Individual Differences in Proactive and Reactive Control in Bilinguals

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Abstract

This study investigated individual differences in bilinguals' use of proactive and reactive control processes during an executive control task (the AX-CPT) in relation to aspects of the bilingual experience (e.g., second language proficiency). Participants were presented with cue-target letter pairs, one letter at a time (AX, AY, BX, or BY; B and Y are any letter other than A or X) and were instructed to press the "yes" button for AX pairs and the "no" button for any other pair. They completed three blocks which varied in terms of the most frequent trial type (AX-70% vs. AY-70% vs. BX-70%). Event-related brain potentials (ERPs) were recorded from 15 young adult bilinguals during the AX-CPT. The N2, an ERP related to conflict detection, was analyzed in conjunction with behavioural performance.

Individual variations in cognitive control strategy were differentially associated with aspects of bilingualism in the AX-70 and AY-70 blocks. In the AX-70 block, greater engagement of proactive control was associated with shorter overall reaction times (RTs), lower accuracy, and enhanced conflict detection. In the AY-70 block, a proactive strategy was associated with lower accuracy, but similar RTs compared to a reactive strategy.

Different patterns of association were found between self-reported language-switching behaviours and cognitive control strategy in the AX-70 block compared to the AY-70 block.

The results support the idea of individual differences in the relative use of proactive and reactive mechanisms in bilinguals. These differences were related to aspects of language-switching which is an important source of interindividual variability among bilinguals.

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Individual Differences in Proactive and Reactive Control in Bilinguals

Executive control (also referred to as cognitive control) is an integral part of the cognitive system and is involved in the regulation and coordination of one's cognitive processes (Koechlin, Ody, & Kouneiher, 2003). Some examples of cognitive control processes include working memory (i.e., the capacity to maintain, manipulate, and update information for brief periods of time in the presence of concurrent distractions or processing demands), problem solving, inhibiting irrelevant information, planning, and the ability to flexibly alternate between tasks. Evidence suggests that bilingualism influences cognitive control, with bilinguals faring better than monolinguals on various tasks that involve inhibition (e.g., Bialystok et al., 2005), task switching (e.g., Prior & Macwhinney, 2009), and conflict resolution (e.g., Costa, Hernández, & Sebastián-Gallés, 2008). However, both the nature (e.g., Kroll & Bialystok, 2013) and the very existence (e.g., de Bruin, Treccani, & Della Sala, 2014; Hilchey & Klein, 2011; Klein, 2014, Paap & Greenberg, 2013) of this bilingual advantage are heavily debated. In an attempt to clarify the nature of the advantage and explain the inconsistent empirical findings, this thesis explored individual differences in aspects of bilingualism (e.g., proficiency, age of acquisition) and their relation to cognitive control.

Prior to examining the reasons behind the emergence of a bilingual advantage in cognitive control, one must review cognitive abilities in general. Cognitive abilities are characterized by their capacity to adapt. This propensity for change and adaptation is often referred to as *plasticity* (Kolb & Whishaw, 1998), a term which has seen many different definitions over the years (for a brief review, see Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010). However, it is generally accepted that cognitive abilities can be influenced or modified through extended use and learning experiences.

Closely related to plasticity is the concept of *flexibility* of cognitive abilities. Whereas plasticity denotes changes in the amount or the nature of cognitive resources available, flexibility refers to the ability to alter how these resources are used in order to efficiently meet task demands (Lövdén et al., 2010).

Both plasticity and flexibility have important ramifications for the extended development and maintenance of cognitive abilities. Extensive use of a given cognitive ability typically yields performance improvements on tasks that involve this particular ability (e.g., Morales, Yudes, Gómez-Ariza, & Bajo, 2014). This boost in performance can theoretically come from three sources: 1) an increase in the amount of cognitive resources available (i.e., plasticity), 2) the development or refinement of strategies to engage cognitive resources more efficiently (i.e., flexibility), or 3) a combination of the above.

Regardless of the mechanism by which the extended use of a given cognitive ability leads to changes in performance, one important question remains: are these gains domain-specific? This idea is akin to the idea of *transfer* in the field of cognitive training (for a review see Barnett & Ceci, 2002). In this field, it is generally accepted that there are two main types of transfer: *near transfer* and *far transfer* (Schunk, 2004). Near transfer occurs when the benefits of cognitive training extend past the specific task that was trained, but stay within the same cognitive domain (e.g., seeing an improvement in a task of working memory following training on a different task of working memory). In contrast, far transfer refers to situations in which training-related gains in a cognitive ability that differs from the one that was explicitly trained (e.g., seeing an improvement in verbal fluency following working memory training).

While bilingualism itself does not constitute a form a cognitive training, the bilingual advantage in cognitive control is reminiscent of the concept of cross-domain (i.e., far) transfer found in the cognitive training literature. Stated differently, it seems that the experience of learning and using two languages can afford extralinguistic cognitive advantages. However, it is unclear how bilingualism modulates the cognitive mechanisms necessary for this advantage to emerge. This explains, in part, why the bilingual advantage is the focus of an intense (and passionate) debate. In turn, this debate led to the development of several theories in an attempt to explain the bilingual advantage.

Why a bilingual advantage in executive control?

There is empirical evidence suggesting that bilingualism can afford an advantage in executive control. However, the mechanism by which this advantage emerges is still debated. It is generally thought that the bilingual advantage stems from the need to manage two different languages that are simultaneously activated. This idea has been supported by behavioral (e.g., Colomé, 2001; Kroll & De Groot, 1997) and imaging studies (e.g., Altvater-Mackensen & Mani, 2007; Hoshino & Thierry, 2012; Li et al., 2012; Marian, Spivey, & Hirsch, 2003; Martin, Dering, Thomas, & Thierry, 2009).

One early behavioral study (Guttentag, Haith, Goodman, & Hauch, 1984) had participants look at words belonging to one of four possible categories (e.g., metal, clothing, furniture, trees). Two of these categories were assigned to one response key and the other two categories were assigned to a second response key. Participants were instructed to press the appropriate response key as quickly as possible. However, each target word had flanker words above and below it. These flanker words were presented in the participants' second language (L2) and could belong to any of four categories: L2 translation of the target word, a different word drawn from the same semantic category as the target word, a word from a different semantic category that requires the same response, or a word from a different semantic category that requires a different response. The authors found that reaction time was much slower in the last two conditions. In other words, the categories of the flankers were analyzed to some degree despite the fact that they were presented in the language that was not actively used.

In another behavioural experiment, Colomé (2001) had Catalan-Spanish bilinguals perform a phoneme judgment task. Participants were presented with a phoneme and a picture, and were asked to determine whether the phoneme was part of the Catalan name of the picture. The phonemes could either be part of the Catalan name, part of the Spanish translation, or absent from both names. Overall, Catalan-Spanish bilinguals took longer to reject the phonemes that appeared in Spanish translations of the name of the picture compared to the control condition in which the phoneme did not appear in either the Catalan or Spanish names. Colomé also tested a group of Catalan monolinguals. This group did not show the same slowing of response time for Spanish translations. Colomé therefore concluded that both languages are activated at the same time.

Brain imaging studies have also yielded evidence for the simultaneous activation of bilinguals' two languages. A study by Martin et al. (2009) used event-related brain potentials (ERPs) to investigate language activation during a cross-linguistic priming task. Participants were presented with one of the following types of prime-target word pairs: semantically related English prime/English target, semantically related Welsh prime/Welsh target, semantically related English prime/Welsh target, semantically related Welsh prime/English target, as well as semantically unrelated versions of all the previous prime-target pair types. The author used the N400 ERP component to investigate the priming effect. This component has been found to be modulated by semantic integration, such that the amplitude of the N400 is typically smaller when a target word has been semantically primed by the preceding word (Kutas & Hillyard, 1980). Martin and colleagues found a reduction in the amplitude of the N400 component when the target words were primed, regardless of whether the prime and the target words were in the same language. From this, they concluded that both languages can be simultaneously activated.

In another brain imaging study, Altvater-Mackensen and Mani (2007) had German-English bilinguals listen to German sentences while recording ERPs. In each sentence, the target word (i.e., the subject of the clause) was either a German-English homophone, a German word that shares phonological similarities with English words, or a German word that shares no phonological relation to English words. The authors found reduced amplitude of the N400 component for German-English homophones and German words that shared phonological similarities with English words. However, this effect was restricted to early bilinguals who learned their second language before age 6.

In yet another study, Thierry and Wu (2004) investigated cross-linguistic activation in Chinese-English bilinguals. They presented their participants with pairs of English words and were asked to determine whether the words were semantically related. Half of the pairs were composed of semantically related words whereas the other half was comprised of unrelated words. Unbeknownst to the participants, the Chinese translations of the English word pairs either shared a Chinese character or not (i.e., hidden form repetition). Unsurprisingly, semantically unrelated word pairs elicited the largest N400 components. However, this effect was modulated by form repetition such that semantically unrelated word-pairs that shared a Chinese character elicited the largest N400 component. The authors suggested that this modulation in the N400 component is due to conflict that arises when the English words are not semantically related but are nonetheless associated through the shared Chinese character in their translated form.

In a follow-up study, Thierry and Wu (2007) updated their methodology to control for word concreteness, length of the implicit Chinese translations, and position of the shared character in the Chinese translations of the English stimuli. Word concreteness is known to influence the amplitude of the N400 component, with concrete words yielding larger N400 components compared to abstract words (Kounios & Holcomb, 1994). The length of Chinese translations and the position of the shared character was controlled in order to allow participants to build an unconscious representation of how character repetition may occur (Thierry & Wu, 2007). Using this updated paradigm, the authors found a main effect of semantic relatedness (i.e., smaller N400 components for semantically related words) and a main effect of character repetition (i.e., smaller N400 components for pairs that share a Chinese character). In contrast to what was found in the previous experiment, these two effects did not interact. This is further evidence that bilinguals' two languages are activated during language processing, although this phenomenon may occur outside of individuals' awareness.

With two languages simultaneously activated, bilinguals are put in a unique position. During language production, they have to resolve competition not only from within-language alternatives (something that monolinguals also have to deal with), but also from between-language alternatives for the same idea or concept (e.g., dog, chien). This creates the need for a language selection mechanism. Because bilinguals may have to deal with both of their languages on a regular basis, this frequent use of language selection mechanisms is thought to be the reason for the development of a bilingual advantage in executive control.

While most researchers agree that there must be a language selection mechanism, the nature of this mechanism is a topic of debate. There are two main competing theories: inhibitory language selection (e.g., Green, 1998; Green & Abutalebi, 2013; Green, 2011), and language-specific selection (Costa, Santesteban, & Ivanova, 2006).

Selection through inhibition. Green's inhibitory control model (Green, 1998) is perhaps the most influential example of a selection mechanism driven by inhibition. According to this model, there exists a conceptualizer that builds language-independent conceptual representations.

In other words, these representations are not initially bound to any particular language. According to Green (and following Levelt, 1989), language-independent conceptual representations eventually map onto lexical concepts. These lexical concepts are in turn associated with lemmas which specify the syntactic properties necessary to use the concept in a sentence. Furthermore, Green (1998) suggests that these lemmas have *language tags*, which identify the language to which each lemma belongs.

According to Green's theory, the course of language selection goes as follows: 1) the conceptualizer produces a conceptual representation accompanied by the intention to produce speech in a specific language, 2) relevant lexical concepts and their associated lemmas are activated, 3) lemmas with languages tags from the unwanted language are suppressed, resulting in higher activation levels of lemmas with language tags from the wanted language, 4) the lemma with the highest level of activation is presumably selected. Because the suppression of irrelevant lemmas is applied after they have been activated, Green's model is a **reactive** model of language selection (Green, 1998).

The inhibitory control model of language selection makes an interesting prediction regarding language switching. Since the unwanted language must be inhibited in order for the wanted language to be selected, the amount of inhibition required should be proportional to the activation level of the unwanted language. When unbalanced bilinguals (bilinguals who are much more proficient in their L1 than their L2) use their L2, they must exert a considerable amount of inhibition to suppress a strong L1. In comparison, inhibiting their weaker L2 is much easier. Therefore, this should lead to asymmetrical language-switching costs, with L2 to L1 switches taking longer than L1 to L2 switches. This is precisely what Meuter and Allport (1999; see also Campbell, 2005) found when asking bilinguals to switch between their two languages in an unpredictable manner during a number naming task. Furthermore, Costa & Santesteban (2004) replicated these results in L2 learners but found symmetrical language-switching costs in highly proficient bilinguals (in which L1 and L2 should presumably be activated to the same extent).

Language-specific selection. Green's inhibitory language selection model is reactive in nature because it postulates that irrelevant language nodes are suppressed after they have been initially activated by the conceptualizer. However, another popular view is that language selection could happen through a **proactive** mechanism. Costa and Caramazza (1999) have described a model in which only nodes belonging to the wanted language are considered for production. Because the selection mechanism is language-specific, there is no need for inhibitory mechanisms to suppress the unwanted language (Costa et al., 2006).

This language-specific selection theory suggests that language selection goes as follows: 1) a conceptual representation (along with a representation of the wanted language) is produced, 2) relevant lexical concepts and their associated lemmas are activated, 3) the selection mechanisms considers all activated concepts from the target language, and 4) the concept with the highest level of activation is presumably selected for production.

Costa and Santesteban (2004) found asymmetrical language-switching costs in highly proficient bilinguals under certain circumstances. These individuals showed the symmetrical language-switching cost typical of highly proficient bilinguals when switching from L1 to L2 and from L2 to L1. This is consistent with the inhibitory control model. However, these bilinguals showed symmetrical language-switching costs when switching from a strong L2 to a weak L3. The authors proposed that highly proficient bilinguals (and individuals who speak more than two languages) may consistently show symmetrical switching costs because they stop relying on inhibitory mechanisms and use a language-specific selection mechanism instead. However, Costa et al. (2006) found asymmetrical language-switching costs in highly proficient bilinguals when switching from a weak L3 to a weak L4. Thus, it seems that highly proficient bilinguals resort to inhibitory mechanisms in some situations and not in others.

Both inhibition and language-specific activation have been proposed as language selection mechanisms. However, they may not be mutually exclusive. In other words, it is possible that bilinguals inhibit the irrelevant language in certain contexts, and instead rely on language-specific selection mechanisms in others.

The bilingual advantage in executive control

Following the hypothesis that executive control mechanisms are intrinsically involved in bilingual language selection, several measures of executive control such as the Stroop (Stroop, 1935) and Simon (Simon & Small, 1969) tasks have been used to compare the performance of monolinguals and bilinguals. While all of these tasks require some engagement of executive functions for optimal performance, they may not all involve the same components of executive control. This is because executive control is not a unitary construct. For example, Miyake and collaborators (2000) identified three separate, but correlated, executive functions: inhibition, shifting between mental sets, and updating and monitoring of working memory. These are considered to be more circumscribed, lower level functions (as opposed to functions like "planning") which are easier to operationally define. Because executive functions are diverse, any findings of a bilingual advantage in executive control should be qualified in terms of the specific executive component –or components– on which bilinguals outperform monolinguals.

Unfortunately, such qualification proves to be a difficult endeavour for many reasons. Firstly, any measurement of executive function must necessarily be embedded within a task. Thus, any score derived from executive function tasks reflects not only executive control itself, but also individual variations in mostly unrelated attributes (e.g., motor speed or articulation speed). In other words, executive function tasks are *impure*: they do not offer a measure of unique variance captured by individual differences in executive control (Fan, McCandliss, & Sommer, 2002; Miyake & Friedman, 2012; Valian, 2014)

Secondly, the components of executive control proposed by Miyake et al. (2000) are correlated. This suggests the existence of a common factor that links the three components. Miyake and Friedman (2012) used a latent variable analysis approach in order to understand this common factor. They concluded that when the common variance shared by all executive control components is accounted for, there is no unique variance left for the inhibition component. In other words, inhibition seems to correlate almost perfectly with the common executive factor previously proposed in Miyake et al. (2000). Based on these results, the authors proposed that there exists a *shifting-specific* component, an *updating-specific* component, and a common factor that reflects the ability to actively maintain goals and task-relevant information in such a way as to bias lower-level processing (Miyake & Friedman, 2012).

On the basis of the preceding information, it becomes difficult to organize the empirical findings on the bilingual advantage in executive control in a coherent manner. Because executive function tasks are impure, organizing the findings according to the tasks that were used says relatively little about the critical executive components at play. For the same reason, outlining the findings according to the specific executive control component involved leaves many tasks unaccounted for. In light of this dilemma, a hybrid approach in which the tasks are organized according to the main executive component they tap into (allowing for tasks to specifically tap into the common executive component outlined by Miyake and Friedman) seems most appropriate.

Shifting

Switching, also known as "shifting", can be conceptualized as flexibility in transitioning from one task-set representation to another (Miyake & Friedman, 2012). This executive control process may be akin to the one(s) used by bilinguals when switching between two languages (Bialystok, Craik, Green, & Gollan, 2009). This idea was suggested by Peal and Lambert (1962) who noted that bilingual children may enjoy greater mental flexibility due to their ability to easily switch between languages.

Experimental studies of task switching often involve the rapid classification of stimuli based on one criterion or another. For example, participants presented with a series of coloured shapes could be asked to classify each stimulus based on its shape *or* based on its colour. Classification time is typically reduced when successive trials use the same criterion (e.g., colour). In contrast, participants take longer to classify a stimulus when the criterion is changed. This phenomenon is known as a *switching cost*. In addition to this switching cost, experimental studies of task switching can evaluate something called a *mixing cost*. This phenomenon refers to the overall slowing of classification time in blocks where participants are asked to switch between sorting criteria compared to blocks in which they always use a single criterion. In other words, switching costs are local effects at the level of the trials whereas mixing costs are a more global effect observed at the level of blocks of trials.

There is evidence that bilinguals have an advantage in maintaining task set (Colzato et al., 2008). Based on this evidence, it was suggested that bilinguals may exhibit reduced mixing costs due to their superior ability to maintain task-relevant information. However, the evidence for a bilingual mixing advantage is inconsistent. Bialystok and collaborators (2006) had monolingual and bilingual participants respond on either the same or the opposite side of a visual target depending on the preceding cue. In this study, bilinguals showed smaller mixing costs than monolinguals. However, this mixing advantage was not replicated in further studies. For example, Prior and MacWhinney (2009) had participants classify stimuli by colour or by shape. While they did not find a mixing advantage for bilinguals, they found a switching advantage. In other words, bilinguals performed faster than monolinguals when instructed to change their classification criterion from one trial to another.

Further experiments narrowed down this bilingual switching advantage. Prior and Gollan (2011) compared two groups of bilinguals: one group that reported frequently switching between their two languages, and another group that reported very few switches. A switching advantage was found for the group of bilinguals who reported frequent switches compared to the second group of bilinguals. In contrast, Soveri, Rodriguez-Fornells and Laine (2011) found a relation between language switching and mixing cost rather than switching cost. Other studies have failed to find either a bilingual switching or mixing advantage (Hernández, Martin, Barceló, & Costa, 2013; Paap & Greenberg, 2013)

Updating

There is a relative paucity of experimental evidence to support a bilingual advantage in working memory. For example, Bialystok (2008) reports no difference in performance between 544 adult monolinguals and bilinguals on simple working memory tasks requiring participants to order increasing strings of words or two-digit numbers.

Bialystok and collaborators (2008) used the Corsi blocks test in which participants have to touch wooden blocks according to a predetermined order demonstrated by the experimenter. Participants were younger and older adults. Both groups were further divided between monolingual and bilingual speakers. There were no group differences (i.e., age or language group) when participants were asked to touch blocks in the same order as the experimenter (i.e., forward span). In contrast, younger adults did better than older adults when asked to touch the blocks in reverse (i.e., backward span). Furthermore, younger bilinguals outperformed younger monolinguals. This suggests that younger bilinguals were more apt to maintain their performance level when faced with greater working memory demands compared to their monolingual counterparts.

