direction to this, we did not expect even this non-significant difference to adversely affect interpretation of our data.

We also assessed the association strength between the expected and unexpected target words using the Edinburgh Associative Thesaurus (the MRC Psycholinguistic Database; Wilson, 1988). Ninety-seven percent of the target words were in the database, and of those stimuli, mean association strength between conditions was .01 ($SD = .03$, *maximum* = .19). We also calculated average association strength between the target words and all content words in the sentence stems for the three critical conditions (i.e., expected targets and high constraint stems, neutral targets and low constraint stems, and unexpected targets and high constraint stems). There were very few associations between targets and prior content words, with only 8.33% of the expected targets having an associate of .2 or above in the high constraint condition (other conditions were at 0%). Mean association strength between targets and prior content words was at or below .01 for all three conditions.

Procedure—Participants completed a sentence reading task, in addition to a battery of individual difference measures,[4] including the AX-CPT and several language proficiency measures. For present purposes, we focus on individual performance on the AX-CPT, a continuous performance task that encapsulates effects of reactive inhibition within the context of proactive goal maintenance, processes that mimic how executive function has been hypothesized to operate in sentence or discourse comprehension (Gernsbacher & Faust, 1991; Gernsbacher et al., 1990).[5]

Verbal Fluency Task: A verbal category fluency task was administered to participants in English. In this task, participants were asked to produce as many words (or tokens) as possible that applied to a specific semantic category within a 30 second time limit (e.g., Luo, Luk, & Bialystok, 2010; Rohrer, Wixted, Salmon, & Butters, 1995; see Linck, et al., 2009, for evidence that a 30 second response interval is sufficient to detect differences in group performance). Four semantic categories were presented. Two of the four categories were animate, while the remaining two were inanimate. Order of presentation for all categories was randomized. At the beginning of the task, participants had the opportunity to practice producing tokens for one semantic category that was unrelated to the main task categories (i.e., tools). All participant responses were recorded for later transcription and coding.

Reading Task: Participants were tested individually in a sound-attenuating, electrically-shielded booth. 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). At the start of a trial, a blank screen appeared for 1000 ms, followed by a fixation cross and then each word in the sentence, presented one at a time (also in the center of the screen) via rapid serial visual presentation (RSVP). The fixation cross and each subsequent word were each presented for 400 ms, followed by a 200 ms inter-stimulus interval (ISI) blank screen. After the last word in the sentence, there was a 750 ms blank screen, after which a prompt appeared. This prompt was either a true or false statement based on the previous sentence or a prompt to continue to the next item. Each prompt or statement remained on screen until the participant responded. Participants were asked to respond to the true or false statements using an E-prime response box, with the leftmost button indicating that the statement was true, and the rightmost button indicating that it was false. True or false statements (e.g., "True or false: He is trying to figure out how to earn money") were presented after all filler items. If participants took longer than 10 seconds to respond to the true or false statement, a prompt appeared on the screen indicating that participants should attempt to respond more quickly (lasting for 1000 ms). After this, a prompt to continue appeared on the screen, which asked participants to press a button to indicate their readiness for the next trial. Participants also had the option to take a break in between each trial block.

---

[4] This battery also included a flanker task and an operation working memory task. While flanker tasks are also often used as measures of selective attention (Ong, Sewell, Weekes, McKague, & Abutalebi, 2016; especially for trial-to-trial changes, e.g., Davelaar & Stevens, 2009; for a review, see Egner, 2007), our goal for this study was to assess the degree to which effortful inhibition, following a task goal, would predict the magnitude of prediction error costs, which has been measured using the AX-CPT in prior work (e.g., Braver et al., 2001).

[5] Results from these other measures are available from the authors upon request.

The AX-Continuous Performance Task: The AX-Continuous Performance Task (AX-CPT; Nuechterlein, 1991) is a version of the Continuous Performance Test (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) that has been modified to test proactive goal maintenance and reactive inhibitory control under conditions that require the maintenance of a task goal over a delay period (see Cohen, Barch, Carter, & Servan-Schreiber, 1999), and has been shown to be sensitive to changes in control ability due to bilingual experience (Morales, Gómez-Ariza, & Bajo, 2013) and healthy aging (Braver et al., 2001). In this task, participants were instructed to respond as quickly as possible to letters that were presented at the center of the screen. These letters appeared in sequences of five, beginning with a red letter cue, followed by three white distractor letters, and ending with a red letter probe. Each letter was presented for 300 ms, with a 1000 ms ISI, and no extra pause between letter sequence trials. Participants were required to respond as quickly as possible to each letter as it appeared on the screen, but also had to attend to the relationship between the cue and probe letters. For the cue and distractor letters, participants were asked to respond using one button (marked "No"). However, for the probe, participants were asked to respond with a second button (marked "Yes") if the probe was an "X," but only if the preceding cue letter was an "A." Otherwise, probe responses should always be "No." Thus, the cue letters could be the letter "A" or some other letter, distractors were any letter other than "A" or "X", and the probe was either "X" or some other letter. The letters "K" and "Y" were never presented, due to their perceptual similarity to "X." In addition, "X" was never presented as a cue and "A" was never presented as a probe. Response button order (left vs. right; yes vs. no) was counterbalanced across participants.

There were four cue-probe trial conditions overall: AX (to which participants were instructed to change their probe response to "Yes"), AY, BX, and BY. Prior to the start of the task, participants were given instructions and 10 practice trials to complete, with feedback concerning the correctness of their probe response following each trial. For this practice block and the main task (which had 100 trials in total), 70% of trials were in the AX condition, while the remaining 30% were distributed evenly between the remaining three conditions. This distribution of trials was designed to make AY and BX trials more difficult, due to the similarity between these trials and their contrast to the more frequently presented AX trial type. Critically, the 70% bias towards AX trials has previously been shown to elicit greater error and response time costs for AY versus other trial types for young adults (see results from the same interference version of this task in Braver et al., 2001), making performance on correct trials in this condition a useful index of successful, if effortful, engagement of inhibitory control ability.

ERP Recording and Data Reduction: EEG was recorded from 28 Ag/AgCl active electrodes, attached to an elastic cap (Brain Products ActiCap, Germany) in accordance with the extended 10–20 system (Jasper, 1958; see Figure 1).

Additional electrodes were placed on the outer canthi and below and above the left eye in order to monitor eye movements and blinks. During recording, scalp electrodes were referenced to the scalp vertex (FCz). Electrodes were also placed at the left and right mastoids for later offline algebraic re-referencing. The EEG signal was amplified with a .05–100 Hz bandpass filter, and digitized online at a sampling rate of 500 Hz (Neuroscan

Synamps RT). EEG was digitized continuously along with accompanying stimulus codes used for subsequent averaging. Impedances were kept below 10 kΩ.

Offline data processing was carried out using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (erpinfo.org/erplab) toolboxes for MATLAB. Prior to offline averaging, all single-trial waveforms were screened for amplifier blocking, muscle artifacts, horizontal eye movements and blinks over epochs of 1000 ms, starting 200 ms before the onset of the critical word (i.e., the target noun). 17% of trials were excluded due to artifact, which did not differ across condition ($F(2,46) = 0.52$, $p = .60$). Average ERPs were computed over artifact-free trials in all conditions. All ERPs were filtered offline with a Gaussian low-pass filter with a 25 Hz half-amplitude cutoff. Statistical analyses were then conducted on the filtered data.

Results and Discussion

Behavioral Data

Comprehension Accuracy: All participants performed well above chance on the true or false statements that followed filler items in the reading task. Out of the 40 total statements, average accuracy for the group was 90.10% ($SD = 4.80\%$), ranging from 80.0 to 97.5%.

AX-CPT: The dependent variables of interest for the AX-CPT were reading times (RTs) and proportions of errors to the probe letters in the AY, BX, and BY conditions. Prior to analyzing participants' performance, trials with probe response times below 100 ms and over 2.5 standard deviations above the mean were removed, comprising 8% of the data. Participants produced the fewest errors in the AX condition, while errors to the BX and BY conditions were higher (see Table 2).

The AY condition produced the largest proportion of errors, suggesting that participants found this type of trial to be most difficult. A one-way ANOVA revealed a significant main effect of trial type (AY, BX, BY; $F(2,71) = 9.40$, $p < .001$). Planned contrasts were conducted to compare performance on the two most difficult trial types (AY and BX, due to their respective variance from the more expected AX trial type) and the baseline condition, BY, which required no change in motor response and did not directly conflict with the AX trials. Analyses indicated that the main effect of condition was driven by the higher proportion of errors in the AY condition vs. the BY condition ($t(69) = 3.47$, $p = .001$), rather than the BX vs. BY condition ($t(69) = .51$, $p = .61$). Reaction times to the probes (for correct trials only) followed a similar pattern, with a significant main effect of trial type ($F(2,71) = 120.15$, $p < .001$) that was driven by the difference between the AY and BY conditions ($t(69) = 13.30$, $p < .001$), while the BX and BY contrast did not reach significance ($t(69) = .25$, $p = .80$). In general, monolingual participants appeared to have the most difficulty with responding to probes in the AY condition, suggesting an overreliance on proactive goal maintenance (reflecting overt preparation for an X probe following an A cue) and subsequent difficulty with reactive or inhibitory control (when an unexpected Y probe was encountered). For the purposes of the regression analyses, we calculated the average RTs to correct trials in the AY and BY conditions for each participant, ranging from 352 to 540 ms and 157 to 345 ms, respectively. AY performance, therefore, should reflect difficulty with successful inhibition of a motor response, while BY performance should reflect overall speed of processing.

Verbal Fluency: We determined performance on the semantic category fluency task by calculating the total number of tokens produced across all four categories ($M = 44$, $SD = 8$). For the individual difference analyses, mean number of tokens was calculated for each participant (*range*: 31 to 65).

ERP Data—Three time windows of interest were selected for analysis (from 300 to 500, 500 to 700, and 700 to 900 milliseconds after the onset of the critical target word) in order to assess changes in the typical N400 time window (typically elicited from 300 to 500 ms) and the early vs. late timecourse of the late frontal positive effect, which has been found between 500 and 900 ms in prior studies. Mean amplitude was calculated for each time window in each of the three critical conditions, and repeated measures ANOVA were conducted using these data. For these analyses, the Greenhouse-Geisser correction for violation of sphericity was applied to all F-tests with more than one degree of freedom in the numerator.

As the goal was to investigate the effect of Unexpectedness in the reading task (i.e., the difference between the High Constraint, Expected and High Constraint, Unexpected conditions), the analyses reported below focus on this contrast. (For a more detailed analysis of the High vs. Low Constraint sentence conditions, comparing the processing of expected and neutral target words, see the Appendix.)

Effect of Unexpectedness: In order to investigate the topographic distribution of the effect of Unexpectedness, a subset of electrodes were chosen for analysis (see Figure 1): five frontal (F3, Fz, F4, FC1, FC2), five central (C3, Cz, C4, CP1, CP2), and five posterior (P3, Pz, P4, O1, O2) electrode sites, where the N400 and frontal positive effects related to prediction are typically maximal (e.g., Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007).[6] We first conducted repeated measures ANOVA with Unexpectedness, Anteriority (with three levels: frontal, central, and posterior), and Electrode (with 5 levels) as within-participants factors (see Table 3). For all significant interactions with Unexpectedness and Anteriority, we then conducted separate repeated measures ANOVA for each electrode region (frontal, central, and posterior; see Table 4).

To summarize the ERP results reported below, we found evidence for an effect of Unexpectedness in the N400 time window across all regions, that was strongest over central-posterior regions (see Figure 2). In addition, there was a significant frontal positive effect in the two later time windows that extended from the frontal to the central electrode region.

First, we report the results for the set of analyses with all electrode regions included. For the 300 to 500 ms time window, there was an interaction between Unexpectedness and Anteriority, Unexpectedness and Electrode, as well as a three-way interaction between Unexpectedness, Anteriority, and Electrode. In the 500 to 700 ms time window, the two-way

---

[6] Repeated measures ANOVA with Electrode as a within-participants factor (with 28 levels) revealed main effects of Unexpectedness and Unexpectedness by Electrode interactions in all time windows (Fs > 3.75, ps < .01).

interactions of Unexpectedness by either Anteriority or Electrode remained significant. This was also true for the 700 to 900 ms window, which also produced a significant three-way interaction between Unexpectedness, Anteriority and Electrode.

Next, we report the results for the set of analyses with the electrode regions considered separately. For the frontal region, there was a significant Unexpectedness by Electrode interaction for all time windows, with unexpected targets eliciting an N400 that was only 0.05 μV greater on average than that for expected targets, and a later positivity that was 1.13 and 1.76 μV greater for the 500 to 700 and 700 to 900 ms windows, respectively. For central sites, there was a main effect of Unexpectedness and an Unexpectedness by Electrode interaction in the N400 time window, with a 1.61 μV larger N400 effect in the unexpected condition. A similar, but much smaller .09 μV negative difference appeared in the latest 700 to 900 ms time window (reflected by an Unexpectedness by Electrode interaction). From 500 to 700 ms, however, unexpected targets were more positive than expected targets (0.18 μV difference; Unexpectedness by Electrode), much like the effect found for frontal sites, suggesting that this positivity was more widely distributed than expected. Analyses for the posterior region revealed an N400 effect of Unexpectedness and a late negative effect from 700 to 900 ms (Unexpectedness by Electrode), with unexpected targets eliciting a 2.38 and 0.29 μV larger negativity, respectively. This late negativity, like the one found for the central region, is difficult to interpret, but is possibly an indication that, for some participants, the N400 effect in response to unexpected targets occurred quite late and continued longer than is typically found in the literature.

Individual Difference Analyses: In order to determine the extent to which inhibitory control ability and verbal fluency may predict the magnitude of any effects of Unexpectedness, step-wise multiple regression analyses were conducted for the frontal, central, and posterior regions separately. For our dependent variables, we calculated the magnitude of the effect of Unexpectedness (i.e., the Unexpected minus Expected mean amplitude for each time window) by averaging across all electrode sites within each region for every participant. The independent variables were participants' average RT performance for correct trials in the AY condition of the AX-CPT and average production performance in the verbal fluency task.

When assessing the independent influence of performance on the AX-CPT, it is possible that baseline speed of processing may more broadly boost effects, especially in the more difficult AY condition. To account for this possibility, we followed the steps taken by Braver and colleagues (2001) and conducted step-wise multiple regressions, with processing speed (average RTs for correct trials in the baseline BY condition) entered in the first step, and our other independent variables (AY and verbal fluency performance, as well as their interaction) in the second step. There was no significant correlation between processing speed in the BY condition and control in the AY condition. In addition, processing speed in the BY condition was only a significant predictor of Unexpectedness effect sizes for Frontal and Central electrodes in the 700 to 900 ms window, and was not a significant predictor when included in the full model (*p*s > .05). These two analyses also did not reveal any subsequent effects of control or fluency. As such, speed of processing did not appear to impact our critical analyses, and we only report findings for AY and verbal fluency performance below.[7]

We expected that participants' inhibitory control ability and verbal fluency would predict the magnitude of the frontal positive effects elicited by unexpected targets in the High Constraint condition. Critically, there was no significant correlation found between inhibitory control ability (i.e., AY performance on the AX-CPT) and verbal fluency ($p < .05$). Correlation analyses (see Table 5) also indicated a significant positive relationship between control ability and the magnitude of the effect of Unexpectedness in all time windows for the frontal region. Longer RTs on correct trials in the AY condition, indicating difficulty with inhibiting an inappropriate response, were associated with a larger frontal positive ERP effect. No independent effects of verbal fluency were observed. In the multiple regression analyses (see Table 6), AX-CPT performance significantly predicted the magnitude of the effect of Unexpectedness for the frontal region, but only from 500 to 700 ms [$r = .54$ ($r^2 = .29$; $p = .01$)]. Figure 2 shows the topographic distribution of this ERP effect and Figure 3 shows the linear relationship between inhibitory control and the effect of Unexpectedness from 500 to 700 ms. This result confirmed the hypothesis that performance on the portion of the AX-CPT related to effortful engagement of inhibitory control would predict the magnitude of participants' ERP response to unexpected words in highly semantically constraining contexts (as indicated by a frontal positive effect), when costs related to prediction error are most likely to have occurred. This suggests that the underlying mechanisms involved in resolving conflict when predictions are disconfirmed are related to those engaged during a non-linguistic response inhibition task like the AX-CPT.

Notably, in none of the analyses performed on the monolingual data in Experiment 1 was there any indication of modulation of the observed patterns as a function of verbal fluency or an interaction between verbal fluency and control (see Table 5 for correlational data; there were similarly no main effects or interactions with verbal fluency in the multiple regressions; ps > .14). Unlike results reported by Federmeier and colleagues (2010) for older adult monolinguals, the presence of a frontal positivity in response to unexpected words was not modulated by performance on the verbal fluency task, but only by individual differences in inhibitory control as indexed by AX-CPT performance. It is possible that young monolingual speakers are less likely to reveal individual differences in their ability to regulate their native language than older and more vulnerable adult monolinguals whose cognitive resources may be more stressed.

In summary, it appears that cognitive control ability, specifically inhibitory control, is recruited when readers encounter prediction errors in their native language. Monolingual readers who experienced more difficulty in the inhibition-demanding portion of the AX-CPT also tended to produce the greatest frontal positivity in response to unexpected targets. We interpret this finding as support for the idea that the frontal positivity reflects, at least in part, difficulty with negotiating conflict when predictions are disconfirmed. Once readers commit

---

[7] All multiple regression analyses were also conducted using a composite score on the AY condition of the AX-CPT (i.e., summed z-scores for RTs on correct trials and proportion of errors) to determine whether speed-accuracy tradeoff may have been driving the RT results. However, this led to no change in any of the reported results, including no change in model fit for our data.

to a particular prediction, when an unexpected, though plausible, word is encountered, inhibitory control processes appear to be engaged. This could be in order to mediate conflict between competing representations (i.e., the prediction and the word actually encountered), to specifically inhibit the previously generated prediction, or some combination thereof. This interpretation complements prior ERP work that has found consistent frontal positive effects of unexpectedness in young adult, monolingual readers (e.g., DeLong et al., 2012; Federmeier et al., 2002; 2007; 2010), but provides more insight into the nature of the prediction that is generally assumed to have been generated in these types of paradigms, and the type of work that readers must do when conflicts inevitably arise.

Experiment 2: Chinese-English Bilinguals

By utilizing an individual differences approach, the results from Experiment 1 indicated that inhibitory control ability can mediate the costs associated with prediction error when individuals are reading and comprehending in their native language. The goal in Experiment 2 was to determine whether the ability to recruit control processes at this later stage in the prediction process can be utilized by individuals who are engaged in an even more resource-demanding task: when they read in the L2. In Experiment 2, we tested highly proficient, young adult Chinese-English bilingual readers, using the same English sentence materials and individual differences approach.

Method

All methods were the same as those in Experiment 1, except for those described below.

Participants—Twenty-eight Chinese-English bilinguals (18 female), with an average age of 23 years (*SD* = 4.40; *range*: 18 to 33) participated in this experiment. All participants were native Chinese speakers, immersed at Pennsylvania State University but still dominant in Chinese, who reported high proficiency in Chinese (*M* = 9.28, *SD* = 0.68) and moderate to high proficiency in English (*M* = 7.30, *SD* = 1.21).

Procedure

Verbal Fluency Task: A verbal category fluency task was administered to participants in both of their languages (L1 = Chinese; L2 = English). Four semantic categories were presented for the L1 and for the L2, and categories did not overlap between languages. Two of the four categories in each language were animate, while the remaining two were inanimate, and within one language, order of presentation for categories was randomized. The fluency task in the L2 was always administered prior to the L1, and both were administered on separate days. Prior to each main task (L1 or L2), participants completed a practice trial.

ERP Recording and Data Reduction: 25% of trials were excluded due to artifact, which did not differ between conditions (*F*(2,58) = 1.09, *p* = .34).

Results and Discussion

Behavioral Data

Comprehension Accuracy: Bilingual participants performed well above chance on the true or false questions, with an average accuracy rate of 83% (SD = 7.07; range: 70 to 95%).

AX-CPT: Trial rejection was carried out similarly to that in Experiment 1, resulting in the removal of 7% of trials overall. Participants produced fewer errors in the AX condition than any other condition (see Table 7). A one-way ANOVA with trial type (AY vs. BX vs. BY) as a within-participants factor was not significant ($F(2,81) = 1.81$, $p = .17$). Neither were planned contrasts of AY or BX trials vs. BY trials (*t*s < 2, *p*s > .05). However, a similar analysis for RTs to correct trials was significant ($F(2,81) = 27.55$, $p < .001$). This effect was driven by the difference between AY and BY trials ($t(81) = 6.08$, $p < .001$), but not BX vs. BY trials ($t(81) = 0.64$, $p = .52$). Similar to Experiment 1, these results indicated that bilingual participants had the most difficulty with inhibiting an incorrect response during the AY condition. For the individual difference analyses, average RTs to the AY condition (*range*: 331 to 632 ms), as well as the BY condition (*range*: 188 to 441 ms), were calculated for each participant.

Verbal Fluency: In order to assess participants' performance on the semantic category fluency task, the total number of tokens across all four categories was calculated for each language. As is expected of an L1-dominant bilingual group, all participants produced significantly more tokens in their L1 ($M = 49$, $SD = 8$) than their L2 ($M = 33$, $SD = 6$; $F(1,54) = 55.31$, $p < .001$). For the individual difference analyses, total number of tokens was calculated for each participant in each language (L1 *range*: 32 to 66; L2 *range*: 23 to 50).

ERP Data

Effect of Unexpectedness: As in Experiment 1, we conducted two sets of analyses to assess the magnitude and topography of any effect of unexpectedness: one with all electrode regions (frontal, central, and posterior) included, and the other with each region analyzed separately.[8] To summarize the results reported below, this analysis of the response of all bilingual participants indicated an effect of unexpectedness in the form of a long-lasting, central-posterior N400. We also found evidence for a shift in ERP response across electrode regions in the later time windows. However, this did not correspond to a significant frontal positive effect in an analysis of the frontal electrode region alone. In general, these ERP effects pattern similarly to those found for monolinguals in Experiment 1.

First, we report the results for the analysis with all electrode regions included, with Unexpectedness, Anteriority (Frontal, Central, Posterior), and Electrode (5 levels) as within-participants factors. There were significant Unexpectedness by Anteriority interactions in all time windows, as well as a main effect of Unexpectedness in the N400 time window and an Unexpectedness by Electrode interaction in the 500 to 700 ms window (see Table 8).

---

[8] See Appendix for individual difference analyses contrasting High vs. Low constraint sentence contexts and expected vs. neutral target words.

Next, repeated measures ANOVA were conducted within each electrode region separately (see Table 9). Analyses for the central and posterior regions both indicated significant N400 effects of Unexpectedness (with 1.61 and 2.38 μV larger negativities, respectively), which extended to the 500 to 700 ms time window for posterior sites (with a 0.41 μV difference). In contrast, there were no significant effects in the frontal region, which was supported by visual inspection of the grand average ERP waveforms (see Figure 4).

On initial view, this suggests that bilingual participants did not tend to produce a frontal positivity for unexpected targets in highly semantically constraining contexts. One interpretation for this result is that bilinguals reading in the L2 do not have the resources necessary to generate predictions online (e.g., Martin et al., 2013). However, as we saw in Experiment 1, the absence of a frontal positivity could instead be due to participants' inhibitory control ability, a cognitive skill that has been shown to change as a function of second language experience (e.g., Bialystok et al., 2012). The reduction of the frontal positivity in response to prediction error could, therefore, reflect inhibition skill, a failure to generate a prediction, or some combination of the two within this group of bilingual readers. As such, we conducted two sets of individual difference analyses on these data in order to determine the extent to which not only cognitive control ability, but L2 proficiency (via L2 verbal fluency performance in an L2 immersion context) and L1 regulation (via L1 verbal fluency performance in an L2 immersion context) may contribute to our ERP results. We expected that higher domain general inhibitory control ability would lead to a reduction in prediction error costs, but only for those bilingual readers whose ability to generate prediction in the L2 was either supported by their proficiency in the less dominant language, and/or their ability to regulate the demands imposed by parallel L1 and L2 activation. Thus, while inhibitory control ability was hypothesized to support recovery from prediction error, we counterintuitively expected that higher L2 proficiency or L1 regulation may exacerbate prediction error response in the ERPs.