Feng and collaborators (2007) designed a working memory task to test this hypothesis. They presented adult participants with matrices composed of 25 squares arranged in a 5x5 pattern. During the task, some squares are filled in with red. Participants are asked to memorize and subsequently recall the location of the red squares. There was no difference in performance between monolinguals and bilinguals when they were asked to simply recall the red squares in the same order. In contrast, bilinguals outperformed monolinguals when the task required participants to recall the red squares according to a complex ordering rule (e.g., from left to right for each row, going from the top row to the bottom row). The authors argued that this difference in performance was not due to absolute differences in working memory capacity since both groups performed similarly in baseline conditions. Rather, bilinguals may be more apt than monolinguals to effectively and efficiently engage their working memory resources in the face of demanding executive control tasks.

Common executive factor

A large proportion of the empirical evidence for a bilingual advantage in executive control comes from studies which used tasks that primarily involve what Miyake et al. (2000) formerly labeled “inhibition” or “inhibitory control”. However, the interpretation that the bilingual advantage on these tasks represents “enhanced inhibitory control” may not be accurate given Miyake and Friedman’s (2012) finding that inhibition is virtually indistinct from the common executive factor. For historical reasons, the findings outlined below will be interpreted in light of both the inhibition factor (Miyake et al., 2000) and the common executive factor (Miyake & Friedman, 2012).

Inhibitory control. Inhibitory control can be defined as the ability to volitionally inhibit prepotent, dominant, or automatic responses (Miyake et al., 2000). One task that involves such inhibitory processes is the Simon task (e.g., Craft & Simon, 1970; Simon & Small, 1969; see Lu & Proctor, 1995 for a review). In this task, stimuli hold two potentially conflicting types of information: target information that cues the participant for the correct response (e.g., different colours for the left or right responses keys) and irrelevant spatial information (i.e., the stimuli are presented either on the left or right portion of the computer screen). The conjunction of these two properties yields congruent trials (i.e., the colour and the position converge on the same response key) and incongruent trials (i.e., the colour and the position indicate contradictory responses). On incongruent trials, participants have to inhibit a prepotent answer indicated by the position of the stimulus presented on the screen, and instead answer based solely on its colour. This leads to longer reaction times (RT) on incongruent trials compared to congruent trials, a phenomenon known as the Simon effect.

Some studies have found that bilinguals exhibit a smaller Simon effect than monolinguals (e.g., Bialystok, 2006; Bialystok et al., 2005; Bialystok, Craik, Klein, & Viswanathan, 2004). This has been taken as evidence that bilinguals enjoy superior inhibitory control, thus allowing them to swiftly suppress the prepotent answer indicated by incongruent spatial cues in order to quickly produce a correct answer.

The Simon task is not the only task of inhibitory control on which bilinguals outperform monolinguals. Indeed, there is evidence of a bilingual advantage on the Stroop task (Stroop, 1935). In the original version of this task, participants are asked to name the colour of the ink that words are printed in. For some of these words, the colour of the ink and the name of the colour are congruent (i.e., the word RED printed in red ink). On other trials, the colour of the ink and the name of the colour are incongruent (i.e., the word GREEN printed in blue ink). On incongruent trials, participants must therefore inhibit a strong prepotent response (i.e., reading the word that is presented to them) and name the colour of the ink instead. This results in shorter reaction times on congruent trials compared to incongruent trials (the Stroop effect).

As with the Simon effect, there is some evidence for a smaller Stroop effect in bilinguals (e.g., Bialystok, Craik, & Luk, 2008; Zied et al., 2004; but see Kousaie & Phillips, 2012 for a conflicting account in which no difference in Stroop effect was found). In other words, this evidence suggests that bilinguals are better than monolinguals at inhibiting the prepotent tendency to read words. This leads to a smaller difference in reaction time between congruent and incongruent trials.

There is evidence for a bilingual advantage in other tasks such as the flanker task both on its own (Emmorey, Luk, Pyers, & Bialystok, 2008) and as part of the Attention Network Task (e.g., Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa et al., 2008). In the flanker task, participants are presented with a central target (usually an arrow or a chevron) accompanied by distractors on either side (*flankers*). The flankers can either point in the same direction as the target (i.e., congruent trials) or in the opposite direction (i.e., incongruent trials). On incongruent trials, participants must inhibit the prepotent tendency to answer based on the direction of the flankers, leading to slower RTs. Here, the bilingual advantage is characterized by faster RTs on incongruent trials for bilinguals compared to monolinguals.

Monitoring. The tasks outlined in the previous section were described as having a strong component of inhibitory control. However, in light of recent developments in the study of executive functions (Miyake & Friedman, 2012), this interpretation may not be accurate. Miyake and Friedman proposed that the factor common to all executive functions is the ability to actively maintain goals and task-relevant information in such a way as to bias lower-level processing. Based on this conceptualization, the tasks outlined above can be interpreted as involving a strong monitoring component. Going a bit further, it seems that all of these tasks require individuals to monitor for potentially conflicting task-relevant information. Thus, the common executive factor may involve mechanisms by which conflict is detected and resolved.

The Simon, Stroop, and flanker tasks all contain stimulus-stimulus conflict (Stroop), stimulus-response conflict (Simon), or both (flanker). Therefore, the fact that bilinguals exhibit faster RTs than monolinguals on these tasks may reflect an advantage in conflict detection and resolution.

This interpretation is substantiated by the finding that bilinguals do not only exhibit faster RTs than monolinguals on incongruent trials, but also on congruent trials. This has been found using the Simon task (Bialystok et al., 2004; Bialystok, 2006), the flanker task (Emmorey et al., 2008), and the Attention Network Task (Costa et al., 2008).

Dual modes of cognitive control

Miyake and Friedman's (2012) conceptualization of executive control is mostly concerned with the **nature** of the executive processes that individuals use. Another popular conceptualization of executive control is primarily concerned with **how** executive processes are engaged. This conceptualization asserts that individuals can exert **proactive control** and/or **reactive control** (Braver, Paxton, Locke, & Barch, 2009). In the proactive control mode, goal-relevant information is actively maintained before the onset of cognitively challenging tasks (Braver et al., 2009). As a result, the proactive control mode biases one's attention to task-relevant information in order to anticipate and help prevent interference before it happens.

In contrast, the reactive control mode is akin to a late correction mechanism that engages and directs attentional resources on an "as needed" basis. Thus, reactive control relies on the detection and resolution of conflict after its onset (Braver et al., 2009).

Interestingly, the definition of the proactive control mode closely resembles that of the common executive control factor proposed by Miyake & Friedman (2012). On the other hand, the reactive control mode is reminiscent of Miyake et al. (2000)'s earlier concept of inhibitory control. Since inhibitory control has since been integrated to the common executive control factor, this suggests that proactive and reactive control are not necessarily two distinct types of executive function, but perhaps two ways to engage executive control resources in general.

The AX version of the Continuous Performance Test (AX-CPT; Braver et al., 2001) is often used to examine fluctuations in the use of executive control mechanisms. In this task, participants are presented with four types of cue-target pairs of letters: AX, AY (where Y is any letter other than A or X), BX (where B is any letter other than A or X), and BY. Participants are asked to press a key every time they see an X target preceded by an A cue.

The AX-CPT is thought to be sensitive to the use of both proactive and reactive control mechanisms. Since there is a delay between the offset of the cue and the onset of the target, participants can prepare their response based on the information given by the cue. When participants see a cue, they can already prepare their response (or lack thereof) by actively maintaining both the goal of the task (i.e., press a button only for AX pairs) and the nature of the cue (A cue vs. B cue). This is indicative of proactive control processes.

However, another viable strategy is to simply wait until the target is presented. In the event that the target is an X, the participants can retrieve the cue that was presented before in order to decide whether they should press the button or not. On the other hand, if the target is a Y there is no need to mentally go back to the cue in order to choose the appropriate answer. This type of "just-in-time" engagement of cognitive control processes is indicative of a reactive control strategy.

The AX-CPT has been used in studies that aim to compare the use of proactive and reactive control mechanisms in bilinguals and monolinguals. Morales and collaborators (2013) used the AX-CPT in a behavioural study comparing Spanish monolinguals and early bilinguals who spoke Spanish and another language. In this experiment, they instructed participants to produce a response for every single trial (i.e., a "yes" button press in response to AX pairs and a "no" button press for all other pairs). This difference in methodology was introduced in order to compare participants' RT and accuracy across all trial types. Participants completed 100 trials of the AX-CPT split into the typical proportions (i.e., 70% AX, 10% AY, 10% BX, and 10% BY). The authors analysed error rates for non-AX trials across both language groups. They found that accuracy was lowest for AY trials for both monolinguals and bilinguals. However, bilinguals committed significantly fewer errors than monolinguals on AY trials. The authors subsequently compared participants' performance on AY trials and BY trials in order to investigate cognitive control strategies. They reasoned that high error rates on AY trials may be in part due to participants' reliance on a proactive strategy which biases them towards a "yes" answer when they see an A cue. In contrast, reliance on a proactive strategy should lead to few errors on BY. If participants use a reactive strategy, there should be little to no difference in accuracy between AY and BY trials. The authors found that both monolinguals and bilinguals committed more errors on AY trials than on BY trials, suggesting that most participants relied on a proactive strategy. However, they argued that monolinguals relied on a proactive strategy to a greater degree than bilinguals as evidenced by higher error rates on AY trials. The authors further suggested that bilinguals may be better able to flexibly alter the way they exert their cognitive control resources (i.e., switching between proactive and reactive control strategies).

In a follow-up study, Morales and collaborators (2014) used electroencephalograpy and event-related brain potentials to further investigate differences in how monolinguals and bilinguals exert their cognitive control resources. They used a similar methodology to the one in their 2013 article. Once again, monolinguals and bilinguals relied primarily on a proactive strategy to complete the AX-CPT. As well, bilinguals committed fewer errors than monolinguals on AY trials. The authors also compared monolinguals' and bilinguals' evoked brain responses after seeing the Y target in AY trials. They found evidence that bilinguals were more sensitive to the conflict between the A cue (i.e., "you will likely have to press the yes button") and the Y target (i.e., "you have to press the no button"). Furthermore, bilinguals showed greater electrophysiological evidence of inhibitory processes coming into play upon seeing the Y target compared to their monolingual counterparts. The authors suggested that bilinguals may be more accurate than monolinguals on AY trials because they are better able to flexibly disengage from a proactive mode and use reactive control mechanisms when necessary.

The state of the bilingual advantage hypothesis

The empirical findings of a bilingual advantage in executive control are notoriously inconsistent (e.g., Hilchey & Klein, 2011; Paap & Greenberg, 2013). This is sometimes taken as evidence that the bilingual advantage simply does not exist (e.g., de Bruin et al., 2014) and that positive findings reflect spurious associations between bilingualism and cognitive control (perhaps mediated by other variables such as socioeconomic status).

The burden of proof therefore falls on proponents of the bilingual advantage hypothesis who must find a way to explain the empirical inconsistencies. There are different viable explanations to choose from. One possibility is that the size of the effect of bilingualism on cognitive control is quite small, especially in young adults at the peak of their cognitive capabilities.

Another possibility is that individual differences in the bilingual experience may modulate the way individuals engage their cognitive control resources. This could explain why some studies find a bilingual advantage in executive control, whereas some studies do not replicate these findings.

Bilinguals clearly differ on a wide range of language-related variables. For example, even if we assume that two bilinguals have the same L1 and L2, they may differ in terms of when they acquired their L2, how proficient they are in their L2, how often they use both of their languages, etc. All of these differences may affect how bilinguals manage their two languages, thereby modulating what is believed to be the root of the bilingual advantage in executive control. In this perspective, bilingualism does not inherently afford an advantage in executive control. Rather, certain aspects of the bilingual experience may differentially contribute to the development of domain-general executive control mechanisms. If this is the case, it would not be surprising to find that not all bilinguals exhibit an advantage in cognitive control.

Assessing individual differences

The fact that bilinguals are not all cut from the same cloth presents an exciting –albeit challenging – opportunity to investigate specific aspects of the bilingual experience. For theoretical and practical reasons, we will narrow down to a few that seem important and promising, namely proficiency, age of acquisition, code-switching. We will also assess dynamic variations in the use of executive control mechanisms as they relate to the aforementioned aspects of the bilingual experience.

Assessing individual differences in the bilingual experience. Bilinguals can differ on a large number of factors (e.g., proficiency in L2, age of acquisition of L2, social context, switching between languages). For this reason, it could be argued that there are as many "bilingual experiences" as there are bilingual individuals. Thus, it makes little sense to look at bilingualism as a monolith. It is more productive to study specific aspects of bilingualism and investigate how individual differences in these specific aspects may or may not relate to differences in cognitive control.

In the context of this study, we focused on two particular aspects of the bilingual experience: proficiency in L2, and code-switching. These factors were chosen because individual differences may have strong implications for how bilinguals manage their two languages. Since language selection mechanisms are thought to be at the core of the bilingual experience, proficiency and code-switching should be carefully studied.

As bilinguals become more proficient in their second language, they are faced with a greater number of opportunities for intra and cross-linguistic competition. Presumably, higher L2 proficiency requires the recruitment of more cognitive control mechanisms in order to properly manage the two languages and select one of them for speech production.

Code-switching is another important –albeit complex – factor to consider. The concept of code-switching refers to bilinguals' unique ability to alternate between or mix their two languages within the context of a single speech production episode (Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012). Code-switching can be elicited proactively (e.g., actively monitoring for relevant languages cues) or reactively (e.g., in response to an interlocutor switching), allowing for a large range of individual variations. Assuming similar levels of proficiency, differences in patterns of code-switching behaviours may reflect more fundamental differences in language control mechanisms such as the ones described earlier in this text. For example, bilinguals who generally code-switch proactively may be more apt to deal with cross-linguistic interference in a controlled, deliberate fashion by using language cues available in the environment to aid in language selection. In contrast, bilinguals who primarily code-switch reactively may be more likely to switch in response to stimuli (internal or external) without having planned to do so. In other words, differences in types of code-switching may be mediated by differences in language control mechanisms.

Assessing behavioral differences in cognitive control. In order to assess individual differences in cognitive control, a fairly sensitive task is needed. The AX-CPT (Braver et al., 2001) is particularly advantageous because it allows one to investigate how individuals engage both proactive and reactive control processes. As described earlier, participants are presented with different types of cue-target pairs of letters (AX, AY, BX, and BY) and are asked to press a key every time they see an X target preceded by an A cue. However, in the original version of the paradigm, the AX pairs are much more frequent than the other trials types (i.e., 70% AX vs. 10% AY, BX, and BY). This asymmetry in the number of pairs from each type creates a prepotent tendency to prepare a response when seeing an A cue (i.e., proactive process). However, this preprotent tendency must be overridden from time to time (i.e., on AY trials) through a more reactive process.

The AX-CPT offers a practical way to index the degree to which participants generally rely on proactive or reactive processes. This can be done by comparing the average RT on BX trials and AY trials (Braver et al., 2001). Of course, this technique necessitates that participants produce a response (i.e., a button press) for each trial rather than only for AX trials.

Proactive processes during the AX-CPT. If an individual uses mostly proactive processes, their RT should be faster on BX trials compared to AY trials. Indeed, the cue on BX trials (i.e., B) contains all the information necessary to determine the appropriate answer. In contrast, A cues are ambiguous because there is still the possibility that a Y target will appear. This results in slower RTs on AY trials in a mostly proactive mode.

Reactive processes during the AX-CPT. The opposite pattern is expected when participants rely principally on reactive control processes. In the reactive mode, cognitive control processes are only engaged *as needed*. On AY and BY trials, the target holds all the information needed to determine the appropriate response. This negates the need to mentally go back to the cue and appraise the pair. In contrast, AX and BX trials contain an ambiguous target. Upon seeing the X, participants must mentally go back to the cue in order to determine the appropriate answer. This results in faster AY and BY trials compared to AX and BX trials. However, the comparison of AY and BX trials is the most useful because both trial types have the same frequency (i.e., 10% of trials) and use the same response key.

In the context of this study, the AX-CPT is used to investigate whether individual differences in the degree to which bilinguals use proactive or reactive control processes relates to aspects of the bilingual experience such as L2 proficiency and code-switching.

Assessing electrophysiological differences in cognitive control. Variations in the use of proactive and reactive control mechanisms may not be easily detected through behavioural measures alone. Indeed, comparable behavioural performances (e.g., reaction time, accuracy) may be mediated by different patterns of cognitive control. These dynamic patterns of use of cognitive control mechanisms can be investigated through ERP analysis. ERPs are derived from an electroencephalogram (EEG) which measures the ongoing mass summation of neuronal action potentials. While EEG measurement is continuous, ERPs are stimulus-locked. In other words, ERPs reflect neuroelectrical activity following a stimulus of interest. Both EEG and ERPs have excellent temporal resolution (in the realm of milliseconds), making them ideally suited to the study of rapidly changing cognitive processes such as executive control (Michel et al., 2004).

ERP components are typically named after their voltage and their time of onset (latency). For example, the N400 component is a negative shift in voltage that generally occurs approximately 400 milliseconds (ms) after the onset of a stimulus. This component has been linked to semantic processing (Kutas & Hillyard, 1980). In addition to their voltage and latency, ERP components can be described in terms of their distribution on the scalp (topography). Using this information, it is possible to investigate neural responses to various stimuli of interest.

Studies of cognitive control in bilinguals are often interested in the N2 component. Much like the N400, the N2 is characterized by a negative shift in voltage. However, it typically occurs between 200 and 350 ms post stimulus, and is thought to reflect aspects of conflict detection (Folstein & Van Petten, 2008). In terms of topography, the N2 is typically largest in anterior regions of the head (i.e., a fronto-central distribution).

Few studies have investigated the N2 component during the AX-CPT. One such study was conducted by Dias, Foxe and Javitt (2003) with 11 adults (no indication of language status). They analysed ERPs after the presentation of target letters in the AX-CPT and found larger N2 components on AY trials compared to other trials. They reasoned that this increase in amplitude reflects the conflict between cue-generated expectancy about the target letter and the actual target letter. As discussed earlier, the original version of the AX-CPT biases participants to prepare a response when they see an A cue because these cues are most often associated with an X target. When participants see a Y target, there is significant conflict between their plan (i.e., produce a response) and the information provided by the target (i.e., withhold a response). This results in a larger N2 component.

The study by Morales and collaborators (2014; presented earlier) also analysed the N2 component during performance of the AX-CPT by bilinguals and monolinguals. They found that bilinguals exhibited larger N2 components compared to monolinguals on AY trials, suggesting enhanced conflict detection in bilinguals.

In summary, there is a wealth of evidence to suggest the existence of a bilingual advantage in executive control. However, the current literature lacks both consistency and consensus regarding the nature of this advantage and how it manifests itself during the performance of various cognitive and executive control tasks. The bilingual advantage is often taken as a monolithic construct, with scientists debating whether its presence or absence in various groups. However, the bilingual experience is incredibly diverse. Bilingual individuals vary in terms of which L2 they speak, their L2 proficiency, the age at which they acquired their second language, how frequently they use both languages, and more. All of these factors are likely to impact how bilinguals manage and control their two languages. Since language control mechanisms are thought to be at the core of the bilingual advantage, it is crucial to investigate how individual differences in the bilingual experience related to differences in cognitive and executive control performance.

Code-switching is one important source of variability in the bilingual experience. It is a complex pattern of behaviour(s) unique to bilinguals. Of course, L2 proficiency plays an important role in determining the kinds of code-switching behaviours that an individual can use. Thus, code-switching and L2 proficiency are two important aspects of the bilingual experience to study.

The AX-CPT is particularly well-suited to the study of cognitive control because it affords opportunities to exert both proactive and reactive control mechanisms. Because these mechanisms are engaged and disengaged very quickly, ERPs are particularly well-suited to study them. Furthermore, ERPs allow to investigate potential differences in how participants completed the task even if there are no behavioural differences.