Individual Difference Analyses: The dependent variable for the individual difference analyses was the magnitude of the effect of unexpectedness for each time window. However, as the bilingual participants were reading in their L2, we also assessed the degree to which inhibitory control ability and verbal fluency of both languages might influence the magnitude of this effect, and how the two might interact with inhibitory control ability. We first conducted a series of multiple regression analyses with L2 fluency, and then conducted a second set of analyses taking into account L1 fluency. Recall that we expected that for bilinguals, L2 fluency would reflect proficiency, whereas L1 fluency could index their language regulation ability (if negatively correlated with prediction error costs). For each analysis, we used centered participant scores in both tasks (verbal fluency and the AX-CPT). Importantly, there was no significant correlation between either L1 or L2 fluency performance and performance on the AY condition of the AX-CPT (*p*s < .05), supporting our argument that these fluency measures may more reliably index either L2 proficiency, or ability to regulate the L1 in a manner that relies on more than solely inhibitory skill. This partial independence of L1 regulation and domain general inhibition does not imply that these two processes are completely distinct, but allows us to examine how they may be recruited in different ways by bilingual readers during online L2 processing, and the ways in which inhibitory skill may commonly support prediction error recovery across monolingual and bilingual readers alike.

We followed the same procedures as in Experiment 1, by conducting step-wise multiple regressions with speed of processing (RT performance in the baseline BY condition of the AX-CPT) entered in the first step, and control and fluency performance, as well as their interaction, entered in the second step.[9] BY performance was not significantly correlated with AY performance. However, it did significantly predict the magnitude of the effect of Unexpectedness only for frontal electrodes in the 500 to 700 ms time window. In this region and time window, speed of processing impacted the magnitude of the frontal positivity, both in the L2 ($r = .41$ [$r^2 = .17$; $p = .01$]) and L1 analyses ($r = .41$ [$r2 = .17$; $p = .02$]). This was also reflected in the correlation between the frontal positivity and BY performance ($r = .41$, $p = .03$). The faster bilingual participants performed on the baseline condition of the AX-CPT, the smaller their frontal positivity tended to be. This suggests that, at least for bilinguals, faster speed of processing did not correspond with larger prediction error magnitude in the L2 (which would have resulted in the opposite pattern). Instead, bilinguals with better speed of processing showed a reduction in prediction error cost overall.

When considering the effect of processing speed on prediction error magnitude, we can interpret this finding in a number of ways. If the ability to predict in the L2 relies on cognitive resources, we would expect individuals with more available resources (and correspondingly faster speed of processing) to either a) generate a stronger prediction, b) generate a less graded prediction, and/or c) to be able to generate a prediction at all in the less dominant language. All of these potential outcomes should, in turn, lead to a greater prediction error and frontal positivity when that expectation is not met. This pattern is not observed in our data; faster speed of processing leads to a reduction in prediction error costs. Alternatively, better processing speed could be related to general executive function skill (although BY and AY performance was not correlated). Individuals with faster processing speed may be better able to quickly engage cognitive control in order to inhibit a previously formed expectation. Thus, speed of processing, language proficiency and regulation, and inhibitory control may additively contribute to a reduction in prediction error costs during online processing, especially in the L2. Importantly, including BY performance in the multiple regression analyses (that we report below) improved model fit, and did not impact subsequent results indicating whether control and fluency were significant predictors. The following results reflect the influence of control and fluency after speed of processing is taken into account.

Effect of L2 Fluency: Our initial hypothesis was that, as participants were reading in the L2, reduced fluency performance in the same language may reflect lower L2 proficiency and therefore lead to a reduction in any prediction effects. Specifically, we expected a reduction in prediction error costs, especially if high L2 proficiency is a requirement for successful L2 prediction. This would be indicated by an interaction between inhibitory control and L2 fluency, where bilinguals with high performance in both tasks would show the greatest

---

[9] As in Experiment 1, we also conducted a second set of analyses with composite AY performance (taking into account both RTs and proportion of errors), which resulted in no change to the reported results.

reduction in cost. However, as seen in Table 10, L2 fluency did not significantly correlate with the effect of unexpectedness in any time window or electrode region. Neither, in fact, did the interaction between L2 fluency and inhibitory control ability.

In the multiple regression analysis (see Table 11), L2 fluency did not prove to be a significant predictor of the effect of unexpectedness. However, the interaction between L2 fluency and inhibitory control ability did significantly predict the effect of unexpectedness in the N400 time window for the posterior region [$r = .47$ ($r^2 = .22$; $p = .04$)]. In order to examine in what way these two factors contributed to changes in the magnitude of this N400 effect, we conducted simple slopes analyses to see how L2 fluency has an influence on the effect of unexpectedness at two levels of control ability: high vs. low (defined as 1 SD above and below the mean). The effect of L2 fluency did not reach significance for high levels of control ($t(24) = .79$, $p = .44$), but did for low levels of control ($t(24) = 2.11$, $p = .04$). As seen in Figures 5a, 5b, and 6a, the posterior N400 effect found for unexpected targets was most prominent for bilinguals with high L2 fluency and low levels of control (−2.36 μV in comparison to −0.91 μV for low fluency individuals who were also low in control), while no change in the effect of unexpectedness was observed for bilinguals with low L2 fluency, regardless of their control ability (high control: −1.12 μV; low control: −1.23 μV). Having high L2 fluency appears to have increased the magnitude of the N400 effect for unexpected words, a processing cost that was then reduced for those who performed well on the control task.

Contrary to what we expected, L2 fluency did not appear to play a role in determining whether bilinguals would generate a frontal positivity in response to prediction error, and instead influenced the magnitude of the N400 effect found for unexpected targets. Bilinguals with higher L2 fluency appeared to be more sensitive to the contextual fit of the unexpected target word, resulting in the potential for a larger N400 effect, and subsequently recruited control processes in order to more easily access and integrate this word in the sentence context. Notably, the Chinese-English bilingual participants recruited for this experiment were all enrolled as students in a university in the United States, and had, therefore, already met a very high criterion for English proficiency. With this in mind, this L2 fluency effect may relate to variability in L2 ability above and beyond a traditionally high threshold for acceptance into a university in an English-immersed environment.

Effect of L1 Fluency: Despite the fact that L2 fluency performance did not significantly predict modulation of prediction error costs (at least for the frontal positivity), our second hypothesis was that fluency performance in a bilingual reader's dominant language might be a more suitable measure for language-related regulation ability. In particular, the L2 immersion context in which our bilingual participants were tested should have made the effort required to de-regulate the L1 during the fluency task even more pronounced. In contrast to the monolinguals in Experiment 1, bilinguals' performance in the L1 fluency task relied not only on their ability to select appropriate responses (i.e., by avoiding repetition and tokens that were too highly semantically related), but also on their ability to restrict those responses to the appropriate language: the L1. De-regulating and producing words in the L1, following either a similar task in the L2 or while being immersed in an L2 environment, has been reported to be difficult for bilingual speakers (e.g., Linck et al., 2009;

Van Assche et al., 2013). As such, performance on the L1 fluency task may reflect bilinguals' regulation skill, and the effect of L1 fluency on prediction costs may also pattern quite differently from the effect of L2 fluency, which is more likely to reflect proficiency.

As seen in Tables 12 and 13, L1 fluency did indicate whether bilingual L2 readers were likely to experience prediction error costs. The interaction between inhibitory control and L1 fluency was significantly positively correlated with the magnitude of the effect of unexpectedness in the 500 to 700 ms time window for the frontal region ($r = .37$, $p < .05$). As L1 fluency increased, so too did the magnitude of prediction costs, suggesting that regulation of the L1, and not cross-language interference per se, was important for bilinguals to be able to generate predictions in their less proficient L2. The same effect was only marginally significant in the central region for the same time window ($r = .35$, $p = .06$; although there was a significant correlation with L1 fluency alone: $r = .37$, $p < .05$).

In the multiple regression analyses, the interaction between control and L1 fluency significantly predicted the magnitude of the effect of unexpectedness from 500 to 700 ms in both the frontal region [$r = .66$ ($r^2 = .43$; $p = .04$)] and the central region [$r = .54$ ($r^2 = .29$; $p = .03$)], and there was also a main effect of L1 fluency in the central region ($p = .03$). Simple slopes analyses were conducted to determine how L1 fluency influenced the magnitude of the effect of unexpectedness at two levels of control ability (high vs. low; calculated in the same way as with L2 fluency) in both electrode regions. While the effect of L1 fluency did not reach significance for high levels of control (ts(24) < .55, ps > .59), there were significant effects for low levels of control (frontal: $t(24) = 2.66$, $p = .01$; central: $t(24) = 3.04$, $p < .01$). As seen in Figures 6b and 6c, L1 fluency modulated whether participants generated a larger frontal positivity, or a larger negativity in the central region, in the 500 to 700 ms time window. Specifically, having better L1 regulation ability (i.e., higher L1 fluency performance in an L2 immersion context) led to a greater positivity in the frontal region, which was then modulated by control ability (high control: 0.03 μV; low control: 1.79 μV). In contrast, bilinguals with poorer L1 regulation skill showed evidence for a larger negativity, even in frontal electrode sites, that was subsequently attenuated by control (high control: −0.10 μV; low control: −1.44 μV). The topographic distribution of the positivity was more frontal, as indicated by a similar, but weaker effect in central electrode sites for bilinguals with better L1 regulation (high control: −0.29 μV; low control: 0.64 μV). In contrast, the delayed negativity found in frontal sites was stronger in the central region for bilinguals with poorer regulation skill (high control: −0.79; low control: −2.35 μV).

The presence of ERP costs reflecting sensitivity to prediction error was therefore most evident for bilinguals with better language regulation skill, while bilinguals with poorer regulatory ability appeared to elicit a delayed and centrally-distributed negativity.[10] Across the board, both of these ERP effects were reduced for participants who performed well on the inhibition-demanding portion of the AX-CPT.

---

[10] It is difficult to interpret the presence of this delayed negativity, as it differs in both time-course and topographic distribution from the canonical N400 found for the effect of L2 fluency and control. In addition, the presence of a frontally-distributed positivity in the same time window may have influenced the magnitude of this negativity, especially for bilingual readers who showed the greatest sensitivity to prediction error. We therefore interpret this effect as a consequence of overlapping ERP components, and not as an indication of an alternative linguistic process on the part of some of the bilingual readers in this experiment.

In general, these results confirmed the hypothesis that inhibitory control ability and verbal fluency jointly influence the magnitude of the cost of prediction error in bilingual readers. This effect is typically observed, as in our study, as a late frontal positivity, which is often interpreted as a repercussion of having a prediction disconfirmed. If this is the case, our findings suggest that appropriately regulating and de-regulating the dominant L1 is a strong indicator that a bilingual reader will generate predictions online during L2 reading. However, just as we found for the monolinguals in Experiment 1, cognitive control ability, specifically better inhibitory control, can still attenuate processing costs when prediction errors occur.

General Discussion

In the two experiments presented in this paper, we have demonstrated that cognitive control plays a direct role when readers encounter prediction errors in the native and non-native language. We provide evidence showing that individual differences in L1 and L2 ability can impact this process for bilinguals, and demonstrate how domain-general control processes can be recruited, by both native and non-native readers, in order to overcome conflict when prediction errors occur. For monolinguals reading in their native language, inhibitory control ability influenced whether readers who had previously committed to a prediction subsequently encountered difficulty when that prediction was not verified. Native language readers who exhibited better inhibitory control ability in a non-linguistic task experienced less difficulty with prediction error, as evidenced by a reduced frontal positivity, while native readers with poorer inhibitory control experienced the greatest cost. These effects were independent of native language ability, at least for the young adult monolingual participants in the current study, suggesting that prediction error costs, and their attenuation by control, may extend beyond the language domain.

In combination with this inhibitory effect, there is a reasonable likelihood that the magnitude of the prediction error observed in the ERP record is also related to the strength or gradation of the prediction that had previously been generated. However, if the magnitude of the error-related signal was solely due to prediction strength, and not attempts to revise or suppress the error, then we would expect to see a reduced or no significant relationship between domain general inhibitory control ability and prediction error costs. Instead, we observed a significant relationship between inhibition ability and predicton error. Alternatively, one might expect inhibitory control ability, and potentially a broad range of executive functions, to support the generation of predictions online. If this were indeed the case, then readers with better inhibitory control ability should have been the most sensitive to disconfirmed predictions in the reading task. In constrast, we find the opposite pattern, suggesting that while prediction generation strength is indeed important, inhibitory control ability still mediates whatever costs may arise as a result of prediction error. In addition, the findings discussed above were also replicated for non-native reading, suggesting that the underlying mechanisms that support prediction are similar for L1 and L2 readers (e.g., Kaan, 2014). Bilinguals reading in their non-native L2 are not only capable of generating predictions online, but can be similarly susceptible to prediction error.

Bilinguals reading in the L2 experienced greater costs if they had poorer inhibitory control, a pattern of effects also found for native monolingual readers. These results may explain discrepant findings in prior work on L2 prediction (Martin et al., 2013) that have suggested that bilingual readers either may not be able to generate predictions when reading in the L2 or that the predictions they generate do not come online quickly enough to elicit typical prediction benefits and costs (but see Foucart et al., 2014). As we have seen in the current study, readers may not appear to incur prediction costs if they are also skilled inhibiters. Prediction, therefore, may be a particularly useful reading strategy for both monolinguals and bilinguals, assuming that their inhibitory control ability can compensate for any possible conflicts. Critically, this interplay between prediction and domain general cognitive skill was revealed only when individual cognitive and linguistic skill was taken into account. The current study, therefore, highlights the importance of using individual differences to further our understanding of the neurological basis of language and cognition (e.g., McLaughlin et al., 2010; Tanner, Inoue, & Osterhout, 2014; for further discussion, see Boudewyn, 2015; Fricke, Zirnstein, Navarro-Torres, & Kroll, under review).

The findings from this study also reveal the potential impact that bilingual language use might in turn have on language comprehension itself. The relationship between bilingual language regulation and inhibitory control in the current study was complex. While domain general inhibitory control ability aided prediction error recovery more generally, regardless of bilingual status, better language regulation skill counterintuitively led to greater processing costs. This suggests that bilinguals who are highly proficient in the L2, and who also demonstrate skill in regulating the relative activation of their languages to suit the task at hand, may be a prime example of the type of readers one would expect to engage in L2 prediction. They may additionally be more likely to utilize their inhibitory control when overcoming conflict online. As bilinguals continue to gain experience in switching between and regulating their two languages, they learn to mediate the costs that arise when their L1 and L2 conflict or otherwise compete for selection (Kroll & Dussias, 2013). In large part due to this experience, it has been shown that bilingual experience across the lifespan often has an impact on domain-general executive function skill (e.g., Bak et al., 2014; Bialystok et al., 2012; Gold et al., 2013). This suggests that the brain networks that support domain-general cognitive control are recruited when bilinguals experience language conflict and are subsequently adapted in a manner that should support future, controlled language use (Green & Abutalebi, 2013; see Hsu & Novick, 2016, Loncke et al., 2011, and Teubner-Rhodes et al., 2016, for recent evidence on the interplay between language processing and cognitive control). In particular, the ability to regulate the language not currently in use (e.g., the dominant L1 when engaged in the L2) is a critical skill that supports proficient language production and comprehension for bilinguals. Our data, therefore, point to an aspect of L2 comprehension that actively engages these regulatory processes that have been implicated as critical for bilingual language use. Future work will need to address the extent to which subcomponents of the cognitive control network, such as inhibitory control ability, are recruited to support language regulation, the extent to which each process is weighted, and how this ultimately impacts online comprehension.

To what extent, then, does the prediction process differ for bilinguals and monolinguals? We investigated the demands that prediction imposes when individuals read in the L1 or the L2, and how readers utilize their inhibitory control ability to overcome these demands. However, to fully address the extent to which bilinguals engage in predictive processing of text, one would need to test the same bilingual readers in both their L1 and their L2. Although it is beyond the scope of this paper to address this issue, we believe that these results highlight several intriguing possibilities for how L1 prediction might differ for bilinguals versus monolinguals. As discussed previously, there may be benefits for bilinguals in contrast to monolinguals in terms of their ability to suppress irrelevant or conflicting information. If this is the case, two potential patterns might emerge. First, L1 prediction for bilinguals might pattern quite differently than for monolinguals, especially when these readers are faced with an unexpected prediction error. Bilinguals, especially those with more lifetime experience in regulating language conflict, might be more capable of recovering following a prediction error, an effect that could potentially be reflected in a lower amplitude frontal positivity in contrast to their monolingual peers (an effect that would support neuroimaging work showing that there are enduring consequences of bilingualism for processing in the L1; Parker et al., 2012).

Second, these effects for bilinguals might also extend to recovery from prediction error in other cognitive domains. The current study and prior research both suggest that it may be necessary for bilingual readers to tap into these regulatory and inhibitory control mechanisms in a different way than monolinguals do (e.g., Morales et al., 2013). A critical aspect of bilingual reading, for example, is that the non-target language often conflicts or interferes with target language processing, a problem that monolingual readers, by definition, do not experience. As we have demonstrated, efficient regulation of the non-target language has a direct impact on the predictions that bilinguals can generate in their L2, and the subsequent costs they experience when errors arise. This pattern of behavior may provide beneficial changes to bilingual speakers' ability to recruit cognitive control ability during resource-demanding tasks across multiple cognitive domains. Naturally, this transfer of skill would heavily depend on the nature of the bilingualism of the readers being tested, and the impact that bilingual experience itself has had on language processing ability in both the L1 and L2, which can be quite varied (e.g., Dussias, Marful, Bajo, & Gerfen, 2010). In the future, examining bilingual performance in both the L1 and L2, as well as in prediction paradigms in other cognitive domains, may reveal not only the consequences of having experience in negotiating language-related conflict, but also tell us something about how bilingual experience can impact cognition more broadly.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The writing of this article was supported in part by the following NSF Grants: SMA-1409973 to MZ, JvH, and JK, SMA-1657782 to MZ and JK, OISE-0968369 and OISE-1545900 to JK and JvH, BCS-1535124 to JK, and BCS-1349110 to JvH, as well as NIH Grants HD082796 and HD053146 to JK. The content is solely the responsibility of the authors and does not necessarily represent the official views of the funding agencies. The authors would like to thank Jessica Ambrose, Michelle Bruni, John Elkhoury, and Katie Genovese for their assistance in preparing stimulus materials and with data collection.

References

Bak TH, Nissan JJ, Allerhand MM, Deary IJ. Does bilingualism influence cognitive aging? Annals of Neurology. 2014; 75:959–963. [PubMed: 24890334]

Baum S, Titone D. Moving toward a neuroplasticity view of bilingualism, executive control, and aging. Applied Psycholinguistics. 2014; 35:857–894.

Baus C, Costa A, Carreiras M. On the effects of second language immersion on first language production. Acta Psychologica. 2013; 142:402–409. [PubMed: 23435116]

Bialystok E, Craik FIM, Luk G. Bilingualism: Consequences for mind and brain. Trends in Cognitive Sciences. 2012; 16:240–250. [PubMed: 22464592]

Boudewyn MA. Individual differences in language processing: Electrophysiological approaches. Language and Linguistics Compass. 2015; 9:406–419.

Boudewyn MA, Gordon PC, Long D, Polse L, Swaab TY. Does discourse congruence influence spoken language comprehension before lexical association? Evidence from event-related potentials. Language and Cognitive Processes. 2012; 27:698–733. [PubMed: 23002319]

Boudewyn MA, Long DL, Swaab TY. Cognitive control influences the use of meaning relations during spoken language comprehension. Neuropsychologia. 2012; 50:2659–2668. [PubMed: 22842106]

Boudewyn MA, Long DL, Swaab TY. Effects of working memory span on processing of lexical associations and congruence in spoken discourse. Frontiers in Psychology. 2013; 4:60. [PubMed: 23407753]

Braver TS, Barch DM, Keys BA, Carter CS, Cohen JD, Kaye JA, Janowsky JS, Taylor SF, Yesavage JA, Mumenthaler MS, Jagust WJ, Reed BR. Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. Journal of Experimental Psychology: General. 2001; 130:746–763. [PubMed: 11757878]

Brothers T, Swaab TY, Traxler MJ. Effects of prediction and contextual support on lexical processing: Prediction takes precedence. Cognition. 2015; 136:135–149. [PubMed: 25497522]

Brysbaert M, New B. Moving beyond Kucera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. Behavior Research Methods. 2009; 41(4):977–990. [PubMed: 19897807]

Bubic A, von Cramon DY, Schubotz RI. Prediction, cognition and the brain. Frontiers in Human Neuroscience. 2010; 4(25):1–15. [PubMed: 20204154]

Camblin CC, Gordon PC, Swaab TY. The interplay of discourse congruence and lexical association during sentence processing: evidence from ERPs and eye tracking. Journal of Memory and Language. 2007; 56:103–128. [PubMed: 17218992]

Clahsen H, Felser C. Grammatical processing in language learners. Applied Psycholinguistics. 2006; 27:3–42.

Clark LJ, Gatz M, Zheng L, Chen YL, McCleary C, Mack W. Longitudinal verbal fluency in normal aging, preclinical and prevalent Alzheimer disease. American Journal of Alzheimer's Disease and Other Dementias. 2009; 24:461–468.

Cohen JD, Barch DM, Carter C, Servan-Schreiber D. Context-processing deficits in schizophrenia: Converging evidence from three theoretically motivated cognitive tasks. Journal of Abnormal Psychology. 1999; 108:120–133. [PubMed: 10066998]

Costa A, Hernández M, Costa-Faidella J, Sebastián-Gallés N. On the bilingual advantage in conflict processing: Now you see it, now you don't. Cognition. 2009; 113:135–149. [PubMed: 19729156]

Coulson S, Wu YC. Right hemisphere activation of joke-related information: an even-related brain potential study. Journal of Cognitive Neuroscience. 2005; 17:494–506. [PubMed: 15814008]

Dambacher M, Kliegl R, Hofmann M, Jacobs AM. Frequency and predictability effects on event-related potentials during reading. Brain Research. 2006; 1084:89–103. [PubMed: 16545344]

Davelaar EJ, Stevens J. Sequential dependencies in the Eriksen flanker task: A direct comparison of two competing accounts. Psychonomic Bulletin & Review. 2009; 16:121–126. [PubMed: 19145021]

DeLong KA, Groppe DM, Urbach TP, Kutas M. Thinking ahead or not? Natural aging and anticipation during reading. Brain and Language. 2012; 121:226–239. [PubMed: 22406351]

Delorme A, Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics. Journal of Neuroscience Methods. 2004; 134:9–21. [PubMed: 15102499]

Dussias PE, Marful A, Bajo MT, Gerfen C. Usage frequencies of complement-taking verbs in Spanish and English: Data from Spanish monolinguals and Spanish-English bilinguals. Behavior & Research Methods. 2010; 42:1004–1011.

Egner T. Congruency sequence effects and cognitive control. Cognitive, Affective, & Behavioral Neuroscience. 2007; 4:380–390.