It is hypothesized that the bilinguals in the present study will vary in the degree to which they rely on proactive versus reactive control strategies to complete the AX-CPT. Furthermore, participants who rely mostly on a proactive strategy should tend to respond faster overall but make more errors on high-conflict trials (e.g., AY trials) compared to participants who use a reactive strategy. In contrast, participants who rely primarily on a reactive strategy should be slower overall but be more accurate on high-conflict trials. In terms of electrophysiological results, participants who use a proactive strategy should exhibit larger N2 components with earlier onsets compared to participants who rely on a reactive strategy. This is because proactive strategies reflect the maintenance of the cue until the onset of the target. On high-conflict trials, this should result in more sensitive conflict detection (i.e., greater amplitude of the N2) as well as earlier detection of said conflict (i.e., earlier onset of the N2). In terms of code-switching, participants who use a proactive control strategy should experience fewer unwanted switches compared to participants who use a reactive strategy. Participants who mostly rely on proactive control should tend to actively maintain task-relevant information in mind and language is presumably part of such information. In contrast, participants who rely primarily on reactive control strategies should report more contextual switches. Since reactive control operates on an "as needed" basis, individuals who rely on it should switch based on internal contextual cues (e.g., when talking about specific topics) more often than individuals who rely mostly on a proactive control.

Methods

Participants

All participants had to be right-handed, be between the ages of 18 and 35, and be in self-reported good health. In terms of language use, participants were required to be English-French or French-English bilinguals with no functional knowledge of any other languages. Adherence to these criteria was verified by administering a health history questionnaire over the phone prior to the first testing session (see Appendix A). The goal of this questionnaire was to collect demographic information whilst simultaneously ensuring eligibility of the participants based on the aforementioned criteria.

From this process, 15 individuals (11 females, 4 males) were recruited, tested, and yielded analysable data (see Table 1). All were between the ages of 18 and 35 (*M* = 23.8, SD = 4.26) and were residents of the Montréal area at the time of testing. Participants were tested on two occasions. The first session was dedicated to the collection of ERP data while participants completed the AX-CPT. In the second session, participants completed an extensive battery of cognitive and executive control tests (see Appendix B). This battery was designed to allow us to assess individual differences in cognitive ability and executive functioning, and how these differences may relate to differential patterns of performance on the AX-CPT. The project was approved by the Concordia University ethics research board and all participants provided informed consent prior to participating.

Bilingual Language-Switching Questionnaire

This questionnaire, developed by Rodriguez-Fornells and collaborators (2012), is a self-report measure assessing how frequently bilinguals code-switch and what kind of switches they engage in. The questionnaire contains 12 questions evenly divided between four factors: L2 to L1 Switches, L1 to L2 Switches, Contextual Switches (e.g., topics for which an individual will always switch), and Unwanted Switches (i.e., switches that are involuntary or out of the individual's awareness). Table 2 presents the 12 questions organised into their respective factors.

The Bilingual Language-Switching Questionnaire and its factor structure were validated using data from 566 Spanish-Catalan bilinguals. The authors used exploratory factor analysis to extract the proportion of common variance explained by each of the factors (L2 to L1 Switches = 0.23; L1 to L2 Switches = 0.25; Contextual Switches = 0.24; Unwanted Switches = 0.15).

Stimuli

The task used in this study consisted of a modified version of the AX-Continuous Performance Test (AX-CPT) which itself is a variation of the Continuous Performance Test

(CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956). In the original version of the AX-CPT, participants are presented with cue-target pairs of letters and are instructed to press a button when they see an X (target) only if it was preceded by an A (cue). Four possible cue-target pair types are presented: AX, AY (where Y is any letter other than A or X), BX (where B is any letter other than A or X), and BY. The majority (i.e., 70%) of trials are of the AX variety, with the rest of the trials comprised of an equal proportion of AY, BX, and BY trials. This creates a context in which most trials call for a button press and a small proportion of trials require participants to inhibit this prepotent response tendency.

The current study used a modified version of the AX-CPT as described by Dias et al (2003). This version contains 3 different blocks: AX-70, AY-70, and BX-70. The name of each block refers to the most frequent trial type within the block (e.g., AX-70 contains 70% AX trials). In each case, the distribution of probabilities for the different trial types creates a *global context*. In contrast, the information given by the cue creates a *local context* that is circumscribed to the current trial. The local context can be consistent with or differ from the global context (see Table 3).

The AX-CPT paradigm used in the current study mostly followed the parameters established by Dias and collaborators (2003), with one important difference. In the current study, participants were instructed to produce a motor response (i.e., a button press) for every trial rather than only for AX trials. In other words, participants were to press a “yes” button in response to AX trials and press a “no” button in response to any other combination of letters. This modification was made to ensure that the electrophysiology data recorded for each trial would be comparable and to exclude the possibility that observed differences in brain activity may be due to artifacts introduced by the necessity to produce a motor response on AX trials compared to other trials.

The additional blocks proposed by Dias and collaborators (2003) each pose different cognitive control challenges. In the AX-70 block (the traditional AX-CPT paradigm), X targets are frequent and are often cued correctly (i.e., they frequently occur as part of an AX trial). Thus, this block creates a bias towards pressing the "yes" key in response to the target (i.e., a global *yes* context). For this reason, one of the main challenges of the AX-70 block is for participants to voluntarily inhibit this prepotent "yes" response when presented with a BX trial. A different type of conflict arises during AY trials. In this trial type, participants are presented with a cue that is consistent with the global *yes* context and they must inhibit the prepotent "yes" answer based solely on the information afforded by the Y target.

In the AY-70 block, A cues are still very frequent but they occur within a global *no* context because AX pairs are infrequent. For this reason, the AY-70 block does not create a bias towards a "yes" response. On the contrary, it creates a bias towards associating A cues with a "no" response. Thus, the main challenge of the AY-70 block is for participants to quickly override a "no" response and instead produce a "yes" response upon seeing infrequent X targets.

In the BX-70 block (global *no* context), the challenge is two-fold. On one hand, participants have to maintain a representation of the infrequent A cue in order to produce the correct response. On the other hand, they must override a strong bias towards responding "no" to X targets which are now only infrequently associated with A cues.

This modified version of the AX-CPT allows us to examine dynamic variations in how bilinguals engage their cognitive control resources. Additionally, it allows one to investigate how bilinguals adapt to contextual changes (i.e., going from one block to the other) in order to maintain and achieve a goal.

In the present study, cue-target pairs were presented one letter at a time in the center of a 16.1" CRT monitor with a resolution of 1280 x 1024 pixels. All letters were chosen from the following subset: C, D, H, K, L, N, P, T, V, W, Y, Z. For each trial, the cue was presented for a total of 350 milliseconds (ms), followed by 750 ms of a blank screen with a black background. After this interval, the target appeared and remained on the screen for 350 ms. Participants had a response window of 1.55 seconds, making each trial last a maximum of 3 seconds. In an effort to make it easier to identify cue-target pairings, cues were presented in a white font, whereas targets were presented in a green font. Both cues and targets were shown in a 64 pt Verdana font. A trigger was sent at the onset of each cue and target using *Inquisit 3.0* (2007). This triggers are necessary for ERP analysis as they send a signal to the recording system which is embedded into the participant's EEG recording. This makes is possible to localize and analyze brain activity that happens directly after the cue (i.e., cue-locked activity) or the target (i.e., target-locked activity).

Procedure

Each participant completed the health and language history questionnaire over the phone prior to the first testing session in order to ensure eligibility. On the day of the first testing session, participants were informed of the nature of the experiment, were given the opportunity to ask questions, and were asked to give informed consent. They were then asked to sit in a comfortable chair while the EEG system was set up (following the procedure outlined in the next section). Upon completion of the setup, participants had their seat adjusted in order to ensure that they were at eye-level with the screen.

The experiment was controlled by *Inquisit 3.0.* Participants worked through three blocks (AX-70, AY-70, BX-70) presented in a counterbalanced order. Additionally, participants completed an auditory version of the AX-70 block in which they had to listen to spoken cue-target pairs of letters. This auditory block was also presented in a counterbalanced order, with half of the participants completing it before the visual blocks and the other half completing it after the visual blocks. The data from this auditory block has yet to be fully analysed and is therefore not included in this thesis.

Before the first visual block, participants were given instructions on how to perform the task. Participants were told that they would see pairs of letters on the screen and that the letters would appear one at a time. They were instructed to press the "yes" button (identified by a green sticker) when they saw an A followed by an X. They were also asked to press the "no" button (identified by a red sticker) when they saw any other pair of letters. Of note, the response buttons were also counterbalanced across participants (see Appendix C) for a list of the different presentation orders). Participants then completed a practice block comprised of a total of 30 trials chosen randomly from all four trial types. During this practice block, participants received feedback after each button press.

Before each experimental block, participants were reminded of the instructions. Within each block, they were presented with 300 pairs of letters (see Table 2 for the number of trials from each trial type). In order to minimize fatigue, participants were given the opportunity to take a break every 100 trials. At this time, the experimenter would go back into the room and answer any of the participant's questions or engage in brief conversation in order to alleviate fatigue. The experimenter would also take this opportunity to make any necessary adjustments to the EEG system.

Completion of the task took approximately one hour, after which participants were disconnected from the EEG system and given the opportunity to wash the conductive gel out of their hair if they so desired. Following this, participants were asked if they had any questions, received compensation for their time and the second testing session was scheduled.

On the day of the second testing session, participants were taken to a different room more appropriate for cognitive testing. Once again, they were asked if they had any questions about the previous session. The experimenter then proceeded to administer the cognitive assessment measures outlined above (see Appendix C for the testing order). Participants were instructed to give their best effort and to let the experimenter know if they needed a break. Following the administration of the various cognitive measures, participants completed the Bilingual Language-Switching Questionnaire. Afterwards, a debriefing was provided and participants were once again compensated for their time.

EEG Data Acquisition

Data collection was done using a Biosemi ActiveTwo EEG system in a sound attenuated room. This system records neuroelectrical activity using 64 Ag-AgCl electrodes arranged in the International 10-20 system (Jasper, 1958). Eight additional electrodes were used. The first two were placed on the left and right earlobes in order to be used as references during offline processing of the EEG data. Two electrodes were placed above and below the left eye in order to record vertical electro-oculograms (EOGs) and control for vertical eye movements (i.e., blinks). Two more electrodes were placed at the outer canthi of both eyes in order to record horizontal EOGs and control for horizontal eye movements. The last two electrodes were placed on the tragus of each ear (i.e., locations FT9 and FT10 in the international 10-20 system). The EEG data of each participant was recorded relative to Common Mode Sense and Driven Right Leg (CMS/DRL) electrodes placed at the back of the head. Data were sampled at a rate of 512 Hz using a bandwidth of 104 Hz.

After data collection, the EEG data files were converted to a continuous data format using the *Polygraphic Recording Data Exchange* program (PolyRex; Kayser, 2003). Once converted, each file was opened in *Brainvision Analyzer 2.0.4.* The data from each participant were re-referenced to the average of the activity at the left and right ears. Following this step, the data were visually inspected and periods of time when no trials were presented were marked as bad intervals (i.e., intervals that do not contribute to any further analyses).

A DC detrend was applied to every file and filters were subsequently applied. A low-pass filter (cut-off of 0.1 Hz; 12 dB roll-off) and a high-pass filter (cut-off of 100 Hz; 12 dB roll-off) were used. Following this, eye movement and blink activity was corrected for throughout the entire EEG data by using an ocular correction independent components analysis (ICA). The ocular ICA is a semi-automatic process which extracts temporally maximally independent components from the EEG data. Eye movement and blinks have very distinct temporal and topographical characteristics that can be translated into statistical criteria for the ICA. For example, blinks are typically characterized by "spikes" in the neuroelectrical activity observed in frontal recording sites. In contrast, horizontal eye movement is characterized by plateaus in neuroelectrical activity.

This ocular ICA used activity from both the VEOG and HEOG channels to correct for vertical and horizontal activity respectively.

After the ocular corrections, all trials were segmented (AX, AY, BX, BY). This made it possible to use an artifact rejection process in order to identify and exclude segments compromised due to hardware error, muscle activity, or electrical interference. Following this, the files were further segmented into trials belonging to the different blocks presented to the participants. Only correct trials were analysed. Two more steps were applied to each trial type (AX, AY, BX, BY) in order to segment each trial to -100 ms before and 900 ms after the presentation of both the cue and the target. These segments were averaged for each participant, creating two averaged waveforms (one for the cue, one for the target) for each trial type in each of the three blocks. A baseline correction (-100ms to 0ms before the stimulus onset) was applied to each averaged waveform.

For the purpose of this study, only midline electrode sites (Fz, Fcz, Cz, Cpz, Pz) were extracted for statistical testing. The N2 component was identified in two distinct steps. First, an automated step was used to find the data point with the most negative amplitude within the typical N2 time window. After this automated process took place, the results of the algorithm was visually inspected and the location of the N2 was manually modified if needed. The amplitude of the N2 component was computed as the difference in amplitude between the peak of the N2 component and the most positive point that immediately precedes it. This abstracts natural fluctuations in the amplitude of the EEG signal and computes a more representative index of the magnitude of the N2-related amplitude change. As such, it allows for a more precise analysis of the N2 *effect*. This value was extracted for each participant and was subsequently used in the statistical analyses of the N2 effect. The latency of the N2 component was computed as the amount of time in milliseconds that passed between the onset of the target and the moment at which the N2 component reached its peak amplitude.

Results

Repeated measures ANOVA were computed and results are reported below. This statistical technique relies on the assumption of sphericity which stipulates equal population variances of difference scores for each pair of levels of a given factor (Kline, 2013). However, this assumption is frequently violated when collecting data from the same individuals during a brief time period (Kline, 2013). For this reason, it is best practice to apply a correction factor (i.e., epsilon) for factors that violate the sphericity assumption. Reports of the repeated measures ANOVAs presented below include the following: the uncorrected degrees of freedom, Greenhouse-Geisser epsilon (ε) values where relevant, correct mean square error (MSE) values, and corrected p values. Unless otherwise indicated, $\alpha = .05$ was used in order to determine statistical significance. Simple effects are described where reliable interactions were found.

Behavioural results

Two measures of behavioural performance were analysed in the present study: RT to produce a response and accuracy of responses. Lower RT and higher accuracy are indicative of better behavioural performance on the task.

RT. A repeated measures ANOVA was conducted with factors Block (AX-70, AY-70, BX-70) and Trial (AX, AY, BX, BY). A statistically reliable main effect of Block was found ($F(2, 28) = 3.49$, $MSE = 9{,}582.43$, $p = .044$, $\eta^2 = .05$), with the BX-70 block yielding faster RTs than the AY-70 block. A statistically reliable main effect of Trial was also found ($F(3, 42) = 27.22$, $\varepsilon = .59$, $MSE = 8446.67$, $p < .001$, $\eta^2 = .3$). BY trials were the fastest of the four trials types, followed by BX trials, and AX trials and AY trials (which did not differ from each other).

In addition to the main effects reported above, a statistically reliable interaction was found between Block and Trial found ($F(6, 84) = 10.45$, $MSE = 2730.98$, $p < .001$, $\eta^2 = .13$; see Figure 1). AX trials were slower in the AY-70 block compared to both the AX-70 and the BX-70 blocks which did not differ from each other. AY trials were slowest in the AX-70 block, but they yielded similar RTs in both the AY-70 and BX-70 blocks. For BX trials, the RT was slower in the AY-70 block compared to the BX-70 block but not the AX-70 block. Furthermore, there was no difference in RT for BX trials in the AX-70 block and the BX-70 block. Finally, BY trials yielded similar RTs across all three blocks.

In the AX-70 block, AY trials yielded the longest RTs. AX trials were slower than BY trials, but had similar RTs compared to BX trials. BY and BX trials showed no reliable difference in RT. The pattern of RTs for each trial type in the AY-70 block closely resembles the one found in the AX-70 block with a few important differences. First, AX trials were the ones that yielded the longest RTs. Second, BY trials were the fastest of all trial types. AY and BX trials did not reliably differ in terms of RT. In the BX-70 block, AY trials were slower than both BX and BY trials.

Accuracy. As with RT data, accuracy data were analysed using a repeated measures ANOVA with factors Block and Trial. A statistically reliable main effect of Block was found ($F(2, 28) = 4.29$, $\varepsilon = .63$, $MSE = 25.01$, $p = .045$, $\eta^2 = .03$), with participants being more accurate in the BX-70 block compared to the AX-70 and AY-70 blocks. The latter did not differ from each other. A statistically reliable main effect of Trial was also found ($F(3, 42) = 10.41$, $MSE = 29.47$, $p < .001$, $\eta^2 = .16$). Participants were equally accurate on BY versus BX trials and were equally accurate on AX versus AY trials overall; however, they were more accurate on BX and BY trials compared to AX and AY trials.

In addition to the main effects reported above, a statistically reliable interaction was found between Block and Trial found ($F(6, 84) = 10.45$, $\varepsilon = .40$, $MSE = 59.65$, $p < .001$, $\eta^2 = .34$; see Figure 2). AX trials followed a simple pattern in which accuracy was highest in the AX-70 block and lowest in the AY-70 block. Accuracy for AX trials in the BX-70 block was higher than in the AY-70 block, but lower than in the AX-70 block. A very similar pattern occurred for AY trials with the exception that accuracy was now highest in the AY-70 block and lowest in the AX-70 block. For both BX and BY trials, accuracy remained constant across blocks.

In the AX-70 block, AY trials were the least accurate of all trial types whereas accuracy was similar for AX, BX, and BY trials. In the AY-70 block, AX trials were less accurate than other trials. AY trials and BX trials showed similar levels of accuracy. In contrast, AY trials were less accurate than BY trials but BX trials and BY trials were equally accurate. Finally, accuracy was relatively consistent across all trial types in the BX-70 block. The only difference in accuracy was found between AX trials and BY trials, with the latter being more accurate.

Electrophysiological results

Figures 3 and 4 show the overall electrophysiological results for all four trial types in the AX-70 block. In all four conditions, there is a visual N1 component after which point the conditions begin to differ. P300 activity can been seen in both AX and AY trials, albeit with a delayed onset and larger amplitude for AY trials. Most noticeably, there is a very large N2 component for AY trials. In contrast, this component is virtually inexistent in other trial types.

Figures 5 and 6 show the overall ERP results for all four trial types in the AY-70 block. As with the AX-70 block, there appears to be a visual N1 component in all four conditions. In contrast to what was seen in the AX-70 block, P300 activity occurs at the same time for both AX and AY trials. However, it is noticeably larger for AX trials. Compared to what was seen in the AX-70 block, the N2 component is virtually absent altogether in the AY-70 block with the exception of AX trials.

Figure 7 shows the overall electrophysiological results for all four trial types in the BX-70 block. Once again, there is a visual N1 component in all four conditions. There is P300 activity for both AX and AY trials, with similar amplitude in both cases. However, the onset of the P300 activity appears to be delayed for AY trials compared to AX trials. In terms of the N2 component, the activity seen in the BX-70 block resembles that seen in the AX-70 block with the largest amplitude observed in AY trials. However, the magnitude of the N2 effect for AY trials is visibly smaller in the BX-70 compared to the AX-70 block.

In the context of the current thesis, only the N2 component was analysed and results are presented below.

N2 Amplitude. A repeated measures ANOVA was conducted with factors Block, Trial, and Electrode (Fz, FCz, Cz, CPz, Pz). A statistically reliable main effect of Block was found ($F(2, 28) = 13.16$, $\varepsilon = .67$, $MSE = 141.29$, $p = .001$, $\eta^2 = .07$), with participants exhibiting smaller N2 effects in the BX-70 block compared to both the AX-70 and AY-70 blocks. A statistically reliable main effect of Trial was also found ($F(3, 42) = 9.75$, $MSE = 126.81$, $p < .001$, $\eta^2 = .11$). Overall, AY and BY trials yielded comparable N2 effects that were greater than those observed on AX trials. AY trials also yielded larger N2 components than BX trials. Furthermore, the N2 effect was larger on BX trials compared to AX trials. Finally, a statistically reliable main effect of Electrode was found ($F(4, 56) = 4.82$, $\varepsilon = .40$, $MSE = 108.35$, $p = .024$, $\eta^2 = .02$), with anterior electrodes exhibiting a greater N2 effect compared to posterior electrodes.