Federmeier KD. Thinking ahead: The role of roots and prediction in language comprehension. Psychophysiology. 2007; 44:491–505. [PubMed: 17521377]

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

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

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

Federmeier KD, Wlotko E, De Ochoa-Dewald E, Kutas M. Multiple effects of sentential constraint on word processing. Brain Research. 2007; 1146:75–84. [PubMed: 16901469]

Foucart A, Garcia X, Ayguasanosa M, Thierry G, Martin C, Costa A. Does the speaker matter? Online processing of semantic and pragmatic information in L2 speech comprehension. Neuropsychologia. 2015; 75:291–303. [PubMed: 26115602]

Foucart A, Martin CD, Moreno EM, Costa A. Can bilinguals see it coming? Word anticipation in L2 sentence reading. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2014; 40:1461–1469.

Frenck-Mestre C, Pynte J. Syntactic ambiguity resolution while reading in second and native languages. The Quarterly Journal of Experimental Psychology. 1997; 50:119–148.

Fricke M, Zirnstein M, Navarro-Torres C, Kroll JF. Bilingualism reveals fundamental variation in language processing. under review.

Gernsbacher MA. The structure-building framework: what it is, what it might also be, and why. Models of understanding text. 1996:289–311.

Gernsbacher MA. Two decades of structure building. Discourse processes. 1997; 23:265–304. [PubMed: 25484476]

Gernsbacher MA, Faust M. The mechanism of suppression: A component of general comprehension skill. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1991; 17:245–262.

Gernsbacher MA, Varner KR, Faust ME. Investigating differences in general comprehension skill. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1990; 16:430–445.

Giezen MR, Blumenfeld HK, Shook A, Marian V, Emmorey K. Parallel language activation and inhibitory control in bimodal bilinguals. Cognition. 2015; 141:9–25. [PubMed: 25912892]

Gold BT, Kim C, Johnson NF, Kryscio RJ, Smith CD. Lifelong bilingualism maintains neural efficiency for cognitive control in aging. The Journal of Neuroscience. 2013; 33:387–396. [PubMed: 23303919]

Green DW, Abutalebi J. Language control in bilinguals: The adaptive control hypothesis. Journal of Cognitive Psychology. 2013; 25:515–530. [PubMed: 25077013]

Hasegawa M, Carpenter PA, Just MA. An fMRI study of bilingual sentence comprehension and workload. NeuroImage. 2002; 15:647–660. [PubMed: 11848708]

Henry JD, Crawford JR, Phillips LH. Verbal fluency performance in dementia of the Alzheimer's type: A meta-analysis. Neuropsychologia. 2004; 42:1212–1222. [PubMed: 15178173]

Hintz F, Meyer AS, Huettig F. Encouraging prediction during production facilitates subsequent comprehension: Evidence from interleaved object naming in sentence context and sentence reading. Quarterly Journal of Experimental Psychology. 2016; 69:1056–1063.

Hsu NS, Novick JM. Dynamic engagement of cognitive control modulates recovery from misinterpretation during real-time language processing. Psychological Science. 2016; 27:572–582. [PubMed: 26957521]

Huettig F, Mani N. Is prediction necessary to understand language? Probably not. Language, Cognition and Neuroscience. 2016; 31:19–31.

Jasper HH. Report of the committee on methods of clinical examination in electroencephalography. Electroencephalography and Clinical Neurophysiology. 1958; 10:370–375.

Kaan E. Predictive sentence processing in L2 and L1: What is different? Linguistic Approaches to Bilingualism. 2014; 4:257–282.

Kaan E, Kirkham J, Wijnen F. Prediction and integration in native and second-language processing of elliptical structures. Bilingualism: Language and Cognition. 2016; 19:1–18.

Kroll, JF., Dussias, PE. The comprehension of words and sentences in two languages. In: Bhatia, T., Ritchie, W., editors. The Handbook of Bilingualism and Multilingualism. 2. Malden, MA: Wiley-Blackwell Publishers; 2013. p. 216-243.

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

Lagrou E, Hartsuiker RJ, Duyck W. The influence of sentence context and accented speech on lexical access in second-language auditory word recognition. Bilingualism: Language & Cognition. 2013; 16:508–517.

Laszlo S, Federmeier KD. The N400 as a snapshot of interactive processing: evidence from regression analyses of orthographic neighbor and lexical associate effects. Psychophysiology. 2011; 48:176–186. [PubMed: 20624252]

Linck JA, Kroll JF, Sunderman G. Losing access to the native language while immersed in a second language: Evidence for the role of inhibition in second language learning. Psychological Science. 2009; 20:1507–1515. [PubMed: 19906121]

Loncke M, Desmet T, Vandierendonck A, Hartsuiker RJ. Executive control is shared between sentence processing and digit maintenance: Evidence from a strictly timed dual-task paradigm. Journal of Cognitive Psychology. 2011; 23:886–911.

Luo L, Luk G, Bialystok E. Effect of language proficiency and executive control on verbal fluency performance in bilinguals. Cognition. 2010; 114:29–41. [PubMed: 19793584]

Martin CD, Thierry G, Kuipers J, Boutonnet B, Foucart A, Costa A. Bilinguals reading in their second language do not predict upcoming words as native readers do. Journal of Memory and Language. 2013; 69:574–588.

McDonald JL. Beyond the critical period: Processing-based explanations for poor grammaticality judgment performance by late second language users. Journal of Memory and Language. 2006; 55:381–401.

McLaughlin J, Tanner D, Pitkanen I, Frenck-Mestre C, Inoue K, Valentine G, Osterhout L. Brain potentials reveal discrete stages of L2 grammatical learning. Language Learning. 2010; 60:123–150.

Meuter RFI, Allport A. Bilingual language switching in naming: asymmetrical costs of language selection. Journal of Memory and Language. 1999; 40:25–40.

Misra M, Guo T, Bobb SC, Kroll JF. When bilinguals choose a single word to speak: Electrophysiological evidence for inhibition of the native language. Journal of Memory and Language. 2012; 67:224–237.

Morales J, Gómez-Ariza CJ, Bajo MT. Dual mechanisms of cognitive control in bilinguals and monolinguals. Journal of Cognitive Psychology. 2013; 25:531–546.

Nakano H, Saron C, Swaab TY. Speech and span: working memory capacity impacts the use of animacy but not of world knowledge during spoken sentence comprehension. Journal of Cognitive Neuroscience. 2010; 22:2886–2898. [PubMed: 19929760]

Nuechterlein, KH. Vigilance in schizophrenia and related disorders. In: Steinhauer, SR.Gruzelier, JH., Zubin, J., editors. Handbook of schizophrenia: Vol. 5. Neuropsychology, psychophysiology, and information processing. Amsterdam: Elsevier; 1991. p. 397-433.

Ong G, Sewell DK, Weekes B, McKague M, Abutalebi J. A diffusion model approach to analyzing the bilingual advantage for the Flanker task: The role of attentional control processes. Journal of Neurolinguistics. in press.

den Ouden HEM, Kok P, de Lange FP. How prediction errors shape perception, attention, and motivation. Frontiers in Psychology. 2012; 3(548):1–9. [PubMed: 22279440]

Parker JO, Green DW, Grogan A, Pliatsikas C, Filippopolitis K, Ali N, Lee HL, Ramsden S, Gazarian K, Prejawa S, Seghier ML, Price CJ. Where, when and why brain activation differs for bilinguals and monolinguals during picture naming and reading aloud. Cerebral Cortex. 2012; 22:892–902. [PubMed: 21705392]

Pivneva I, Mercier J, Titone D. Executive control modulates cross-language lexical activation during L2 reading: Evidence from eye movements. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2014; 40:787–796.

Prior A, Degani T, Awawdy S, Yassin R, Korem N. Is susceptibility to cross-language interference domain specific? Cognition. 2017; 165:10–25. [PubMed: 28458090]

Rohrer D, Wixted JT, Salmon DP, Butters N. Retrieval from semantic memory and its implications for Alzheimer's disease. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1995; 21:1127–1139.

Rosvold HE, Mirsky AF, Sarason I, Bransome ED, Beck LH. A continuous performance test of brain damage. Journal of Consulting Psychology. 1956; 20:343–350. [PubMed: 13367264]

Sandoval TC, Gollan TH, Ferreira VS, Salmon DP. What causes the bilingual disadvantage in verbal fluency: The dual-task analogy. Bilingualism: Language and Cognition. 2010; 13:231–252.

Schwartz A, Kroll JF. Bilingual lexical activation in sentence context. Journal of Memory and Language. 2006; 55:197–212.

Swaab, TY., Ledoux, K., Camblin, CC., Boudewyn, MA. Language-related ERP components. In: Luck, SJ., Kappenman, ES., editors. The Oxford Handbook of Event-Related Potential Components. Oxford University Press; 2011.

Tanner D, Inoue K, Osterhout L. Brain-based individual differences in online L2 grammatical comprehension. Bilingualism: Language and Cognition. 2014; 17:277–293.

Teubner-Rhodes SE, Mishler A, Corbett R, Andreu L, Sanz-Torrent M, Trueswell JC, Novick JM. The effects of bilingualism on conflict monitoring, cognitive control, and garden-path recovery. Cognition. 2016; 150:213–231. [PubMed: 26918741]

Titone D, Libben M, Mercier J, Whitford V, Pivneva I. Bilingual lexical access during L1 sentence reading: The effects of L2 knowledge, semantic constraint, and L1-L2 inter-mixing. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2011; 37:1412–1431.

Van Assche E, Drieghe D, Duyck W, Welvaert M, Hartsuiker RJ. The influence of semantic constraints on bilingual word recognition during sentence reading. Journal of Memory and Language. 2013; 64:88–107.

Van Assche E, Duyck W, Gollan TH. Whole-language and item-specific control in bilingual language production. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2013; 39:1781–1792.

Van Berkum JJA. Understanding sentences in context: What brain waves can tell us. Current Directions in Psychological Science. 2008; 17:376–380.

Van Berkum JJA, Hagoort P, Brown CM. Semantic integration in sentences and discourse: Evidence from the N400. Journal of Cognitive Neuroscience. 1999; 11:657–671. [PubMed: 10601747]

Van Hell JG, De Groot AMB. Sentence context affects lexical decision and word translation. Acta Psychologica. 2008; 128:431–451. [PubMed: 18486085]

Van Hell JG, Tanner D. Second language proficiency and cross-language lexical activation. Language Learning. 2012; 62:148–171.

Van Petten C. A comparison of lexical and sentence-level context effects in event-related potentials. Language and Cognitive Processes. 1993; 8:485–531.

Wilson MD. The MRC Psycholinguistic Database: Machine Readable Dictionary, Version 2. Behavioral Research Methods, Instruments and Computers. 1988; 20:6–11.

Appendix

It is possible that an analysis of the high vs. low constraint sentence contexts may reveal patterns of behavior related to prediction and the use of inhibitory control in online reading. Low semantic constraint, in this type of paradigm, does not mean that there is no constraint whatsoever, but rather that the level of constraint is lower than in the ‘high’ condition. Thus, even the low constraint sentence contexts could induce prediction mechanisms, and neutral words, when encountered by the reader, may also elicit prediction error costs like those found for unexpected words in high constraint contexts.

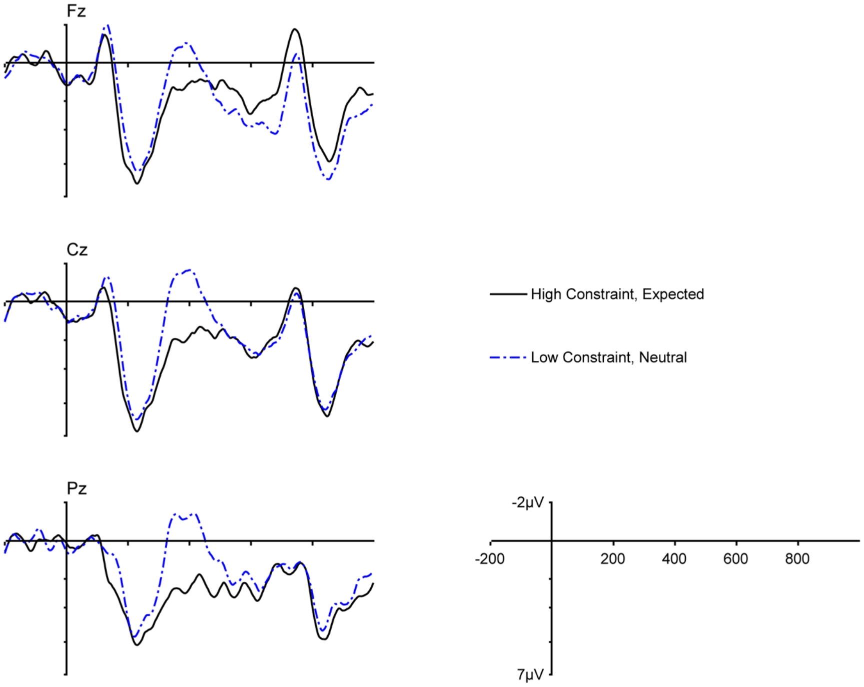
To assess the degree to which neutral vs. expected words might elicit similar effects of control and fluency as those found with unexpected vs. expected words, we conducted a series of correlational and step-wise, multiple regression analyses, like those conducted for the main analysis of Unexpectedness (for more details, please refer to the Results section). First, we report analyses for monolinguals reading in the native language.