In addition to the main effects, several interactions were found. There was a statistically reliable interaction of Block and Trial ($F(6, 84) = 9.30$, $\varepsilon = .55$, $MSE = 1345.99$, $p < .001$, $\eta^2 = .13$; see Figure 8). AX trials yielded similar N2 amplitudes in the AX-70 block versus the AY-70 block. N2 amplitudes for AX trials were larger (i.e., more negative value) in both of these blocks compared to the BX-70 block in which the N2 component was virtually absent. AY trials showed greater N2 amplitudes in the AX-70 block compared to both the AY-70 and BX-70 block which did not differ from each other. BX trials showed similar amplitude values in the N2 time window both the AX-70 and AY-70 blocks. Furthermore, the amplitude was more negative in both the AX-70 and AY-70 blocks compared to the BX-70 block. Finally, BY trials yielded similar amplitude values across all three blocks.

As the visual inspection of the N2 component suggested, AY trials yielded the N2 components with the largest amplitude in the AX-70 block. AX, BX, and BY trials all yielded similar amplitudes in the N2 time window. In the AY-70 block, there was no difference in amplitude during the N2 time window across all trial types. In the BX-70 block, there was virtually no N2 effect for AX trials. For this reason, amplitude during the N2 time window was more positive for AX trials compared to all other trial types. The N2 effect was greatest for AY trials and BY trials, followed by BX trials which yielded slightly smaller N2 amplitudes

A statistically reliable interaction of Trial and Electrode was also found ($F(12, 168) = 36.36$, $\varepsilon = .28$, $MSE = 41.61$, $p = .029$, $\eta^2 = .01$; see Figure 9). N2 amplitude at site FZ was largest for AY trials, although there was no reliable difference between AY trials and BY trials. The amplitude of the N2 effect was similar for BY trials and BX trials, but BX trials yielded smaller N2 amplitudes than AY trials. The N2 amplitude during AX trials was smaller than on AY trials, but comparable to both BX and BY trials. At electrode site FCz, the only reliable difference in N2 amplitude was found when comparing AY trials to AX trials. The exact same pattern was found at sites Cz and CPz. Finally, the amplitude of the activity observed during the N2 time window was comparable for all trial types at site Pz.

During AX trials, the amplitude of the activity observed during the N2 time window was comparable across all electrodes. The same pattern was found for both BX and BY trials. In contrast, N2 amplitude varied across electrodes during AY trials. The largest N2 amplitudes where observed at anterior sites (Fz and FCz) compared to more central and posterior sites (Cz, CPz, Pz). The latter sites showed no reliable differences in amplitudes for the activity observed during the N2 time window

There was no statistically reliable interaction of Block and Electrode ($F(8, 112) = 1.25$, $\varepsilon = .32$, $MSE = 32.18$, $p = .303$, $\eta^2 = .003$), and the three-way interaction (Block, Trial, and Electrode) was not statistically reliable either ($F(24, 336) = 1.33$, $\varepsilon = .17$, $MSE = 26.18$, $p = .269$, $\eta^2 = .004$).

N2 latency. As per the N2 amplitude data, a repeated measures ANOVA was conducted with factors Block, Trial, and Electrode (Fz, FCz, Cz, CPz, Pz) on the N2 latency data. A statistically reliable main effect of Block was found ($F(2, 28) = 4.24$, $MSE = 2737.89$, $p = .025$, $\eta^2 = .04$), with the N2 reaching peak amplitude earlier in the AX-70 block compared to the AY-70 block. There was no statistically reliable main effect of Trial ($F(3, 42) = 1.92$, $\varepsilon = .72$, $MSE =$

4838.84, p = .162, η^2 = .03) or Electrode (F(4, 56) = 1.21, ε = .49, MSE = 625.09, p = .315, η^2 = .002).

There was a statistically reliable interaction of Block and Trial (F(6, 84) = 2.93, ε = .60, MSE = 3253.64, p = .034, η^2 = .05; see Figure 10). There were no statistically reliable differences in the time at which the N2 effect reached its peak amplitude across each trial type in the AX-70 block. A similar pattern was found for both the AY-70 and BX-70 blocks. However, this is unsurprising given the absence of robust N2 components for most trial types in each of the blocks (e.g., only AY trials how large N2 components in the AX-70 block).

The only statistically reliable difference in N2 latency was found for AX trials. For these trials, the N2 component reached its peak amplitude faster in the AY-70 block compared to the AX-70 block. However, this should be interpreted carefully given the the absence of a strong N2 component in both the AX-70 block and the BX-70 block.

There was no statistically reliable interaction of Block and Electrode (F(8, 112) = .966, ε = .31, MSE = 949.01, p = .407, η^2 = .004) or of Trial and Electrode (F(12, 168) = .622, ε = .38, MSE = 678.89, p = .669, η^2 = .003). Finally, the three way interaction of Block, Trial, and Electrode was not statistically reliable (F(24, 336) = .760, ε = .23, MSE = 937.96, p = .594, η^2 = .01).

Correlational analyses

As was previously described, data from the AX-CPT can be analysed in order to determine whether a participant relied primarily on a proactive or a reactive strategy. In the current study, strategy was indexed separately for each of the three visual AX-CPT blocks. For each block, we assessed the degree to which the participants' strategy was associated with behavioural performance on the block, electrophysiological responses (i.e., the N2 component) on the block, and aspects of the bilingual experience such as L2 proficiency and code-switching behaviours. To this effect, Pearson correlations were used. Unless otherwise specified, all correlational analyses were two-tailed.

Strategy in the AX-70 block

In order to assess whether participants primarily relied on a proactive or a reactive strategy in the AX-70 block, we compared their performance (i.e., RT and accuracy) on BX trials and AY trials. In an effort to control for fundamental speed differences between participants, RT for BX and AY trials was normalized by subtracting the RT for BY trials which offer a good baseline measure of speed because they never differ by condition. Comparisons of RT and accuracy for BX and AY trials were computed using the following equations:

$$RT\ Contrast = RT_{BX} - RT_{AY}$$

$$Accuracy\ Contrast = Accuracy_{BX} - Accuracy_{AY}$$

For RT contrasts, negative values are indicative of a proactive strategy whereas positive values suggest a reactive strategy. The opposite is true for the accuracy contrasts because accuracy scores are expressed as a percentage of correct responses. A proactive strategy should result in faster (i.e., lower RT) and more accurate performance on BX trials than on AY trials.

According to both the RT ($M_{RT\ Contrast}$ = -145.71, SD = 60.48) and accuracy ($M_{Accuracy\ Contrast}$ = 8.89, SD = 11.86) contrasts, participants relied mostly on a proactive strategy in the AX-70 block. In fact, there was not much evidence for participants relying mostly on a reactive strategy over the course of this block. This was more apparent in RT contrast than the Accuracy contrast, suggesting that the RT contrast may be a better index of cognitive control strategy. Although all participants used a primarily proactive strategy according to the RT contrast, there was a spread in the degree to which they used proactive mechanisms (indexed by the magnitude of the RT contrast). Table 4 gives a breakdown of the RT and accuracy contrasts in the AX-70 block for each participant.

Correlations between strategy and behavioural performance. Table 5 outlines the correlations between the strategy that participants relied on in the AX-70 block and their behavioural performance on this same block. Participants' strategy as indexed by the Accuracy Contrast was negatively associated with both overall RT (r = -.60, r^2 = .36, p = .017) and overall accuracy (r = -.73 r^2 = .53, p = .002; see Figures 11 and 12 for scatterplots). This suggests that participants whose cognitive strategy was more frankly proactive over the course of the AX-70 block tended to respond faster and to be less accurate than those who did not show such a strong use of proactive strategy.

Correlations between strategy and N2 component. The associations between participants' cognitive control strategy and the evoked N2 component during AY trials in the AX-70 block are outlined in Tables 6 and 7. The amplitude of the N2 component was positively associated with the cognitive control strategy used by participants as indexed by the RT Contrast (r = .56, r^2 = .31, p = .029; see Figure 13) at site CPz. There was also a trend for a positive association between the amplitude of the N2 component and the cognitive control strategy indexed by the RT Contrast at site Cz (r = .50, r^2 = .25, p = .057). In contrast, the strategy was negatively associated with N2 latency (r = -.60, r^2 = .36, p = .017; see Figure 14) at site CPz. In other words, the more participants relied on a frankly proactive strategy over the course of the AX-70 block, the more N2 components tended to have larger amplitudes and have later onsets at site CPz in contrast to participants who did not show such a strong use of proactive mechanisms.

Neither N2 amplitude nor N2 latency was associated with the cognitive control strategy used by participants as indexed by the Accuracy Contrast.

Correlations between strategy and code-switching. Table 8 illustrates the relations between participants' cognitive control strategy and their reported patterns of code-switching. We had theoretical reasons to believe that low L2 proficiency would be associated with increased self-reported code-switching regardless of cognitive control strategy. For this reason, the analyses reported below are partial correlations that control for L2 proficiency. Additionally, we used one-tailed tests because we had strong hypotheses on the direction of the association between participants' executive control strategy and the incidence of different categories of self-reported code-switching.

The strategy used by participants (as indexed by the RT Contrast) was positively associated with scores on the Unwanted Switches factor of the Bilingual Language-Switching Questionnaire ($r = .50$, $r^2 = .25$, $p = .033$; see Figure 15) when controlling for L2 proficiency. This suggests that participants whose overall strategy in the AX-70 block was more proactive tended to report fewer unwanted switches than participants who did not show such a strong use of proactive mechanisms.

Strategy in the AY-70 block

As with the AX-70 block, RT and accuracy contrasts were computed for the AY-70 block. The following equations were used:

$$RT\ Contrast = RT_{BX} - RT_{AX}$$

$$Accuracy\ Contrast = Accuracy_{BX} - Accuracy_{AX}$$

One notable difference between the contrasts in the AX-70 block and the contrasts in the AY-70 block is that the latter compare BX trials to AX trials rather than AY trials. This is because AY trials are much more frequent than BX trials in the AY-70 block. Thus, any differences in RT or accuracy between BX and AY trials may be strongly influenced by frequency effects. For this reason, the comparison of BX and AX trials (which have the same frequency) was used as an index of participants' strategy. In this context, a proactive strategy should result in faster (i.e., lower RT) and more accurate performance on BX trials than on AX trials.

As was the case with the AX-70 block, most participants relied on a proactive strategy in the AY-70 block ($M_{RT\ Contrast}$ = -115.19, SD = 131.70; $M_{Accuracy\ Contrast}$ = 13.75, SD = 10.66). In contrast to what was observed in the AX-70 block, some participants did show evidence of a more globally reactive strategy in the AY-70 block (indexed by the magnitude of the RT contrast; see Table 9). Amongst participants who relied mostly on a proactive strategy, there was also evidence of a spread in the degree to which they used proactive mechanisms over the course of the AY-70 block.

Correlations between strategy and behavioural performance. Participants' cognitive control strategy (as indexed by the Accuracy Contrast) was negatively associated with overall accuracy on the AY-70 block (r = -.62, r^2 = .38, p = .015; see Figure 16). Because the Accuracy Contrast does not offer strong evidence for the use of a reactive control strategy over the course of the AY-70 block (see Table 10), this correlation cannot be interpreted as a difference between participants who relied mostly on a reactive strategy and those who relied mostly on a proactive strategy. Instead, it should be interpreted as an association between accuracy on the AY-70 block and the degree to which participants relied on a proactive strategy throughout the block. In this context, the correlation suggests that participants who used a more frankly proactive strategy over the course of the AY-70 block tended to be less accurate than those who did not show such as strong use of proactive mechanisms (see Table 10 for additional correlations).

Correlations between strategy and N2 component. Tables 11 and 12 outline the correlations between participants' control strategy and the N2 component in the AY-70 block. There were no significantly reliable associations between participants' strategy and properties of the N2 component (i.e., amplitude or latency). This suggests that the amplitude and latency of the N2 component was largely independent from participants' cognitive control strategy.

Correlations between strategy and code-switching. Table 13 outlines the associations between participants' cognitive control strategy and their reported patterns of code-switching on the Bilingual Language-Switching Questionnaire. Similar to the analyses conducted for the AX-70 block, the analyses presented below are one-tailed partial correlations that control for L2 proficiency.

The cognitive control strategy (as indexed by the RT Contrast) was positively associated with Contextual Switches (r = .59, r^2 = .35, p = .014; see Figure 17) and negatively associated with switches from L2 to L1 (r = -.56, r^2 = .31, p = .017; see Figure 18). This suggests that participants who used a proactive strategy tended to report less contextual switches and more switches into their L1 compared to participants who used a reactive strategy.

Strategy in the BX-70 block

The distribution of trial types in the BX-70 makes it impossible to determine whether participants used a proactive strategy or a reactive strategy. Indeed, the very frequent BX trials cannot readily be compared to the infrequent AX and AY trials. For this reason, the BX-70 block did not yield interpretable results for the analyses used in the scope of this thesis. Going forward, and with the addition of analyses of cue-locked neuroelectrical activity, the BX-70 still has the potential to inform our understanding of proactive and reactive control processes.

Discussion

Studies that have investigated the bilingual advantage in cognitive control have mainly been concerned with determining whether the advantage is present or absent in a given group compared to a reference group. While this constitutes groundwork that is crucial to a proper understand of the bilingual advantage in cognitive control, it also fails to capture the complexity of the bilingual experience. Indeed, it is possible that differences in factors such as L2 proficiency or code-switching behaviours play a role in determining how individuals engage their cognitive control mechanisms. This may have important implications for the emergence and maintenance of a bilingual advantage in cognitive control.

The present study sought to investigate how individual differences in specific aspects of the bilingual experience are associated with individual differences in cognitive control. To investigate this, ERP analysis was utilized during the completion of the AX-CPT. The AX-CPT affords opportunities to exert both proactive and reactive control mechanisms and quickly alternate between the two. This makes ERPs particularly well-suited to study performance on the AX-CPT. Furthermore, the AX-CPT creates a strong prepotent response (e.g., a strong bias towards pressing the “yes” key when seeing an A cue in the AX-70 block) which must occasionally be overcome. For this reason, the present study focused on analysing the N2 which reflects aspects of conflict detection (Folstein & Van Petten, 2008).

Overall, the results of the present study support the idea that there are individual differences in how bilinguals engage their cognitive control processes during a task which strongly biases participants towards a proactive strategy. This interindividual variation in cognitive control strategy was related to electrophysiological activity during the AX-CPT and to aspects of code-switching. However patterns of individual differences in cognitive control strategy and their association to aspects of bilingualism varied across blocks. Therefore, the results are first interpreted for each block and subsequently integrated in a broader discussion.

AX-70 block

Analysis of the RT and Accuracy contrasts in the AX-70 revealed that all participants relied on a proactive strategy overall when completing this block. This is consistent with what was found in previous studies (Morales et al., 2013, 2014) and unsurprising given that the original AX-CPT biases individuals towards adopting a proactive strategy. However, they was some variability in the degree to which participants engaged proactive mechanisms. This variability manifested itself in the magnitude of the RT and Accuracy contrasts.

Since none of the participants relied primarily on a reactive strategy in the AX-70 block (according to the RT and Accuracy contrast values), it is impossible to directly compare individuals who used a proactive control strategy to those who used a reactive control strategy. Therefore, only our hypotheses about the use of proactive strategies could be analysed.

We hypothesized that participants who used a proactive control strategy would tend to answer faster than those who used a reactive strategy. This hypothesis could not be verified because no participant relied primarily on a reactive strategy. However, participants who used a more frankly proactive strategy on the AX-CPT block (indexed by larger magnitudes of both the RT and Accuracy contrasts) tended to answer faster than those who showed less evidence of strong proactive control engagement. In addition, this advantage in reaction time came at the cost of accuracy. This is unsurprising since a proactive strategy involves actively maintaining information or even preparing an answer before all the relevant information is known (Braver et al., 2009). On trials where the prepared answer is consistent with the target letter, a proactive strategy offers a considerable speed advantage. However, when the target invalidates the prepared answer, there is a greater potential for erroneous answers.

A second hypothesis was that participants who relied on a proactive strategy would show larger N2 components with earlier peaks for AY trials in the AX-70 block compared to participants who relied mostly on a reactive control strategy. This was hypothesized because the active maintenance of task-relevant information inherent to proactive strategies should lead to greater sensitivity to conflictual information. This should translate into earlier N2 components with larger amplitudes.

Once again, this hypothesis could not be verified because all participants relied primarily on a proactive control strategy. However, the more participants relied on a frankly proactive strategy over the course of the AX-70 block, the more N2 components tended to have larger amplitudes compared to participants who did not show such a strong use of proactive mechanisms. Additionally, this effect was only seen at the most posterior electrode site (i.e., CPz). This is a surprising result because the N2 is traditionally an anterior component (Folstein & Van Petten, 2008).

The bigger N2 components at site CPz for participants who show greater evidence of proactive strategy use suggests that these individuals may engage in more active conflict monitoring. However, this should also be reflected at more anterior sites. One possible explanation is that the amplitude of the N2 component is already at its maximum at anterior sites for all participants regardless of the degree of proactive control that is used.

Additionally, participants who showed greater evidence of proactive strategy use tended to display N2 components with later onsets at site CPz compared to participants who did not show such a strong use of proactive mechanisms. This result is surprising and difficult to interpret. One possibility is that greater use of proactive mechanisms may lead to increased sensitivity to conflict but slower resolution of said conflict. This would result in later N2 components in posterior sites.

In addition to participants' behavioural and electrophysiological performance on the AX-CPT, we also investigated self-reported code-switching behaviours and their correlation to participants' control strategy. We hypothesized that participants who rely on a proactive strategy would tend to report fewer unwanted language switches compared to participants who rely on a reactive strategy. Once again, we could not verify this hypothesis because all participants used a proactive strategy in the AX-70 block. However, participants who made greater use of proactive mechanisms (as indexed by larger magnitude of the RT and Accuracy contrasts) tended to report fewer unwanted language switches compared to those who did not show such strong evidence of proactive strategy use.

Results from the AX-70 suggest that individuals who rely on a strongly proactive control strategy may be less likely to engage in unconscious switches and may have greater control over when and why they decide to switch compared to individuals who do not show such strong evidence for the use of proactive mechanisms. Alternatively, it is possible that individuals who have greater control over language switching use proactive control strategies more effectively. It is important to note that the association between cognitive control strategy and self-reported unwanted switches is controlling for L2 proficiency, excluding spurious associations due to differences in verbal abilities in the second language. This means that differences in the number of unwanted switches reported by participants did not simply reflect lower L2 proficiency.

Finally, we hypothesized that participants who relied primarily on a reactive control strategy would report more contextual switches than participants who rely on a proactive strategy. We could not verify this hypothesis because none of our participants relied primarily on a reactive strategy.

AY-70 block

In the AY-70 block, most participants relied on a proactive strategy. In contrast to the AX-70 block, a proportion of participants did rely primarily on a reactive control strategy. To our knowledge, this is the first study to examine cognitive control strategies in the AY-70 block. The AY-70 block is conceptually very similar to the AX-70 block. In both cases, participants are presented with A cues 80% of the time and B cues 20% of the time. The major difference lies in the fact that the AY-70 block only contains 10% AX trials compared to the 70% present in the AX-70 block. Thus, the AY-70 block biases participants towards a “no” answer whereas the AX-70 block biases them towards a “yes” answer. This crucial difference is the reason why the AY-

70 was included in the present study.

For both the AX-70 block and the AY-70 block, a proactive strategy is advantageous because it will quickly lead to the correct answer a majority of the time. Therefore, it is not surprising that most participants relied primarily on a proactive strategy.

We hypothesized that participants who used a proactive strategy would be faster and less accurate than participants who relied on a reactive control strategy. While results from the AY-70 block supported the accuracy hypothesis, there was no difference in reaction time. This was a surprising result. However, it makes sense when considering how participants' cognitive strategy was inferred in the AY-70 block. Since AY trials are very frequent in this block, the traditional contrast between BX trials and AY trials could not be used to yield a meaningful index of cognitive control strategy. To circumvent this problem, we contrasted BX trials with the equiprobable AX trials. However, this may be a flawed comparison. For participants who used a proactive strategy, the contrast of BX and AX trials in the AY-70 block is equivalent to the contrast of BX and AY trials in the AX-70 block. In other words, BX trials should be faster and more accurate than AX trials for these participants. However, for participants who used a reactive control strategy, the reaction time difference between BX and AX trials should be close to 0. This makes it difficult to draw a clear distinction between participants who used a proactive strategy and those who used a reactive strategy.