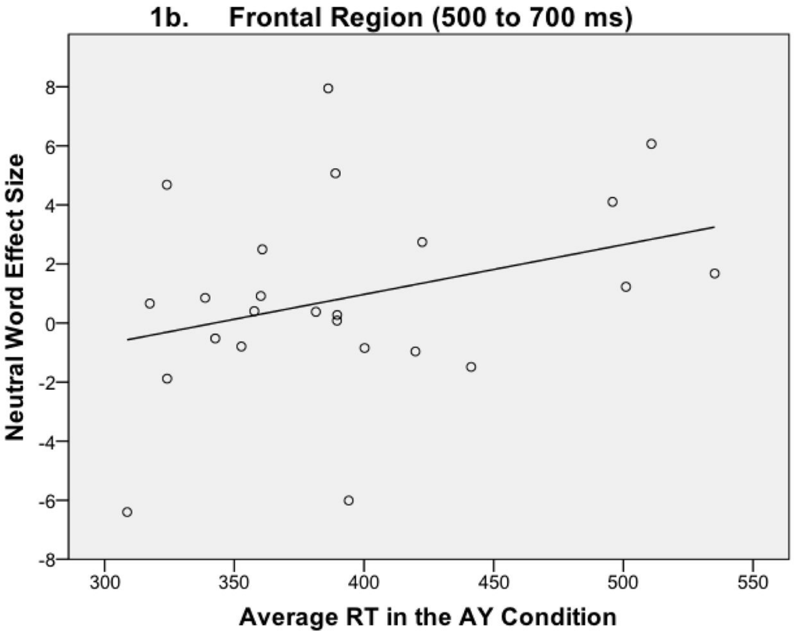
The magnitude of the effect of encountering a neutral vs. expected word did not correlate with verbal fluency or control performance in any of the three time windows for monolinguals (ps > .06). In a multiple regression analysis in the 500 to 700 ms time window, control ability significantly predicted the magnitude of a frontally-distributed positivity for neutral words ($r = .49$ [$r^2 = .24$, $p = .03$]); see Figures 1a and 1b). There were no significant effects for fluency or fluency by control interactions. Thus, it appears that for monolingual readers, neutral words in lower constraint sentence contexts also elicit costs that can be mediated by inhibitory control, suggesting that native readers engage in prediction processes even for moderately constrained sentences.

However, to what extent does low contextual constraint engage prediction processes for L2 readers? For bilinguals reading in the L2, control ability significantly correlated with the magnitude of neutral word cost in the 500 to 700 ms time window, but only for Posterior electrodes ($r = -.42$, $p = .03$). In the 700 to 900 ms time window, speed of processing, as calculated by average RT for correct trials in the control BY condition of the AX-CPT, significantly correlated with the magnitude of neutral word cost for frontal electrodes ($r = .41$, $p = .03$). No other correlations reached significance (ps > .05).

Multiple regression analyses for the effect of L2 fluency and inhibitory control revealed significant effects for the N400, both in the typical 300 to 500 ms time window and beyond (from 500 to 700 ms). From 300 to 500 ms, L2 fluency significantly predicted neutral word costs in posterior electrodes ($r = .52$ [$r^2 = .27$, $p = .02$]), with greater L2 fluency leading to the largest cost for neutral words, and so also the greatest benefit for expected words (see Figures 2a and 2b). From 500 to 700 ms, control performance alone predicted neutral word cost, also for posterior electrodes ($r = .49$ [$r^2 = .24$, $p = .02$]; this main effect of control was also found in the multiple regression analysis for L1 fluency: $r = .51$ [$r^2 = .26$, $p = .03$]). Bilinguals with better inhibitory control had a reduced posterior negativity in this time window, while those individuals with poorer control had a larger and more delayed negativity for neutral words (see Figure 2c). Across all time windows and electrode regions, there was no effect of L1 fluency.

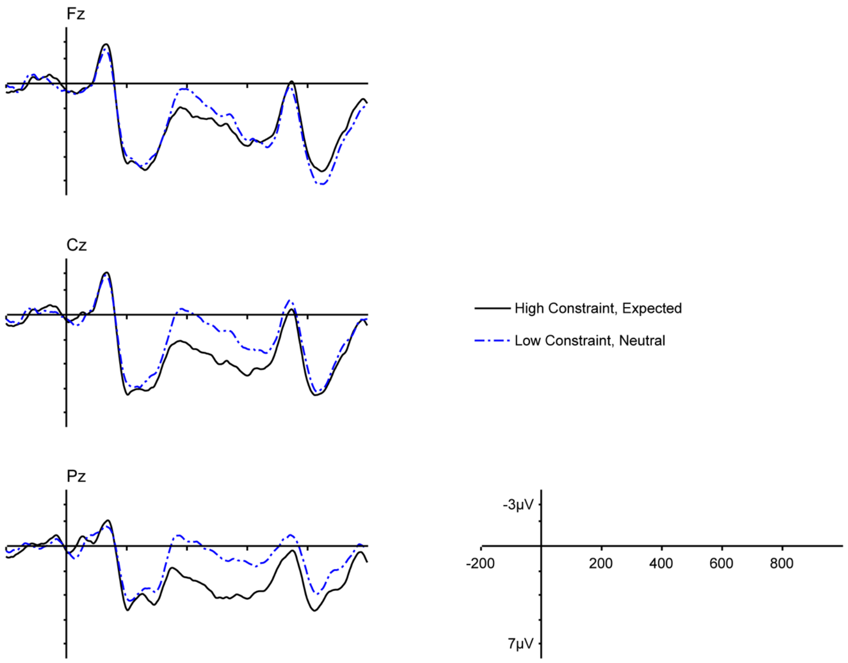
To summarize, bilingual readers did show effects of control and fluency when we contrasted neutral vs. expected target words. Just like in the unexpected vs. expected analysis, L2 fluency impacted the magnitude of the N400 effect for words that were less supported by context, with poorer L2 proficiency leading to a greater cost for neutral or less expected words. Whether this N400 effect extended to the 500 to 700 ms window was mediated by control ability, with lower control bilinguals eliciting larger and later N400 effects. In contrast with monolingual readers, for bilingual readers, we did not find any evidence of a frontal positivity for neutral words. This may indicate that L2 readers do not engage in prediction processes and recovery from prediction error the same way in moderately constrained contexts as monolingual or native readers. High contextual constraint itself may serve as a cue to L2 readers that predictive reading strategies are likely to be useful in that moment, and not add undue burden to the already taxing task of reading in the less dominant language.

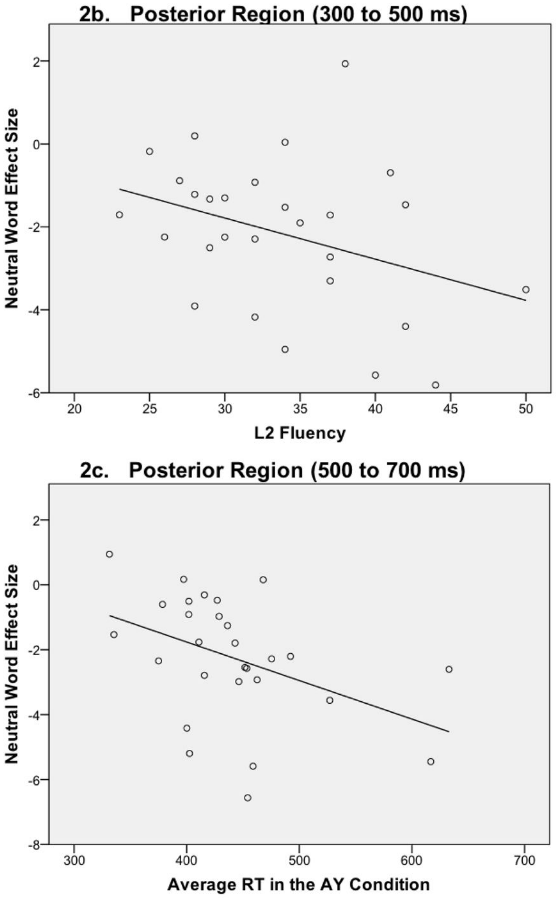




Figures 1a and 1b.

Results for Monolinguals. 1a shows grand average ERP waveforms for the effect of Neutral vs. Expected words. Waveforms are depicted across three representative electrodes in the frontal, central, and posterior regions. 1b shows the linear relationship between AX-CPT performance (in milliseconds) and Neutral word effect size (in microvolts) in the frontal region from 500 to 700 ms. Faster reaction times (RTs) in the AY condition of the AX-CPT indicate better performance, while slower RTs indicate poorer performance.





Figures 2a, 2b, and 2c.

Results for Bilinguals. 2a shows grand average ERP waveforms for the effect of Neutral vs. Expected words. Waveforms are depicted across three representative electrodes in the frontal, central, and posterior regions. 2b shows the linear relationship between L2 fluency (number of words produced) and Neutral word effect size (in microvolts) in the posterior region from 300 to 500 ms. Greater number of words produced indicates higher fluency performance. 2c shows the linear relationship between AX-CPT performance (in milliseconds) and Neutral word effect size (in microvolts) in the posterior region from 500 to 700 ms. Faster reaction times (RTs) in the AY condition of the AX-CPT indicate better performance, while slower RTs indicate poorer performance.

Highlights

- Readers incur processing costs when prediction error occurs in the L1 and L2.
- Inhibitory control ability mediates prediction error costs in the L1 and L2.
- Prediction in the L2 depends on the ability to regulate the native language.
- Bilingualism provides a rich context for the study of control and comprehension.
- The effect of control on prediction error may extend beyond the language domain.

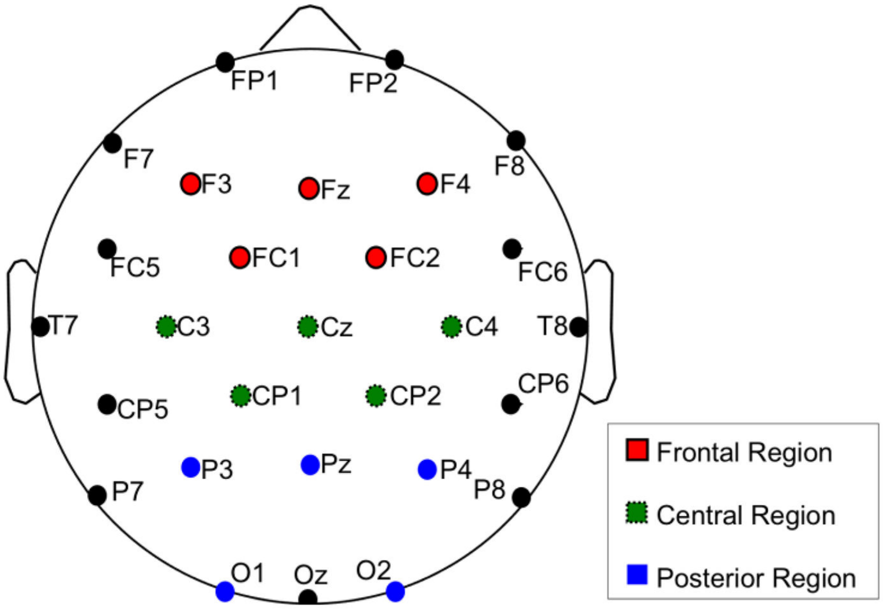


Figure 1.