Similar to the AX-70 block, we hypothesized that participants who used a proactive control strategy would show larger N2 components with earlier peaks for high-conflict trials (i.e., AX trials in the AY-70 block) compared to participants who used a reactive control strategy. Surprisingly, this hypothesis was not supported. In contrast to what was found in the AX-70 block, participants who used a proactive control strategy exhibited N2 components similar to those of participants who used a reactive control strategy in terms of both amplitude and time of onset. One possible explanation lies in the counterbalancing of the experiment. Data collection for this project is still under way. For this reason, counterbalancing is not yet fully implemented. As a result, a large proportion of participants have been presented with the AX-70 block before the AY-70 block. This number is even more important when considering that even amongst participants who were presented with the visual AY-70 block before the AX-70 block, half were presented with an auditory AX-70 block prior to the visual portion of the experiment. This may have had an impact on how participants approached the task. When transitioning from one block to another, participants typically carry over the expectancies that they have developed over the course of the previous block. However, they presumably realize that these expectancies are no longer accurate or advantageous. Proactive strategies rely on such expectancies in order to operate. Thus, participants who use proactive strategies may be more likely revert to a reactive control strategy at the beginning of a new block until they get a better idea of the probabilities associated with each trial type. This “switching effect” could be magnified by incomplete counterbalancing and may colour the association (or lack thereof) between cognitive control strategy and properties of the N2 component in the AY-70 block.

We hypothesized that participants who relied on a proactive strategy would report fewer unwanted switches than participants who used a reactive strategy. However, this hypothesis was not supported in the AY-70 block. We also hypothesized that participants who relied on a reactive strategy would report more contextual switches than participants who used a proactive strategy. Results from the AY-70 block support this hypothesis. As was the case in the AX-70 block, these associations control for L2 proficiency.

It may seem surprising that some participants relied primarily on a reactive strategy in the AY-70 block when none of them did so in the AX-70 block. After all, both blocks tend to bias participants towards a proactive strategy. However, the partial counterbalancing (see above for details) of the experiment may have played a role in this phenomenon. As was explained earlier, participants who normally rely on a proactive strategy probably revert to a reactive control strategy at the beginning of a new block until they get a better idea of the probabilities associated with each trial type. Depending on how quickly and efficiently they adapt to these new probabilities, they may be classified as using a reactive control strategy when using the RT and Accuracy contrasts. Thus, the results presented in this thesis will need to be revised once proper counterbalancing has been achieved. Nonetheless, the two blocks are qualitatively different from each other. The AX-70 block creates a global *yes* context whereas the AY-70 block creates a global *no* context. This difference may have played role in the emergence of individuals who relied primarily on a reactive control strategy in the AY-70 block.

The idea of an adaptation period when switching blocks opens the door for further research using the modified AX-CPT paradigm. Indeed, prior research on the AX-CPT in bilinguals suggest that bilinguals are better than monolinguals at flexibly alternating between proactive and reactive control mechanisms as needed (Morales et al., 2013, 2014). Therefore, the adaptation period between two blocks may hold promising information on the flexibility and efficacy of individuals' cognitive control mechanisms. In light of this information, individual differences in how quickly bilinguals adapt their cognitive control strategy based on the demands of the situation at hand may be more interesting than simply analyzing which cognitive control strategy they favored overall. This opens ups exciting new avenues for research using this modified AX-CPT paradigm.

Limitations and future research

A significant limitation of the present study concerns the current suboptimal status of the counterbalancing of presentation order. As was discussed earlier, this may partially explain why we found different patterns of association between participants' cognitive control strategy and electrophysiological measures as well as code-switching. Related to this limitation is the fact that the sample of participants is currently quite small. These limitations will be addressed in the upcoming months as we continue data collection for this study.

Another important limitation concerns the composition of the sample presented in this thesis. The current sample collapses English-French and French-English bilinguals. Since we are interested in how individual differences in cognitive control relate to individual differences in aspects of the bilingual experience, it may be unwise to collapse these two groups of bilinguals. Beyond the more pragmatic aspects of the bilingual experience (e.g., L2 proficiency or age of acquisition), sociopolitical factors may colour the way bilinguals use their two languages as well as when and why they switch between them (Green, 2011). Thus, as we continue data collection for this study we should strive to create two separate groups of bilinguals: an English-French group and a French-English group.

Yet another limitation of the present study is that it does not currently include a group of monolingual participants. Monolinguals, like their bilingual counterpart, likely show individual differences in cognitive control. As we continue to collect data for this study, we should include a group of monolinguals and compare their performance to our bilingual groups. By contrasting bilinguals and monolinguals, we may be able to shed light on specific aspects of the bilingual experience that are associated with behavioural or neuroelectrical advantages on a task of cognitive control.

Additionally, the data presented in this thesis are only a small subset of the information we collected for each participant. As we continue exploring individual differences in cognitive control and their relation to aspects of the bilingual experience, we will analyze other ERP components that arise after the onset of the target. For example, we will analyze the P300, another component sensitive to aspects of conflict detection and resolution (Morales et al., 2013).

Another promising ERP component is the lateralized readiness potential (LRP; Masaki, Wild-Wall, Sangals, & Sommer, 2004). This component is thought to reflect motor activation. As such, it may help us investigate how participants prepare their responses.

We will also investigate the electrophysiological activity evoked by the onset of the cue. This may be particularly useful to distinguish between proactive and reactive control mechanisms. One possibility is that participants who use a proactive control strategy will exhibit N2 components after the onset of cues that are in conflict the global context of a block. In contrast, participants who use a reactive strategy should show little cue-locked activity in the same time window. Finally, we have a wealth of neuropsychological and cognitive data for each participant which have yet to be analyzed. These will allow us to investigate the association between individuals' cognitive control strategy, aspects of their bilingual experience, and performance on well validated tasks of executive functioning often used in the bilingualism literature. The analysis of this data may help us shed light on which aspects of the bilingual experience may play a role in the development and maintenance of a bilingual advantage in cognitive control.

Conclusion

In light of the results outlined in the present thesis, it appears that the AX-CPT has great potential as a tool to investigate individual differences in how bilinguals engage their cognitive control processes. In its current form, this research project found individual variations in the degree of proactive and reactive control used during the AX-CPT. Furthermore, there was some evidence of proactive and reactive control being differentially associated with conflict detection (i.e., the amplitude and the latency of the N2 ERP component) and the types of code-switching that participants reported.

The use of the AX-CPT paradigm in the present study yielded valuable lessons which should be used to guide future research using this paradigm. First, variations in proactive and reactive control are likely to occur dynamically over to course of the task. Therefore, it may be preferable to analyse the data in smaller segments rather than one block at a time. This may yield crucial information about how quickly individuals adjust to the task and shift their cognitive strategy accordingly.

Second, cue-locked neuroelectrical activity likely holds important information concerning individuals' cognitive control strategy. In particular, a proactive control strategy should be associated with a greater degree of cue-locked activity, representing maintenance of task-relevant information and response preparation. This information may prove particularly useful when analysing the BX-70 block which is not very amenable to the use of RT and Accuracy contrasts. Additionally, this may provide further insight into how individuals engage their cognitive control processes even when the RT and Accuracy contrasts do not offer a clear categorization between proactive and reactive control.

Overall, the AX-CPT is a complex –albeit exciting– tool with the potential to inform our understanding of how bilinguals use proactive and reactive control mechanisms during challenging cognitive tasks. With this knowledge, it becomes possible to investigate how dynamic patterns of proactive and reactive control use are associated with individual differences in the bilingual experience (e.g., L2 proficiency, code-switching), hereby shedding light on the cognitive consequences of bilingualism.

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Table 1

Demographic data for all participants

		M	SD	*n*
Age (years)		23.8	4.26	15
Education (years)		15.47	1.06	15
L1 English		-	-	11
L1 French		-	-	4
L1 Proficiency (/5)		4.84	0.33	15
	Reading (/5)	4.60	0.83	15
	Writing (/5)	4.90	0.28	15
	Listening (/5)	5.00	0.00	15
	Speaking (/5)	4.87	0.52	15
L2 Proficiency (/5)		3.86	0.76	15
	Reading (/5)	3.43	0.94	15
	Writing (/5)	3.60	0.99	15
	Listening (/5)	4.27	0.80	15
	Speaking (/5)	4.12	0.75	15

Table 2

The Bilingual Language Switching Questionnaire and its four factors

Factor	Statement
L2 to L1 Switches	I do not remember or I cannot find some English words when I am speaking in English. When I cannot find a word in French, I tend to immediately produce it in English. Without meaning to, I sometimes produce the English word faster when I am speaking in French.
L1 to L2 Switches	I do not remember or I cannot find some French words when I am speaking in French. When I cannot find a word in English, I tend to immediately produce it in French. Without meaning to, I sometimes produce the French word faster when I am speaking in English.
Contextual Switches	I tend to switch languages during a conversation (for example, I switch from English to French or vice versa). There are situations in which I always switch between the two languages. There are certain topics or issues in which I normally switch between the two languages.
Unwanted Switches	When I switch languages, I do it on purpose. It is difficult for me to control the language switches I introduce during a conversation (e.g., from French to English). I do not realize when I switch the language of a conversation (e.g., from English to French) or when I mix the two languages; I often realize only if I am informed of the switch by another person.

Note: For each statement, participants were asked to rate to what degree the statement is representative of the way they speak the languages they know using the scale below.

□ *never* □ *very infrequently* □ *occasionally* □ *frequently* □ *always*

Table 3

Probabilities in the three blocks of the AX-CPT

	Trial type								
Block	AX	BX	AY	BY	Global prepotency	P(A) (%)	P(X) (%)	P(X | A) (%)	Local prepotency after cue A
AX-70	210 (70%)	30 (10%)	30 (10%)	30 (10%)	Yes	80	80	87.5	Yes
AY-70	30 (10%)	30 (10%)	210 (70%)	30 (10%)	No	80	20	12.5	No
BX-70	30 (10%)	210 (70%)	30 (10%)	30 (10%)	No	20	80	50	Yes = No

Table 4

RT and Accuracy contrasts in the AX-70 block for all participants

Participants	RT contrast (BX - AY) expressed in milliseconds	Accuracy contrast (BX - AY) expressed as % difference
1	-147.58	0.00
2	-72.60	-3.26
3	-130.55	0.00
4	-154.05	23.33
5	-162.67	0.00
6	-139.28	0.00
7	-222.79	3.33
8	-139.11	16.67
9	-116.50	10.00
10	-127.27	30.00
11	-87.40	6.67
12	-187.32	16.67
13	-187.79	30.00
14	-279.81	6.67
15	-30.94	-6.67

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 5

Correlations between cognitive control strategy and behavioural performance in the AX-70 block

	RT Contrast (BX - AY)		Accuracy Contrast (BX - AY)	
	r	*p*	*r*	*p*
Average RT in AX-70 block	0.07	0.798	-0.60	0.017*
Average Accuracy in AX-70 block	-0.21	0.463	-0.73	0.002*

*$p < 0.05$, ** $p < 0.001$

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 6

Correlations between cognitive control strategy and N2 amplitude on AY trials in the AX-70 block

	RT Contrast (BX - AY)		Accuracy Contrast (BX - AY)	
	r	*p*	*r*	*p*
Average N2 amplitude at Fz for AY trials	0.38	0.164	-0.10	0.713
Average N2 amplitude at FCz for AY trials	0.44	0.102	-0.06	0.824
Average N2 amplitude at Cz for AY trials	0.50	0.057	-0.03	0.904
Average N2 amplitude at CPz for AY trials	0.56	0.029*	-0.63	0.823
Average N2 amplitude at Pz for AY trials	0.28	0.313	-0.05	0.233

*$p < 0.05$, ** $p < 0.001$

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 7

Correlations between cognitive control strategy and N2 latency on AY trials in the AX-70 block

	RT Contrast (BX - AY)		Accuracy Contrast (BX - AY)	
	r	*p*	*r*	*p*
Average N2 latency at Fz for AY trials	-0.33	0.230	0.18	0.530
Average N2 latency at FCz for AY trials	-0.29	0.296	0.07	0.802
Average N2 latency at Cz for AY trials	-0.28	0.308	0.04	0.886
Average N2 latency at CPz for AY trials	-0.60	0.170	0.29	0.296
Average N2 latency at Pz for AY trials	-0.22	0.431	0.13	0.643

$^*p < 0.05$, $^{**}\ p < 0.001$

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 8

Partial correlations between code-switching and cognitive control strategy, after controlling for L2 proficiency in the AX-70 block

	RT Contrast (BX - AY)		Accuracy Contrast (BX - AY)	
	r	*p*	*r*	*p*
L2 to L1 Switches	-0.32	0.131	0.03	0.454
L1 to L2 Switches	0.02	0.470	-0.11	0.352
Contextual Switches	0.37	0.099	-0.01	0.485
Unwanted Switches	0.50	0.033*	-0.17	0.282

*$p < 0.05$, ** $p < 0.001$

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 9

RT and Accuracy contrasts in the AY-70 block for all participants

Participants	RT contrast (BX - AY) expressed in milliseconds	Accuracy contrast (BX - AY) expressed as % difference
1	-223.70	20.00
2	60.59	3.33
3	-197.94	19.52
4	-58.73	16.67
5	-73.91	3.33
6	91.64	13.33
7	-440.50	3.33
8	-27.10	-3.33
9	-152.67	10.00
10	-95.54	20.00
11	-55.23	36.67
12	-178.20	26.67
13	-198.52	20.00
14	-173.85	13.33
15	-4.17	3.33

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 10

Correlations between cognitive control strategy and behavioural performance in the AY-70 block

	RT Contrast (BX - AX)		Accuracy Contrast (BX - AX)	
	r	*p*	*r*	*p*
Average RT in AY-70 block	-0.39	0.147	-3.46	0.207
Average Accuracy in AY-70 block	-0.44	0.099	-0.62	0.015*

**p* < 0.05, ** *p* < 0.001

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials

Table 11

Correlations between cognitive control strategy and N2 amplitude on AY trials in the AY-70 block

	RT Contrast (BX - AX)		Accuracy Contrast (BX - AX)	
	r	*p*	*r*	*p*
Average N2 amplitude at Fz for AY trials	0.05	0.867	0.14	0.614
Average N2 amplitude at FCz for AY trials	0.29	0.291	0.25	0.370
Average N2 amplitude at Cz for AY trials	0.32	0.248	0.09	0.740
Average N2 amplitude at CPz for AY trials	0.31	0.269	0.04	0.881
Average N2 amplitude at Pz for AY trials	0.14	0.624	0.17	0.544

**p* < 0.05, ** *p* < 0.001

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 12

Correlations between cognitive control strategy and N2 latency on AY trials in the AY-70 block

	RT Contrast (BX - AX)		Accuracy Contrast (BX - AX)	
	r	*p*	*r*	*p*
Average N2 latency at Fz for AY trials	-0.22	0.432	0.04	0.899
Average N2 latency at FCz for AY trials	-0.16	0.567	0.09	0.758
Average N2 latency at Cz for AY trials	-0.16	0.568	0.14	0.629
Average N2 latency at CPz for AY trials	0.05	0.854	-0.17	0.556
Average N2 latency at Pz for AY trials	-0.05	0.852	-0.13	0.651

*$p < 0.05$, ** $p < 0.001$

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

Table 13

Partial correlations between code-switching and cognitive control strategy, after controlling for L2 proficiency in the AY-70 block

	RT Contrast (BX - AX)		Accuracy Contrast (BX - AX)	
	r	*p*	*r*	*p*
L2 to L1 Switches	-0.57	0.017	0.12	0.338
L1 to L2 Switches	0.12	0.340	-0.16	0.294
Contextual Switches	0.59	0.014*	-0.24	0.206
Unwanted Switches	0.14	0.315	0.00	0.500

*$p < 0.05$, ** $p < 0.001$

Note: A proactive control strategy is typically associated with faster RT and higher accuracy on BX trials compared to AY trials. A reactive control strategy is typically associated with faster RT and higher accuracy on AY trials compared to BX trials.

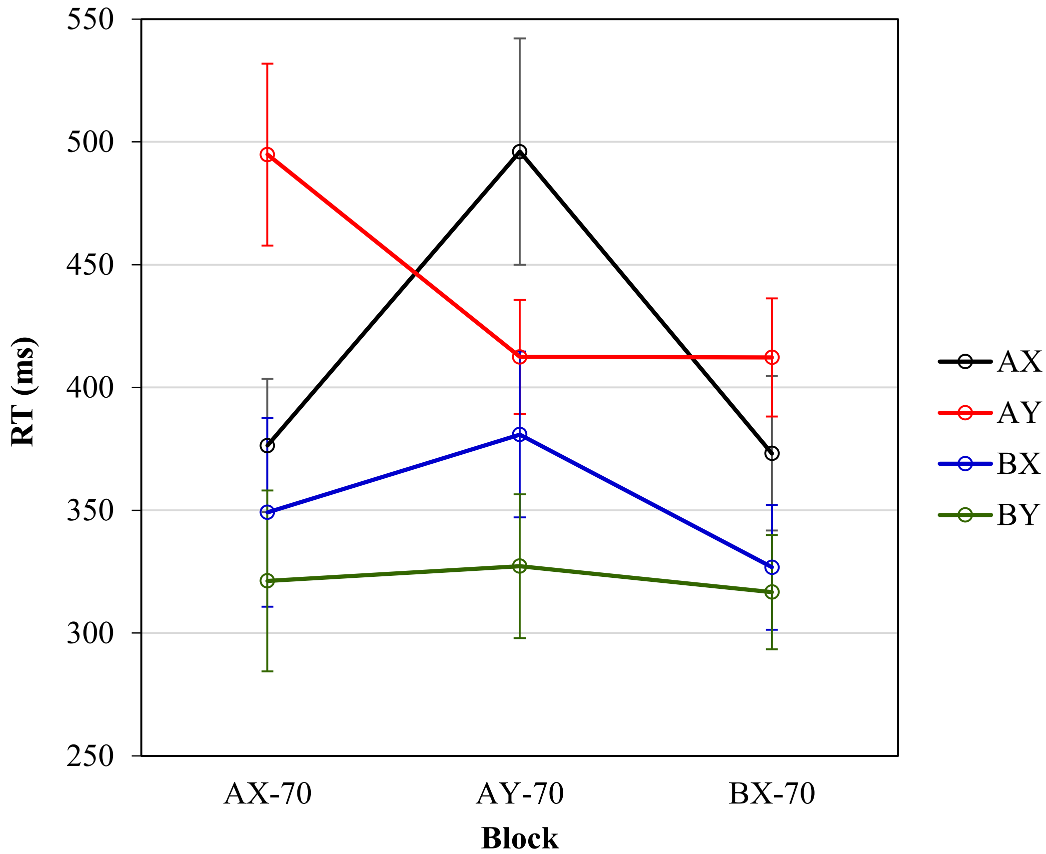

Figure 1 – Reaction time on all four trial types (AX, AY, BX, BY) across three blocks (AX-70, AY-70, BX-70)

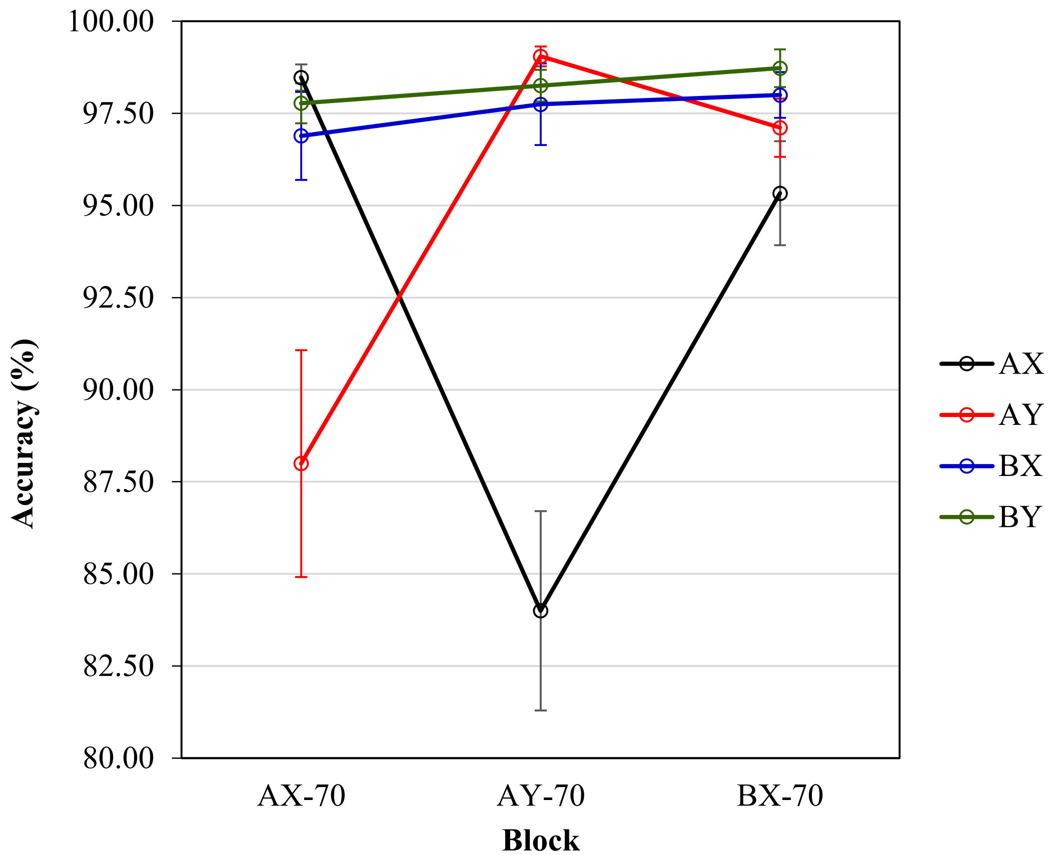

Figure 2 – Accuracy on all four trial types (AX, AY, BX, BY) across three blocks (AX-70, AY-70, BX-70)

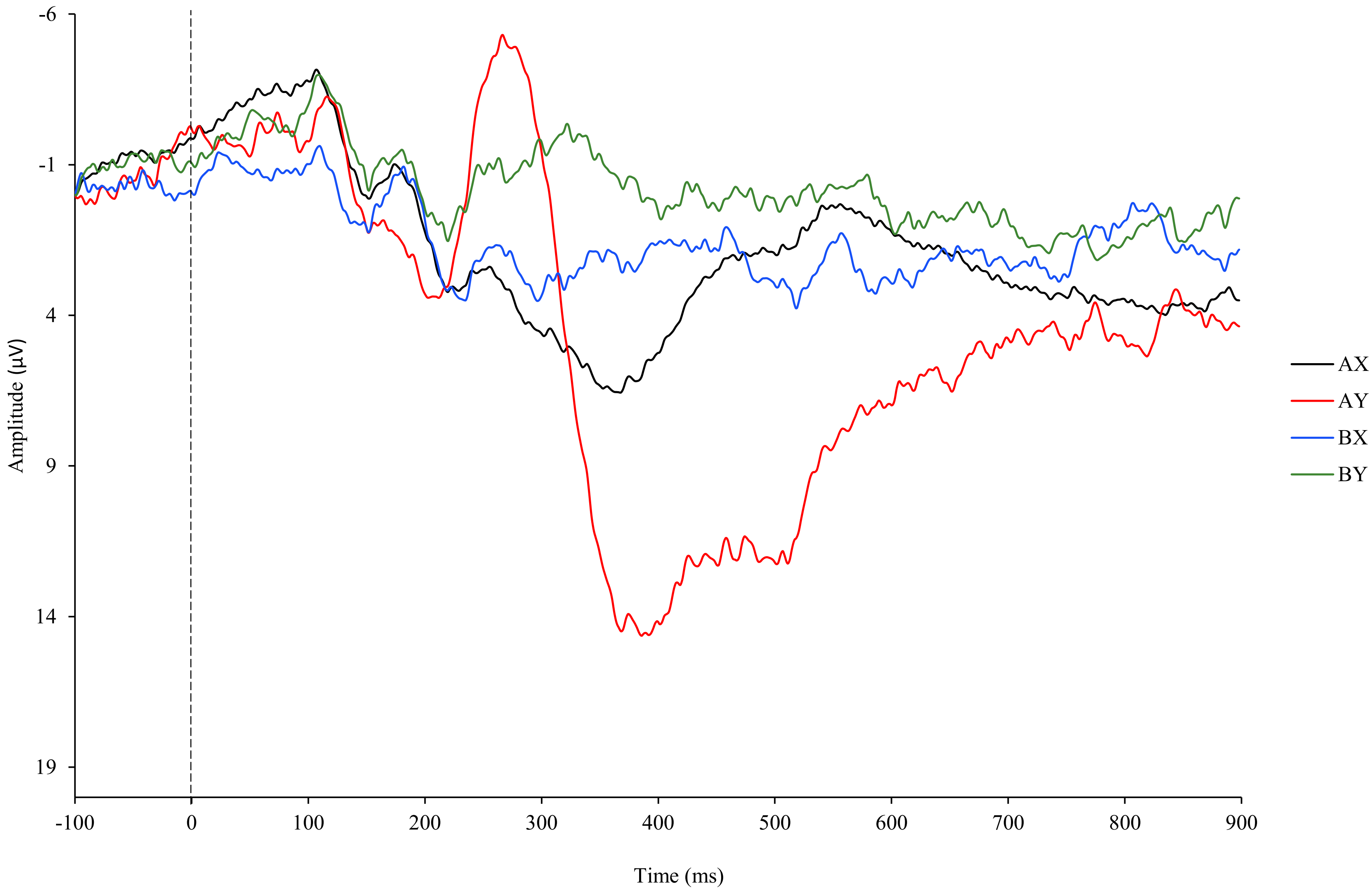

Figure 3 – Target-locked electrophysiological activity for all four trial types in the AX-70 block at site FCz

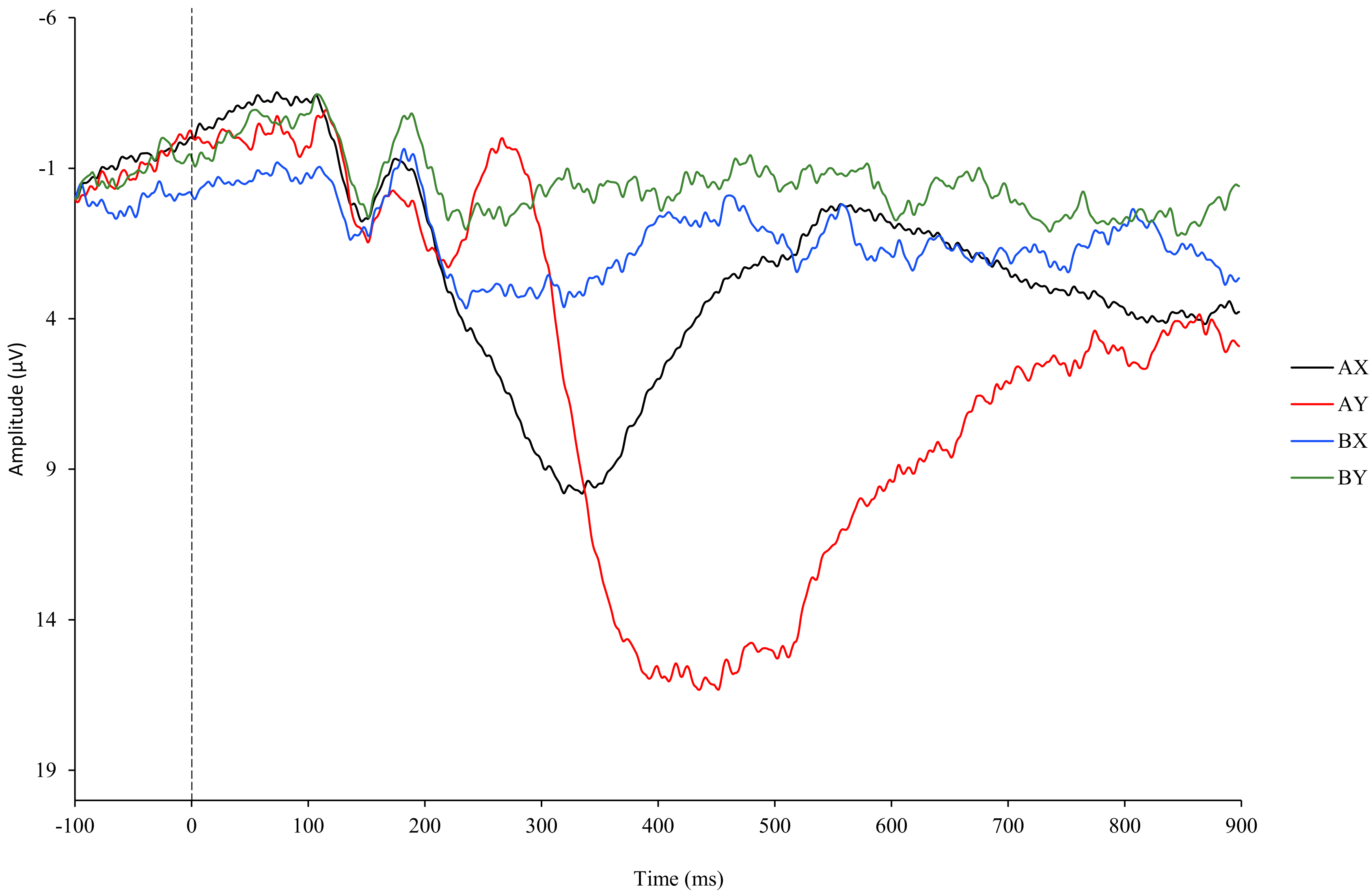

Figure 4 – Target-locked electrophysiological activity for all four trial types in the AX-70 block at site CPz

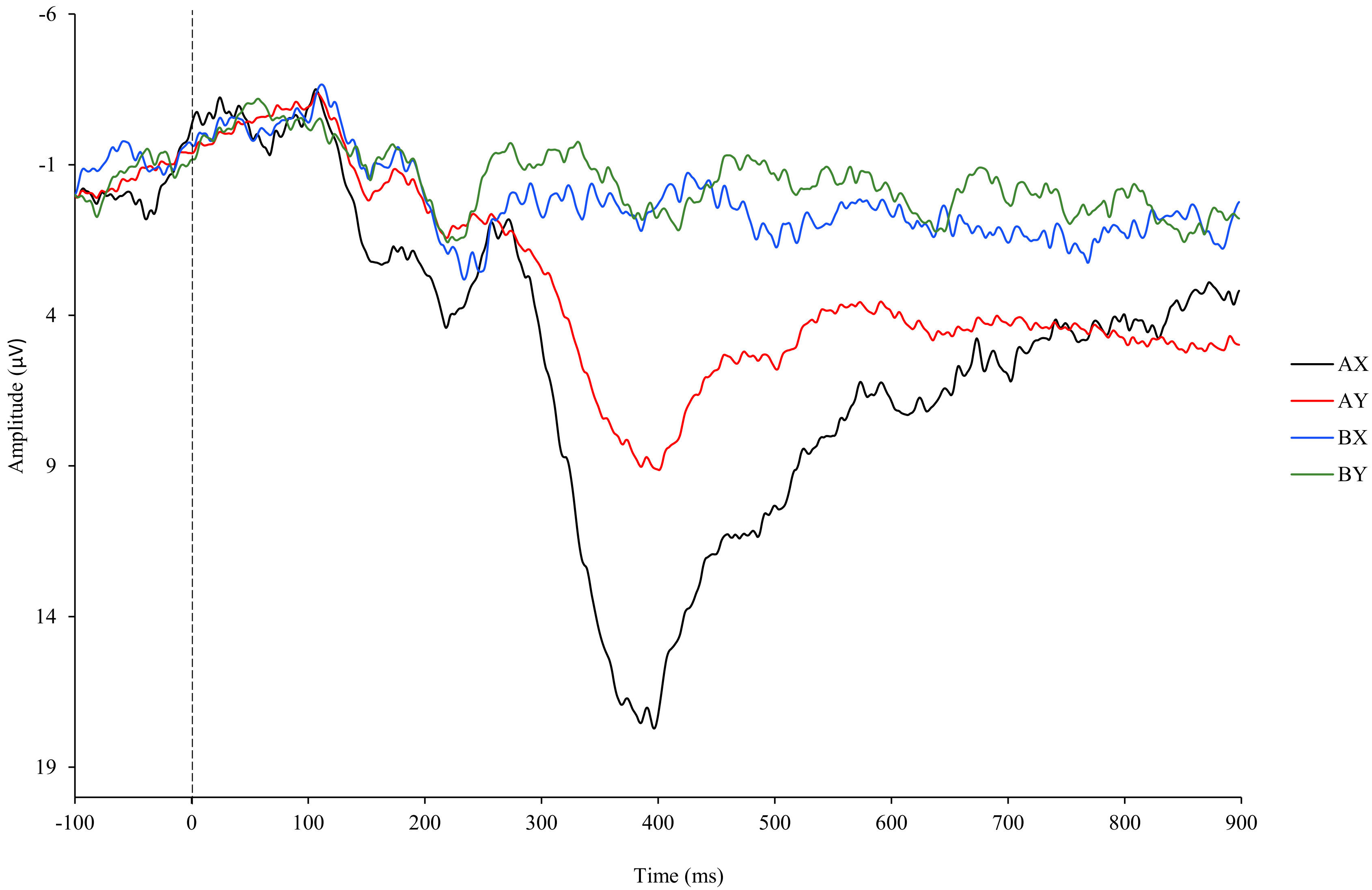

Figure 5 – Target-locked electrophysiological activity for all four trial types in the AY-70 block at site FCz

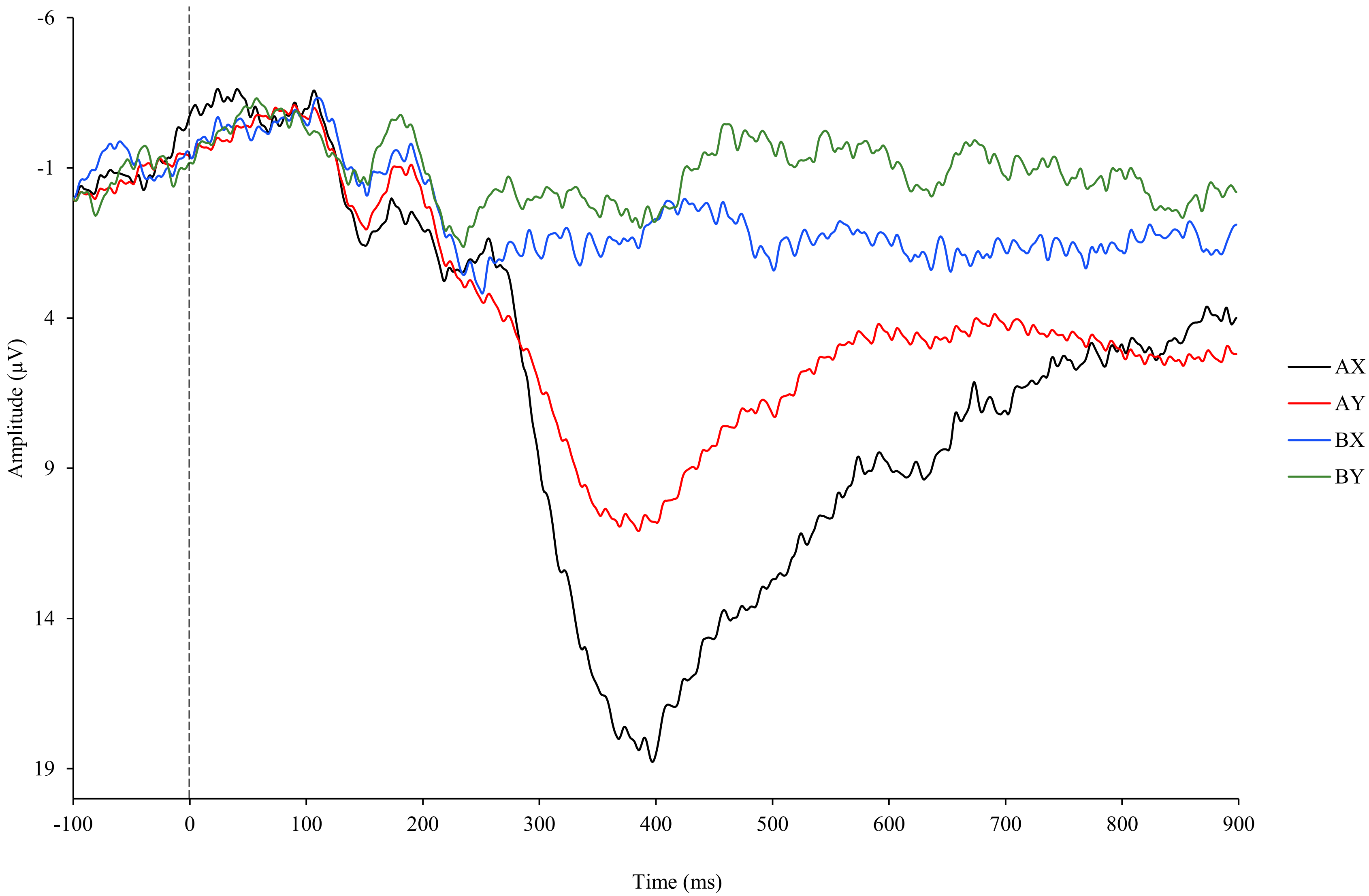

Figure 6 – Target-locked electrophysiological activity for all four trial types in the AY-70 block at site CPz

Figure 7 – Target-locked electrophysiological activity for all four trial types in the BX-70 block at site FCz

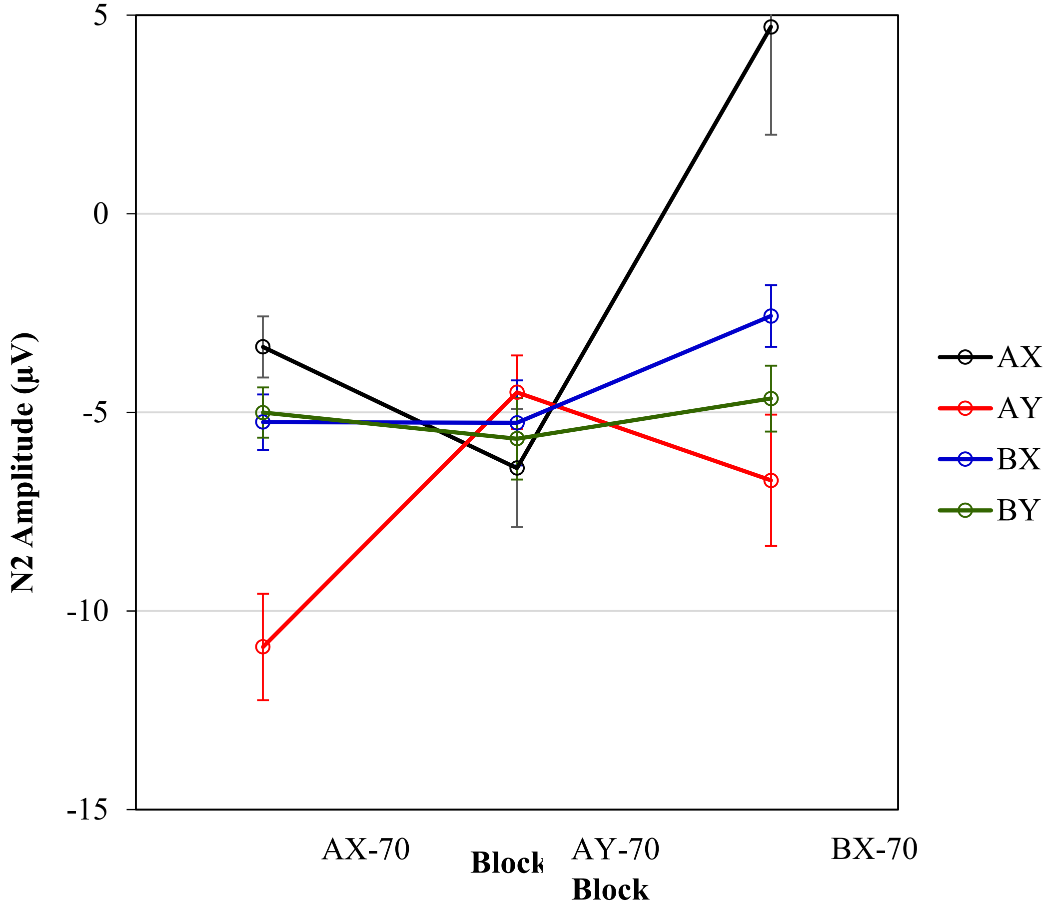

Figure 8 – N2 amplitude on all four trial types (AX, AY, BX, BY) across three blocks (AX-70, AY-70, BX-70)