Scalp montage of recording electrodes with frontal, central, and posterior regions highlighted.

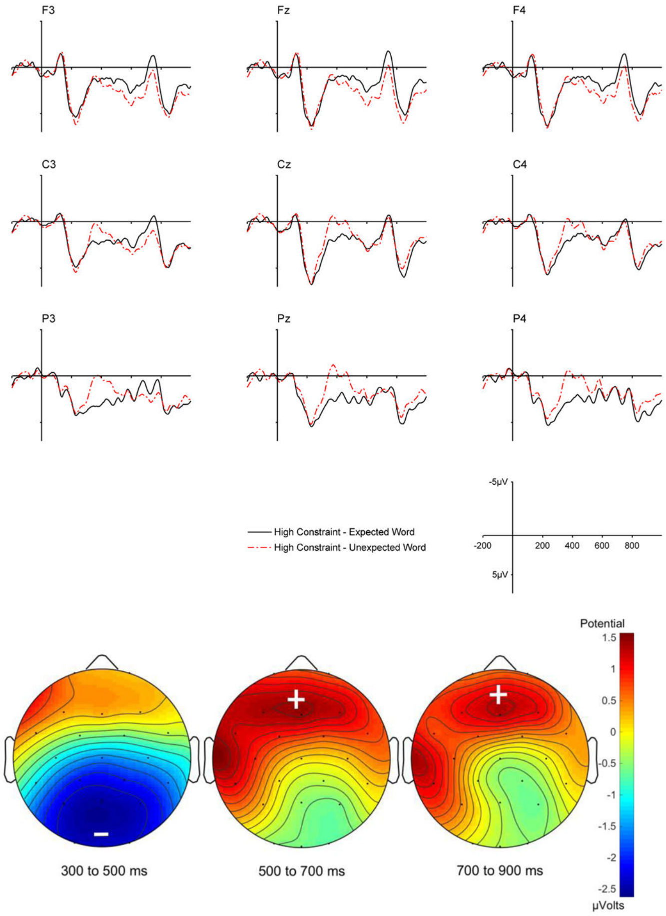


Figure 2.

Grand average ERP waveforms and topographic maps for the effect of Unexpectedness in Monolinguals. Waveforms are depicted across nine representative electrodes in the frontal, central, and posterior regions. The topographic maps indicate the magnitude of the effect of Unexpectedness (unexpected – expected) in High Constraint conditions across all time windows.

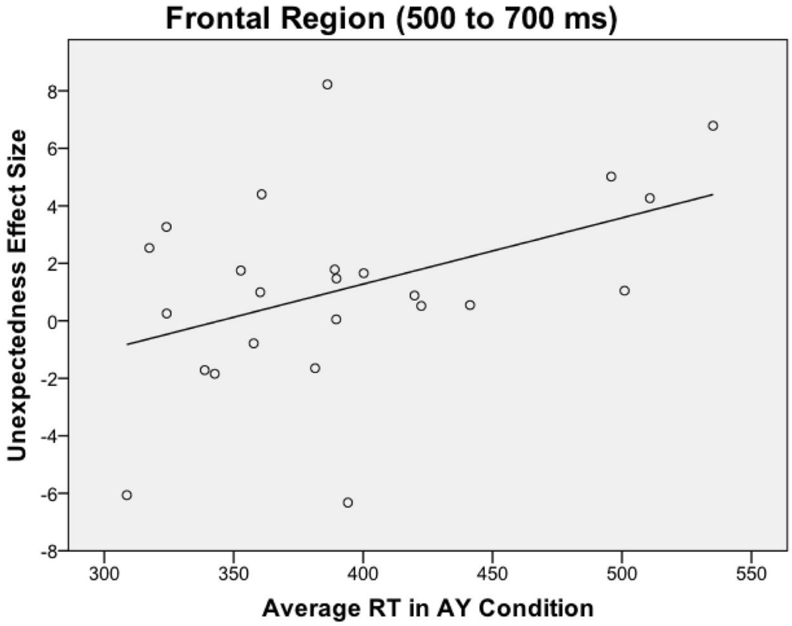


Figure 3.

Linear relationships between AX-CPT performance (in milliseconds) and Unexpectedness effect size (in microvolts) in the frontal region from 500 to 700 ms for Monolinguals. Faster reaction times (RTs) for correct trials in the AY condition of the AX-CPT indicate better control performance, while slower RTs indicate poorer performance.

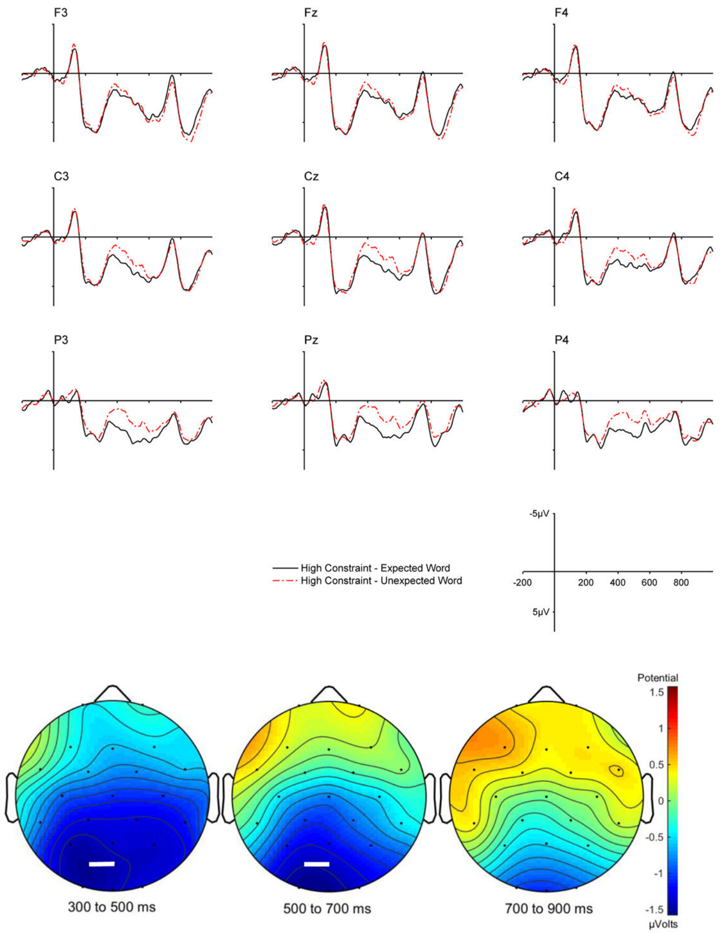
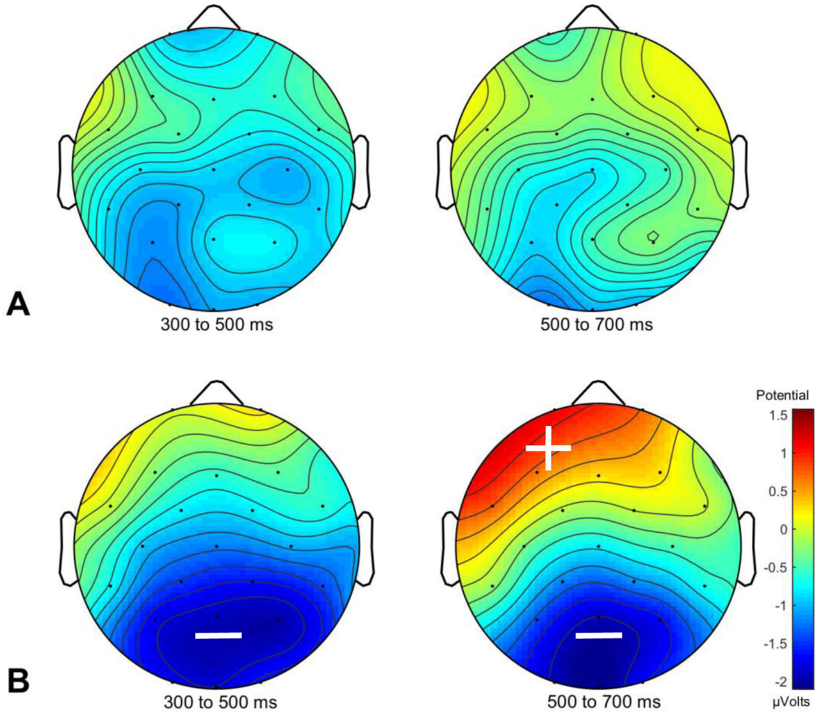


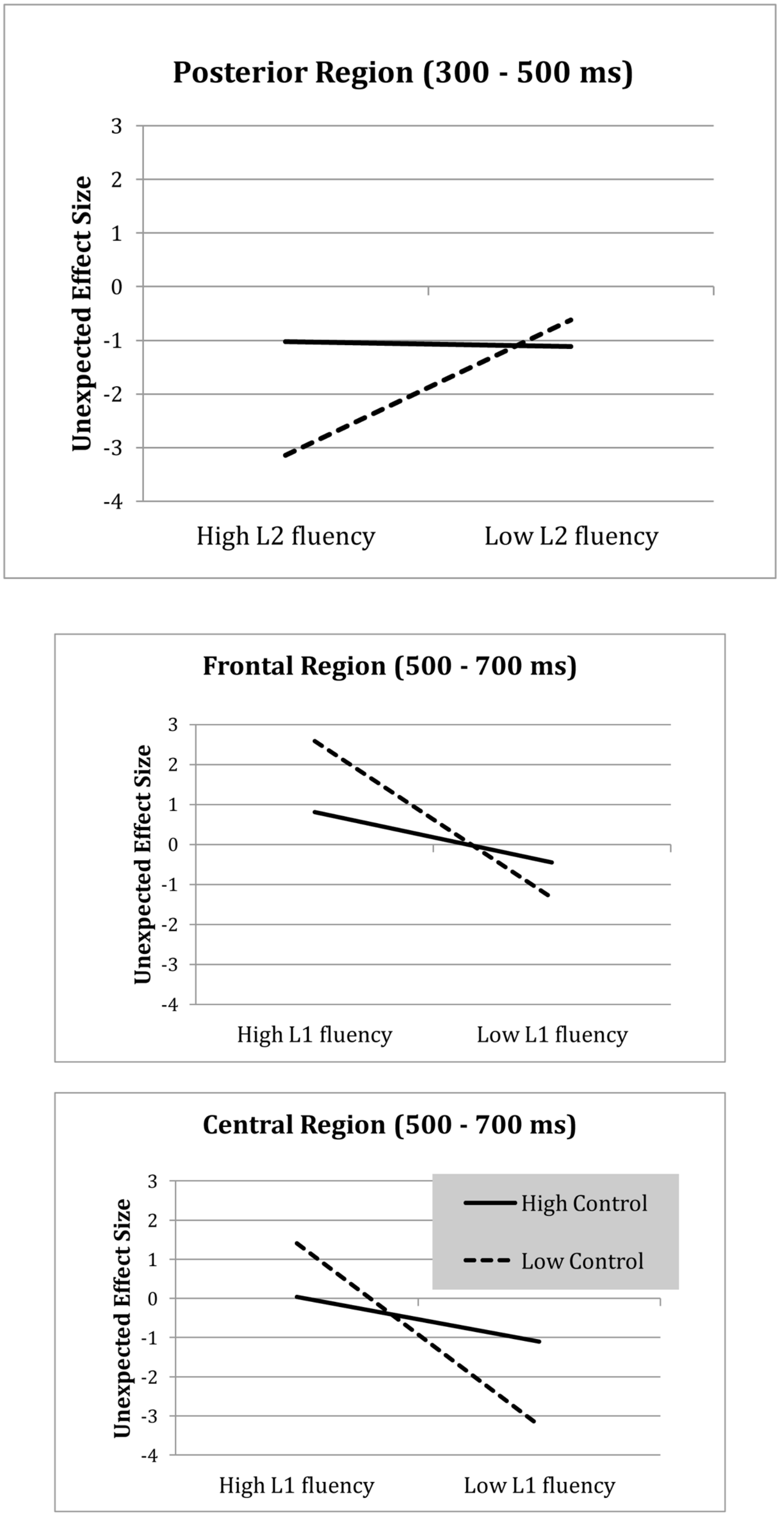
Figure 4.