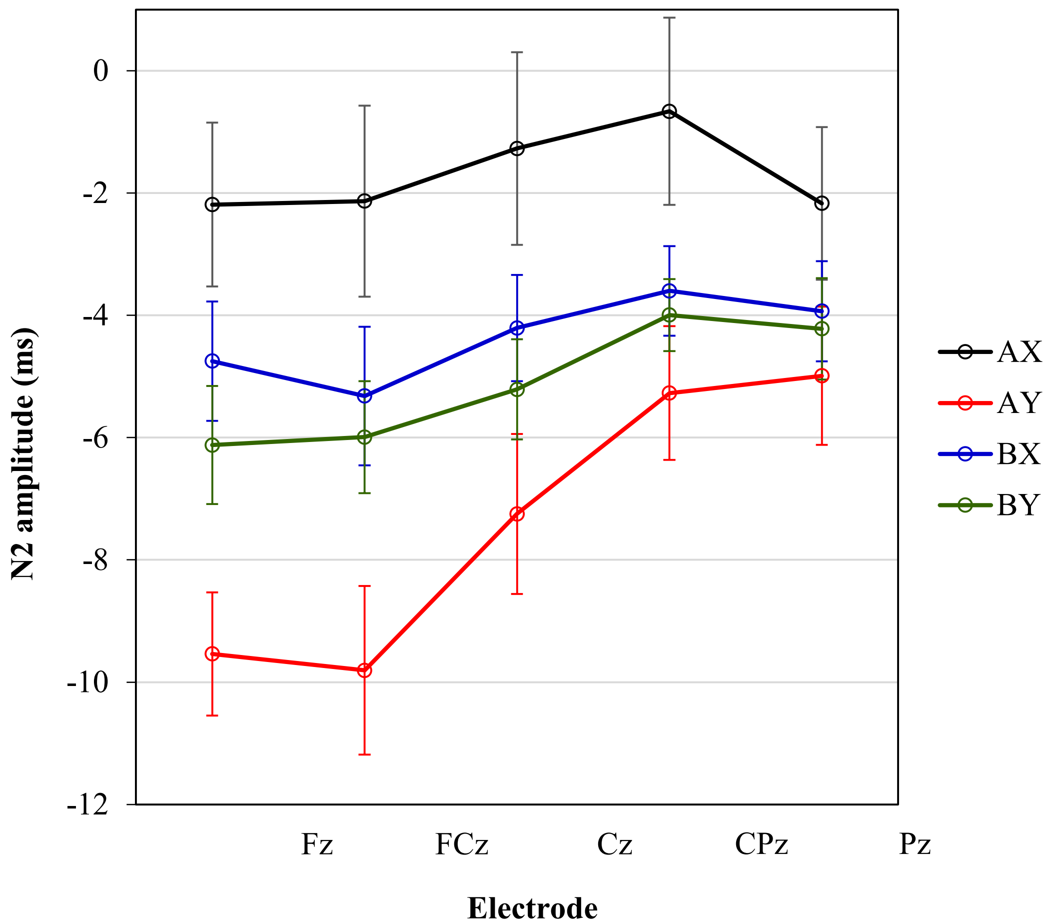

Figure 9 – N2 amplitude on all four trial types (AX, AY, BX, BY) for five electrodes (Fz, FCz, Cz, CPz, Pz) collapsed across the three blocks

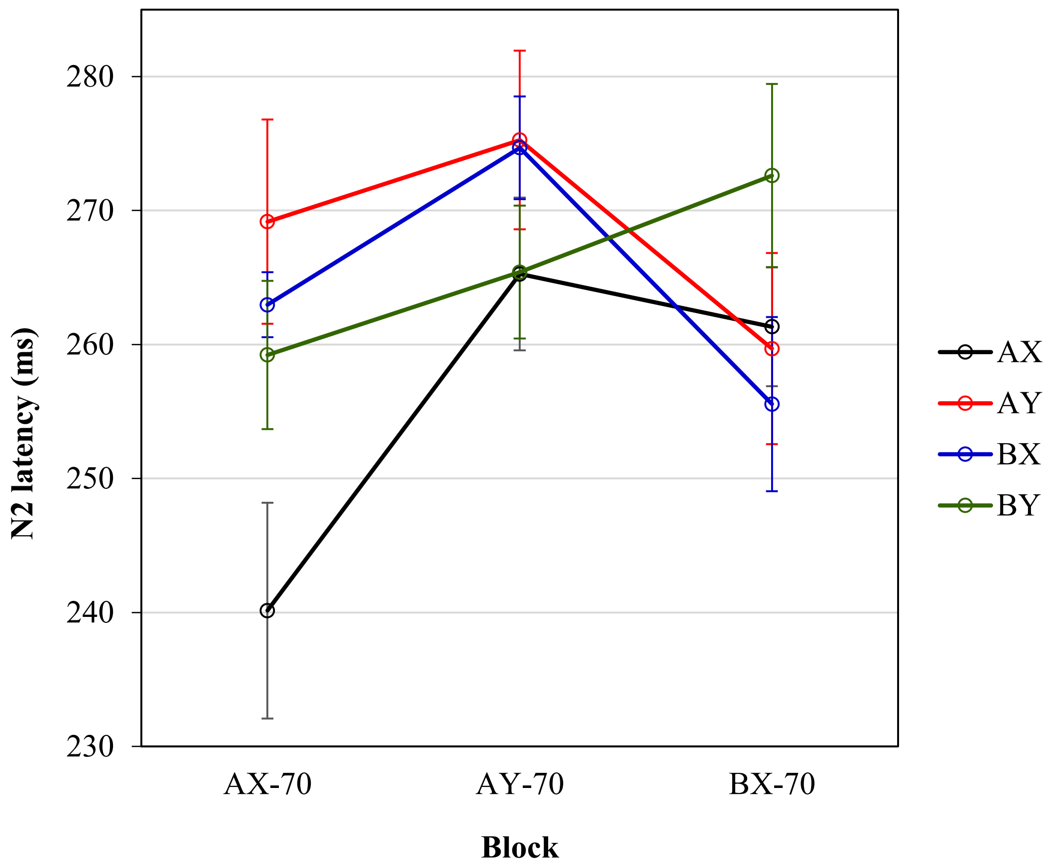

Figure 10 – N2 latency on all four trial types (AX, AY, BX, BY) across three blocks (AX-70, AY-70, BX-70)

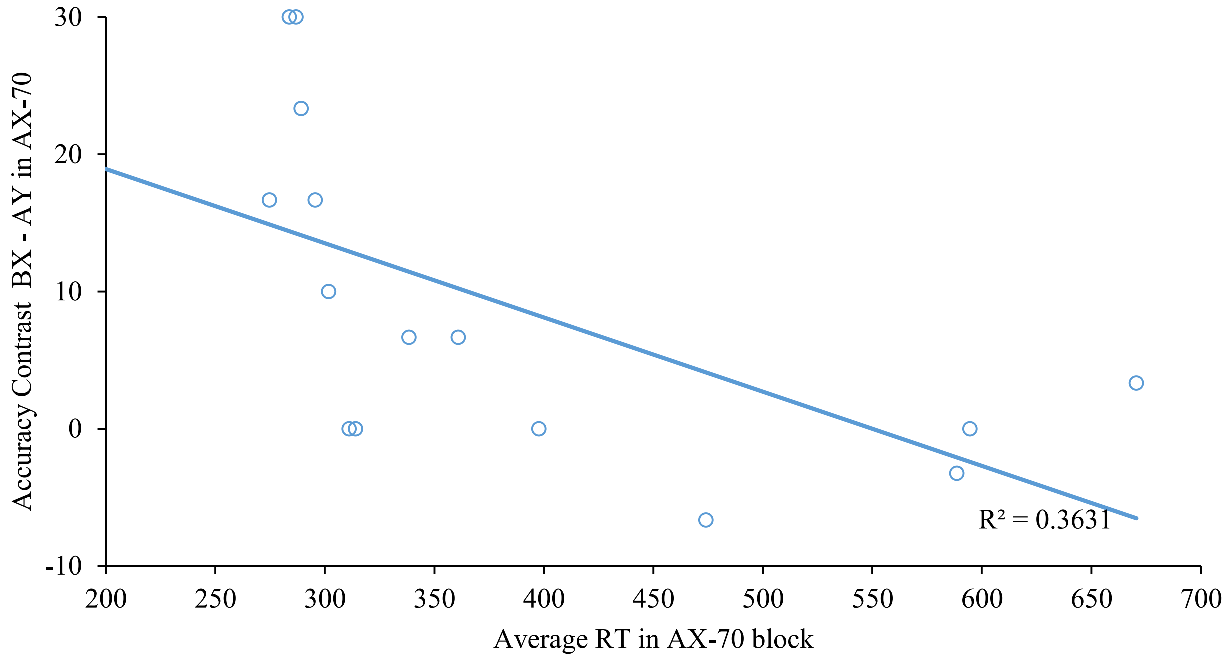

Figure 11 – Correlation between participants' Accuracy Contrast value (BX – AY) and their average RT in the AX-70 block collapsed across trial types

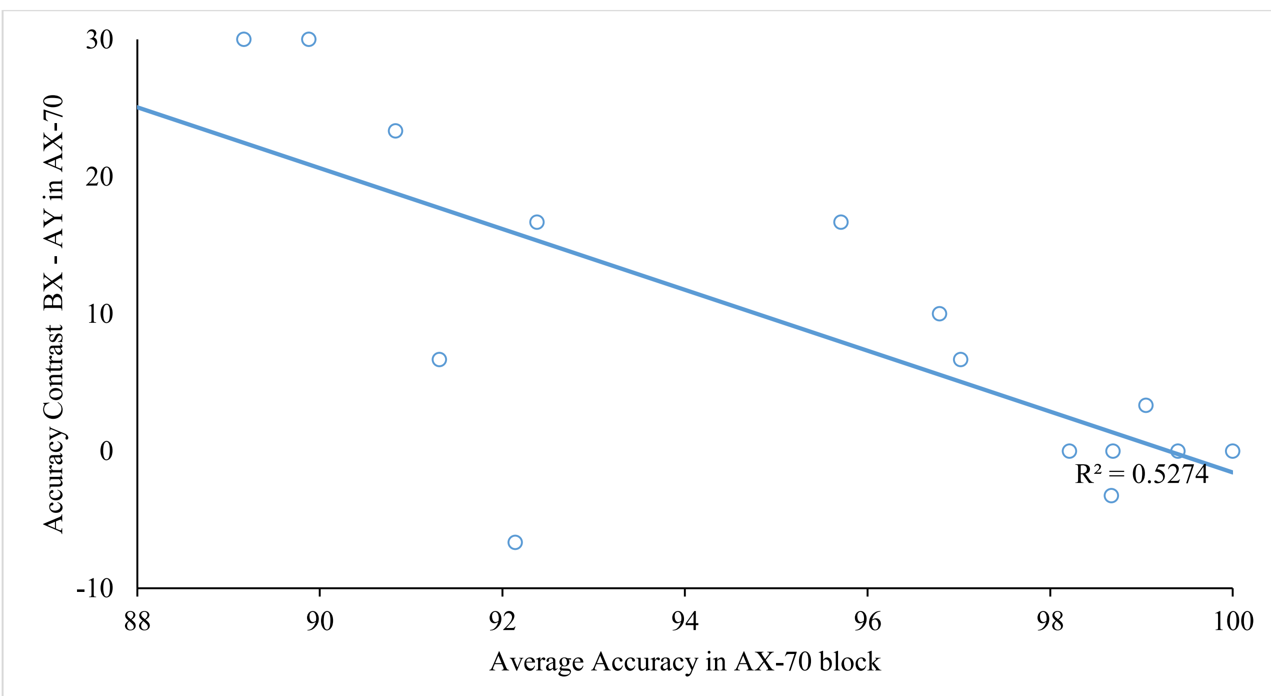

Figure 12 – Correlation between participants' Accuracy Contrast (BX – AY) value and their average accuracy in the AX-70 block collapsed across trial types

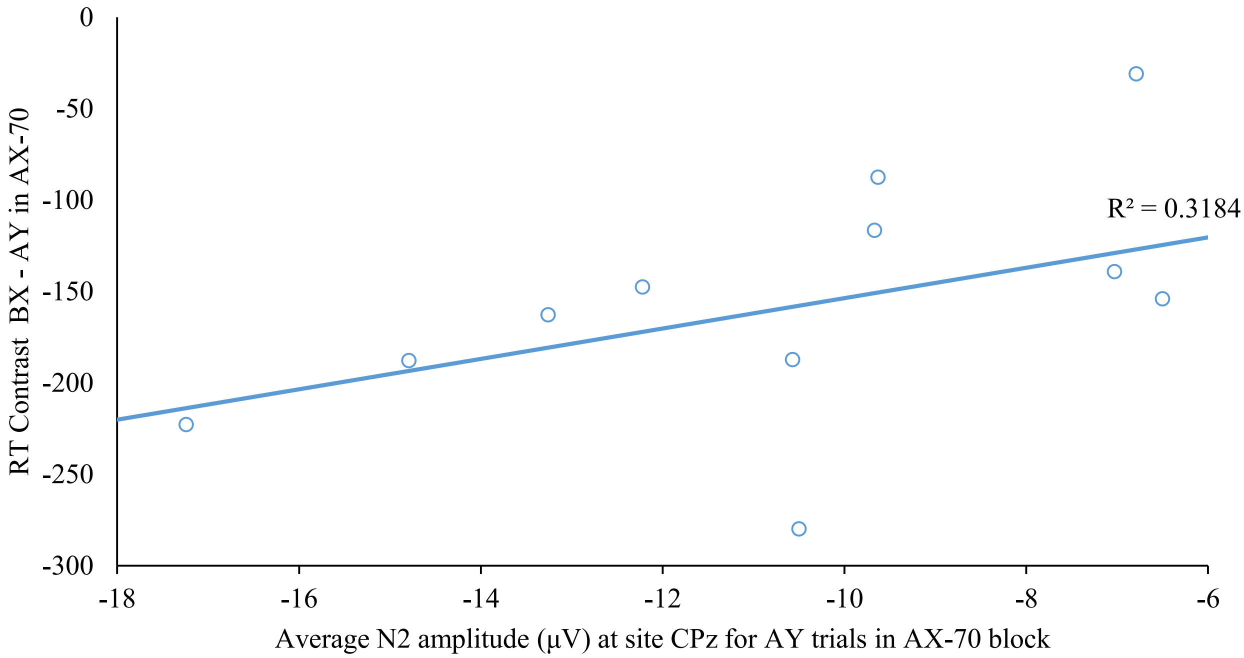

Figure 13 – Correlation between participants' RT Contrast (BX – AY) value and the average amplitude of the N2 component at site CPz for AY trials in the AX-70 block

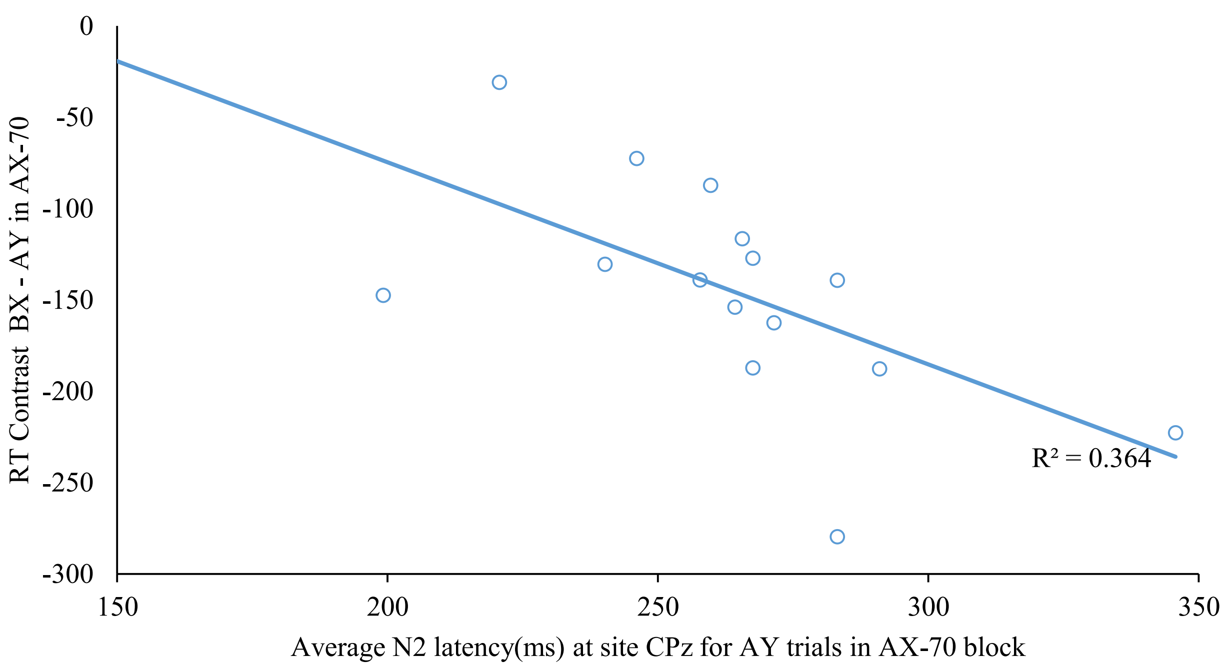

Figure 14 – Correlation between participants' RT Contrast (BX – AY) value and the average latency of the N2 component at site CPz for AY trials in the AX-70 block

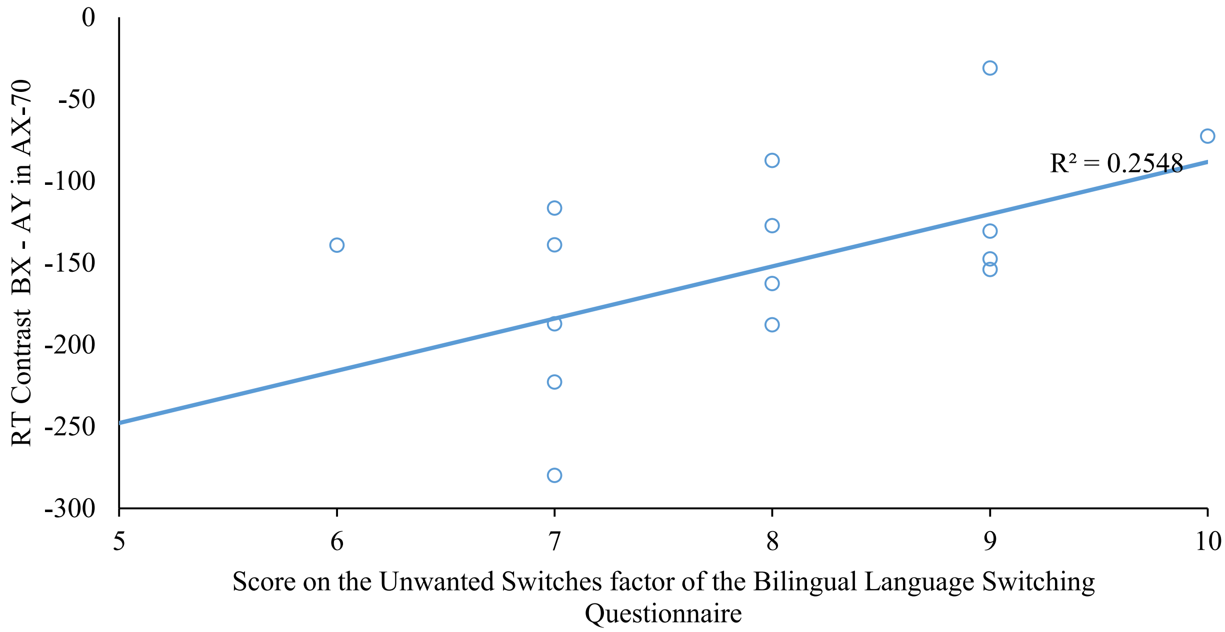

Figure 15 – Partial correlation between participants' RT Contrast (BX – AY) value in the AX-70 block and their score on the Unwanted Switches factor of the Bilingual Language Switching Questionnaire controlling for L2 proficiency