Grand average ERP waveforms and topographic maps for the effect of Unexpectedness in Bilinguals. Waveforms are depicted across nine representative electrodes in the frontal, central, and posterior regions. The topographic maps indicate the magnitude of the effect of Unexpectedness (unexpected–expected) in High Constraint conditions across all time windows.



Figures 5a and 5b.

Topographic maps for the effect of Unexpectedness in (A) High Control Bilinguals and (B) Low Control Bilinguals. The topographic maps indicate the magnitude of the effect of Unexpectedness (unexpected–expected) in High Constraint conditions in the 300 to 500 and 500 to 700 ms time windows. (For illustrative purposes, participants were grouped according to a median split on their performance in the AY condition of the AX-CPT. High control bilinguals responded correctly to AY trials at an average speed of 397 ms, while low control bilinguals performed more slowly, with response times averaging 490 ms.)



Figures 6a, 6b, and 6c.

Simple slopes plots for the influence of Verbal Fluency on the effect of Unexpectedness at High and Low levels of control ability for Bilinguals. (A) shows the simple slopes results for

L2 fluency and the posterior region from 300 to 500 ms, (B) for L1 fluency and the frontal region from 500 to 700 ms, and (C) for L1 fluency and the central region from 500 to 700 ms. All plots demonstrate the magnitude of the effect of Unexpectedness at High and Low levels of Fluency (L1 or L2) for High Control bilinguals (solid line) and Low Control bilinguals (dotted line).

Table 1

Example sentences for each of the three conditions in the reading task.

Sentence Stem	Target	Sentence Ending
High Constraint; Expected Word		
After their meal, they forgot to leave a	tip	for the waitress.
High Constraint; Unexpected Word		
After their meal, they forgot to leave a	ten	for the waitress.
Low Constraint; Neutral Word		
Before leaving, they were asked to leave a	tip	for the waitress.

Note: ERPs were time-locked to target words.

Table 2

Mean proportions of errors and reaction time performance on the AX-CPT for monolinguals.

	Errors	Reaction Times (ms)
Monolinguals		
AX	.07 (.06)	298 (37)
AY	.27 (.16)	407 (49)
BX	.11 (.13)	223 (45)
BY	.13 (.14)	226 (46)

Note: Standard deviations are reported in parentheses.

Table 3

Repeated measures ANOVA results for the effect of Expectedness and Anteriority for Monolinguals in Experiment 1.

	300 to 500 ms			500 to 700 ms			700 to 900 ms		
	F	***df***	***p***	***F***	***df***	***p***	***F***	***df***	***p***
Monolinguals									
Unexpectedness	<1	1,23	n.s.	<1	1,23	n.s.	<1	1,23	n.s.
U x A	6.78	2,46	*	14.32	2,46	***	6.78	2,46	*
U x E	5.70	4,92	**	6.47	4,92	**	5.70	4,92	**
U x A x E	3.29	8,184	*	1,32	8,184	.276	3.29	8,184	*

Note:

[*] p<.05,

[**] p<.01,

[***] p<.001,

n.s. = non-significant; For interactions, U = Unexpectedness, A = Anteriority, and E = Electrode.

Table 4

Results for repeated measures ANOVA analyses within Frontal, Central, and Posterior electrode regions for Monolinguals (Experiment 1).

		300 to 500 ms		500 to 700 ms		700 to 900 ms	
		F	***p***	***F***	***p***	***F***	***p***
Monolinguals							
Frontal	Unexpectedness	<1	n.s.	2.66	n.s.	2.19	n.s.
	U x Electrode	6.77	**	3.36	*	4.36	*
Central	Unexpectedness	5.46	*	<1	n.s.	<1	n.s.
	U x Electrode	6.92	**	5.88	**	6.18	**
Posterior	Unexpectedness	13.36	**	<1	n.s.	<1	n.s.
	U x Electrode	<1	n.s.	3.10	n.s.	3.62	*

Note:

[*] p<.05,

[**] p<.01,

[***] p<.001,

n.s. = non-significant. For interactions, U = Unexpectedness.

Degrees of freedom for main effects of Unexpectedness and Unexpectedness by Electrode interactions were (1,23) and (4,92).

Table 5

Correlations between Control, Verbal Fluency, and their interaction with the effect of Unexpectedness for Monolinguals.

		Control	**VF**	**C x VF**
300 to 500 ms	Frontal	.42*	.13	.33
	Central	.32	.08	.17
	Posterior	.22	.01	.09
500 to 700 ms	Frontal	.43*	−.06	.23
	Central	.31	−.07	.08
	Posterior	.22	.01	.09
700 to 900 ms	Frontal	.41*	.01	−.05
	Central	.20	−.03	−.16
	Posterior	.00	−.07	−.13

Note: VF = Verbal Fluency, C = Control (AX-CPT performance was based on correct RTs to the AY condition only). All correlations reported here are based on centered variables used in the multiple regression analyses. Control, Verbal Fluency, and their interaction term were not significantly correlated (ps>.05).

Note:

*p<.05.

Table 6

Unstandardized (b) and standardized partial coefficients (β) and significance levels (p) for multiple regression analyses on the relationship between Cognitive Control, Verbal Fluency, and Unexpectedness in the 500 to 700 millisecond time window for Monolinguals.

	Predictor	**b**	**β**	**p**
Frontal	Constant	.868		
	Control	.028	.533	.01*
	VF	−.122	−.319	.14
	C x VF	.001	.191	.34
Central	Constant	.118		
	Control	.021	.401	.09
	VF	−.095	−.246	.30
	C x VF	.000	.048	.82
Posterior	Constant	−.494		
	Control	.013	.256	.30
	VF	−.042	−.117	.63
	C x VF	.000	.065	.78

Note: VF = Verbal Fluency, C = Control.

Table 7

Mean proportions of errors and reaction time performance on the AX-CPT for bilinguals.

	Errors	Reaction Times (ms)
Bilinguals		
AX	.07 (.06)	331 (51)
AY	.16 (.15)	440 (67)
BX	.20 (.21)	275 (128)
BY	.11 (.16)	290 (66)

Note: Standard deviations are reported in parentheses.

Table 8

Repeated measures ANOVA results for the effect of Expectedness and Anteriority for Bilinguals in Experiment 2.

	300 to 500 ms			**500 to 700 ms**			**700 to 900 ms**		
	F	***df***	***p***	***F***	***df***	***p***	***F***	***df***	***p***
Bilinguals									
Unexpectedness	12.81	1,27	**	2.56	1,27	n.s.	<1	1,27	n.s.
U x A	7.56	2,54	**	12.23	2,54	**	7.15	2,54	**
U x E	1.01	4,108	n.s.	3.30	4,108	*	2.22	4,108	n.s.
U x A x E	<1	8,216	n.s.	<1	8,216	n.s.	<1	8,216	n.s.

Note:

[*] p<.05,

[**] p<.01,

[***] p<.001,

n.s. = non-significant; For interactions, U = Unexpectedness, A = Anteriority, and E = Electrode.

Table 9

Results for repeated measures ANOVA analyses within Frontal, Central, and Posterior electrode regions for Bilinguals in Experiment 2.

		300 to 500 ms		500 to 700 ms		700 to 900 ms	
		F	***p***	***F***	***p***	***F***	***p***
Bilinguals							
Frontal	Unexpectedness	2.62	n.s.	<1	n.s.	<1	n.s.
	U x Electrode	<1	n.s.	1,39	n.s.	<1	n.s.
Central	Unexpectedness	12.23	**	2.59	n.s.	<1	n.s.
	U x Electrode	1.54	n.s.	2.34	n.s.	<1	n.s.
Posterior	Unexpectedness	30.18	***	9.55	**	2.47	n.s.
	U x Electrode	<1	n.s.	1.78	n.s.	2.71	n.s.

Note:

** p<.01,

*** p<.001,

n.s. = non-significant. For interactions, U = Unexpectedness.

Degrees of freedom for main effects of Unexpectedness and Unexpectedness by Electrode interactions were (1,27) and (4,108).

Table 10

Correlations between Control performance, L2 Verbal Fluency, and their interactions with the effect of Unexpectedness for Bilinguals.

		Control	**L2 VF**	**C x L2 VF**
300 to 500 ms	Frontal	−.12	−.08	.00
	Central	−.12	−.04	−.19
	Posterior	−.25	−.06	−.28
500 to 700 ms	Frontal	−.02	.07	−.08
	Central	−.13	.14	−.19
	Posterior	−.32	.09	−.16
700 to 900 ms	Frontal	.12	.03	−.02
	Central	.09	.09	−.16
	Posterior	−.17	−.01	−.16

Note: VF = Verbal Fluency, L2 = English, C = Control (AX-CPT performance was based on correct RTs to the AY condition only). All correlations reported here are based on centered variables used in the multiple regression analyses. Control, L2 Verbal Fluency, and their interaction term were not significantly correlated (ps>.05).

Table 11

Unstandardized (b) and standardized partial coefficients (β) and significance levels (p) for multiple regression analyses on the relationship between Cognitive Control, L2 (English) Verbal Fluency, and Unexpectedness in the 300 to 500 millisecond time window for Bilinguals.

	Predictor	**b**	**β**	**p**
Frontal	Constant	−.599		
	Control	−.004	−.142	.49
	L2 VF	−.038	−.128	.58
	C x L2 VF	.000	−.074	.75
Central	Constant	−1.172		
	Control	−.004	−.165	.41
	L2 VF	−.052	−.199	.38
	C x L2 VF	−.001	−.294	.20
Posterior	Constant	−1.477		
	Control	−.006	−.322	.09
	L2 VF	−.063	−.301	.15
	C x L2 VF	−.001	−.439	.04*

Note: L2 = English, VF = Verbal Fluency, C = Control.

Table 12

Correlations between Control performance, L1 Verbal Fluency, and their interactions with the effect of Unexpectedness for Bilinguals.

		Control	**L1 VF**	**C x L1 VF**
300 to 500 ms	Frontal	−.12	.05	.35◆
	Central	−.12	.07	.17
	Posterior	−.25	.08	.11
500 to 700 ms	Frontal	−.02	.32	.37*
	Central	−.13	.37*	.35◆
	Posterior	−.32	.28	.31
700 to 900 ms	Frontal	.12	.32	.24
	Central	.09	.33	.22
	Posterior	−.17	.23	.26

Note:

*p<.05,

◆p<.06;

VF = Verbal Fluency, L1 = Chinese, C = Control (AX-CPT performance was based on correct RTs to the AY condition only). All correlations reported here are based on centered variables used in the multiple regression analyses. Control, L1 Verbal Fluency, and their interaction terms were not significantly correlated (ps>.05).

Table 13

Unstandardized (b) and standardized partial coefficients (β) and significance levels (p) for multiple regression analyses on the relationship between Cognitive Control, L1 (Chinese) Verbal Fluency, and Unexpectedness in the 500 to 700 millisecond time window for Bilinguals.

	Predictor	**b**	**β**	**p**
Frontal	Constant	.022		
	Control	−.009	−.243	.21
	L1 VF	.081	.300	.07
	C x L1 VF	.001	.346	.04*
Central	Constant	−.712		
	Control	−.003	−.093	.59
	L1 VF	.109	.398	.03*
	C x L1 VF	.001	.382	.03*
Posterior	Constant	−1.240		
	Control	−.009	−.291	.10
	L1 VF	.074	.307	.09
	C x L1 VF	.001	.318	.08

Note: L1 = Chinese, VF = Verbal Fluency, C = Control.