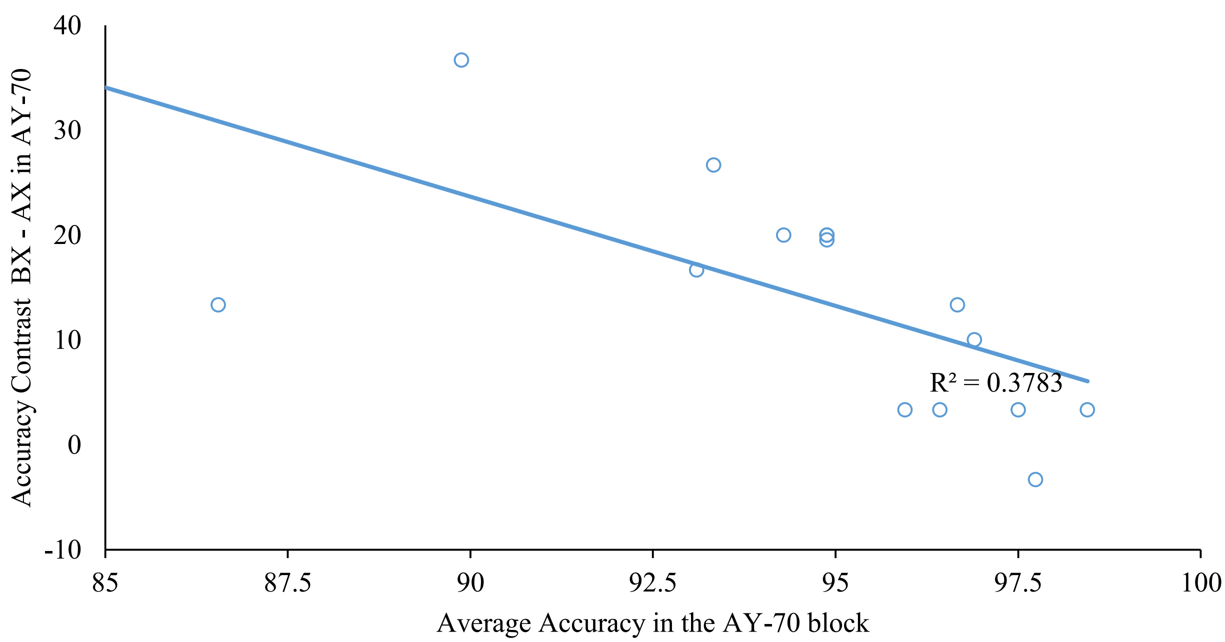

Figure 16 – Correlation between participants' Accuracy Contrast (BX – AX) value and their average accuracy in the AY-70 block collapsed across all trial types

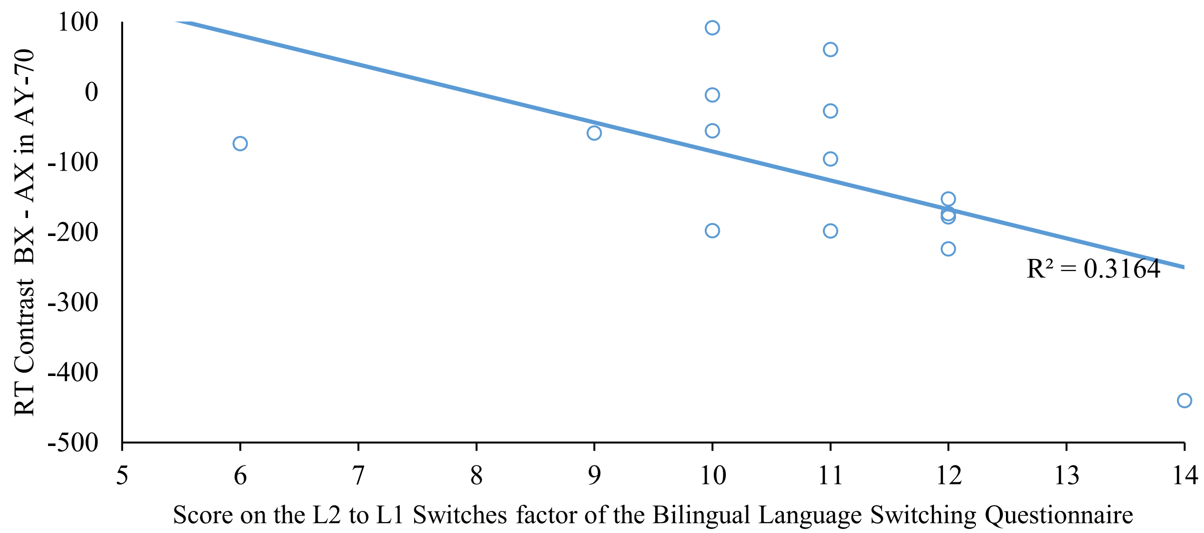

Figure 17 – Partial correlation between participants' RT Contrast (BX – AX) value in the AY-70 block and their score on the L2 to L1 Switches factor of the Bilingual Language Switching Questionnaire controlling for L2 proficiency

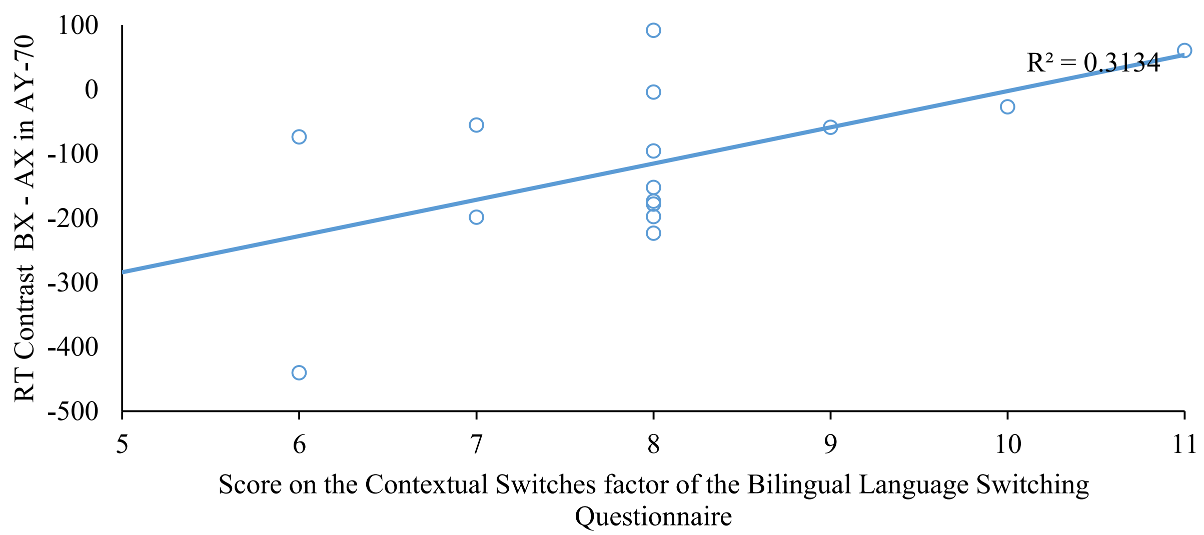

Figure 18 – Partial correlation between participants' RT Contrast (BX – AX) value in the AY-70 block and their score on the Contextual Switches factor of the Bilingual Language Switching Questionnaire controlling for L2 proficiency

Appendix A

Id: __________ Interviewer: _____________ Date (D/M/Y): _____________

History Questionnaire[*]

We are interested in your personal history because it may help us to better understand the results of our study. Your answers to a few short questions will aid us in this effort. All answers will be kept strictly confidential. Thank you for your help.

Demographics:

1. Date of Birth (D/M/Y):_____________ 2. Age:_________________

3. Gender: *(circle response)* (1) Male (2) Female

4. Handedness: *(circle response)* (1) LEFT (2) RIGHT (3) BOTH

5. Present marital status: *(circle response)* (1) Single – never married
(2) Married
(3) Separated
(4) Divorced
(5) Widowed
(6) Cohabit

Language

7. Place of Birth:____

8. If not Canada, how long have you been in Canada? _________________________________

9. Languages Spoken (in order of fluency):____

10. Primary Language/Language of choice:____

11. Language at home:_____________________ 10. At work: _________________________

12. At what age did you first learn English/French? ___________________________________

13. At what age did you become fluent in it ? ______________________________________

14. How would you rate, from 1 to 5[1], your level of proficiency in the languages you speak? What percentage of time do you speak it?

Language	Rating (**L**istening, **R**eading, **S**peaking, **W**riting):
1. ___________________	L: ____ R: ____S: ____ W: ____ %:____
2. ___________________	L: ____ R: ____S: ____ W: ____ %:____
3. ___________________	L: ____ R: ____ S: ____W: ____ %:____
4. ___________________	L: ____ R: ____S: ____ W: ____ %:____

[*] Questionnaire updated January 2010
[1] 1: No ability at all; 2: Very little; 3: Moderate; 4: Very good; 5: Native-like ability

Id: __________ **Interviewer:** _____________ **Date (D/M/Y):** _____________

These questions are to be administered for studies interested in language and/or bilingualism:

6. Parents' places of birth and native languages:
mother: __________________ father: ___________________________________

Have you ever spent a long period of time in another country in which you had to communicate in a language other than your native language? Indicate these cities, languages, and the age at which you lived there:
No.

What is your primary language or language of choice? __________________________

Which languages do you speak… (and if more than one, which is primary?)

- at home? ____
- with close family (parents/siblings)? ____________________________________
- with extended family (grandparents)? ___________________________________
- with friends? ____
- with yourself (e.g. when you dream)? ___________________________________

In what language(s) do you listen to the radio? Watch tv? ___________________________________
Which language(s) do you use at work (estimate percentage for each)?
At school: ____

In which language was your education?
primary________ secondary_________ cegep_________ university____________

How did you learn your second language? ____

____

15 . How many years of education do you have at this time? (i.e., what is the highest level achieved?)

1 2 3 4 5 6	7 8 9 10 11	12 13	14 15 16	17 18 19 20	21 22 23 24 25
Elementary	Secondary	Cegep	Undergrad	Graduate	Professional

16. In what field did you complete your degree? _____________________________

17. Did you skip or repeat a grade?
    A) NO / YES
    B) Which one (s):____

18. Did you have any particular difficulty with any subject in school?
    A) NO/YES
    B) Which one (s): ____

Id: __________ **Interviewer:** _____________ **Date (D/M/Y):** _____________

19. What is or was your main occupation? ____

20. What was your longest held occupation? ____

21. When did you retire? _________________

22. How many hours per week do you engage in physical exercise? ______________________

23. How many hours per week do you engage in a social activity (this can include interacting with members of your household)?_____________

FOR YOUNG ADULTS:

How many years of education does your mother have, or what is the highest level that she completed? (see scale above if necessary) _________________

What is her main occupation? ________________________________

How many years of education does your father have, or what is the highest level that he completed? (see scale above if necessary) _________________

What is his main occupation? ________________________________

FOR OLDER ADULTS (AND YOUNG ADULTS WHO ARE MARRIED):

How many years of education does/did your spouse have, or what was the highest level that he/she completed? (see scale above if necessary) _________________

What was/is his/her main occupation? ________________________________

Medical History

24. Do you have now, or have you had in the past -*(please circle your response)*

- Visual problems:	A) Nearsighted / Farsighted B) Glasses / Contact lenses[2] C) Cataract: Left / Right D) Colour blind: NO / YES
- Trouble hearing:	E) NO / YES F) Hearing Aid: Left / Right

[2] If participant usually wear contact lenses, he/she will have to wear glasses on ERP testing sessions (to prevent blinking).

Id: __________ **Interviewer:** _____________ **Date (D/M/Y):** _____________

25. Have you ever been unconscious[3], had a head injury or had blackouts[4]?
    - A) NO / YES
    - B) Cause:____
    - C) Duration:____
    - D) Treatment:____
    - E) Outcome:____

26. Have you been seriously ill or hospitalized in the past 6 months?
    - A) NO / YES
    - B) Cause:____
    - C) Duration:____

Do you have now, or have you had in the past (conditions susceptible or influencing cognitive functions)...

27. a) A stroke? b) [s] Transient ischemic attack (mini-stoke[5])?	NO / YES NO / YES	
28[s]. Bypass surgery?	NO / YES	
29[S] Heart disease?	NO / YES	Nature (myocardial infarction [MI], angina, narrowing of arteries):
30 [S] High blood pressure?	NO / YES	Is it controlled? NO / YES What medication? ________________
31 [S]. High cholesterol?	NO / YES	Is it controlled? NO / YES What medication? ________________
32 [S]. a) Diabetes? b) Insulin dependent?	NO / YES	Type 1 / Type 2 Age of onset: __________________ Treatment: __________________
33. Other Surgery?	NO /YES	
34. Seizures?	NO / YES	Age Onset: ______________________ Frequency: ______________________ Cause: ______________________ Treatment: ____________________
35. Epilepsy?	NO / YES	
36. Thyroid disease?	NO / YES	
37. Frequent headaches?	NO / YES	Tension / migraine
38. Dizziness?	NO / YES	
39. Trouble walking Unsteadiness?	NO / YES NO / YES	

[3] Falling unconscious ≠ Fainting
[4] Exclude: Substantial head injury relatively recently, several concussions, & coma.
[S] Risk factors for stroke. Exclusion criterion: More than one of those factors, if older participants.
[5] Mini-stroke: symptoms less than 24 hours.
[S] Risk factors for stroke. Exclusion criterion: More than one of those factors, if older participants.

Id: __________ **Interviewer:** _____________ **Date (D/M/Y):** _____________

40. Arthritis?	NO / YES	
41. Any injuries to the lower limb? (e.g. hip, knee, ankle)	NO / YES NO / YES	
42. Serious illness (e.g. liver disease)?	NO / YES	
43. Neurological disorders[6]? (e.g. lupus, MS, Parkinson's)	NO / YES	
44. Exposure to toxic chemicals (that you know of)?	NO / YES	
45. Depression?	NO / YES	Did you seek assistance or feel the need to so? ______________________ Is it controlled? ______________________
46. Anxiety?	NO / YES	Did you seek assistance or feel the need to so? __Yes____________________ Is it controlled? _Yes, since years. I no longer take medication._____
47. Other psychological difficulties?	NO / YES	
48. Hormone replacement?	NO / YES	
49. Steroids?	NO / YES	

50. Medication: Please list the medication you are currently taking and any other medication that you have taken in the past year.

Type of medication		Reason for consumption	Duration of consumption and dose
A			
B			
C			
D			
E			
F			

51. Do you drink alcohol? a) YES, frequently.
b) YES, but infrequently.
c) NO.

If YES, approximately how many drinks[7] of alcohol do you have per week? ________________________________

[6] Automatic exclusion

[7] 1 drink = 1 beer, 1 glass of wine, 1 oz of liquor. 2 drinks/day is considered moderate drinking.

Id: __________ **Interviewer:** _____________ **Date (D/M/Y):** _____________

52. Do you use non-prescription drugs such as homeopathic medications, vitamins, laxatives, syrups ?
NO / YES
If YES, which one (s): ____
How many times per week?
a) Occasionally b) 1 - 3 c) 4 - 6 d) more than 6

53. Do you use non-prescription drugs for recreational purposes?
NO / YES

If yes, do you use marijuana/hashish?
NO / YES
If YES, How many times per week?
a) Occasionally b) 1 - 3 c) 4 - 6 d) more than 6

Do you use any other non-prescription drugs for recreational purposes?
NO / YES
If YES, How many times per week?
a) Occasionally b) 1 - 3 c) 4 - 6 d) more than 6
If yes, which one (s): (*participant not obliged to answer*) ________________________

Ask participant to not use drugs prior to testing (~48hr)

54. Do you smoke[8]?
NO / YES
If YES, How many packs a day (or average quantity)? _____________

55. Current problems: Are you currently troubled by any of the following[8]?
a) Concentration / Attention problems?
NO / YES
Nature: ____
b) Memory problems?
NO / YES
Nature: ____
c) Difficulties finding words?
NO / YES
Nature: ____

56) How would you rate your health? *(circle response)*
1) poor 2) fair 3) good 4) very good 5) excellent

---

[8] Please remind potential older participants who are interested in participating to research because of memory concerns that we do NOT provide full clinical assessments

Id: __________ **Interviewer:** _____________ **Date (D/M/Y):** _____________

57) Have you participated in other studies (outside of our lab)? NO/YES

If **YES**, which lab did the study take place?

____
____
____
____
____

What was the purpose of the study (or any details about the study)?

____
____
____
____
____

When did the study take place?

____
____
____
____
____

Id: __________ Interviewer: _____________ Date (D/M/Y): _____________

<u>Participant contact information</u>:

Name: ____

Phone Number: ____

Email: ____

Address ***(remind participant that this section is optional)***:

____

____

____

Are you willing to be contacted by researchers in Dr. Phillips' lab for future studies?
NO / YES

What year will you graduate? ____

Can we give your contact information to other Concordia researchers (name, tel. #, email address)?
NO / YES

Source: ____

Eligibility:

- You are not eligible for this study due to ________ reasons, but you may be eligible for other studies, so we'll keep your information on file
- I need to discuss some issues with my colleagues, and I will contact you to let you know if you are eligible to participate.
- If they ask why they are ineligible:
  - We are interested in cognitive processing and certain conditions, medications, and habits interfere with cognitive processing, therefore we cannot test people who meet those criteria

Appendix B

Battery of cognitive and neuropsychological measures

Montreal Cognitive Assessment (MoCA; Nasreddine, Phillips, Bédirian, Charbonneau, Whitehead, Collin, Cummings, & Chertkow, 2005). The MoCA is a cognitive screening test used to detect cognitive and executive deficits (e.g., difficulties with attention, concentration, memory, visuo-spatial skills) associated with conditions such as mild cognitive impairment (MCI) and dementia (Nasreddine et al., 2005; Julayanont et al., 2014). The screening tool yields a total score out of 30 points, with a total score below 26 suggesting some degree of cognitive impairment (Nasreddine et al., 2005). Additionally, more specific index scores (e.g., memory index score, executive function index score) can be computed in order to further define the cognitive domains that are impaired (Julayanont et al., 2014). The MoCA has both high sensitivity (90%) and specificity (87%) in correctly detecting individuals with MCI and distinguishing them from individuals who are cognitively normal (Nasreddine et al., 2005).

Briggs-Nebes Handedness Inventory (Briggs & Nebes, 1975). This questionnaire uses 12 items to assess an individuals' hand preference for various everyday tasks (e.g., “Write a letter legibly”). For each item, participants are asked to indicate which hand they habitually use to complete the task using a five-point scale (i.e., always left, usually left, no preference, usually right, always right). Each answer is assigned a value ranging from -2 (always left) to +2 (always right) which is then used to compute a total score ranging from -24 to +24. According to Briggs and Nebes, left-handedness is characterized by scores below -9 whereas scores of +9 and above are indicative of right-handedness. Scores between -9 and +8 suggest “mixed handedness” (Briggs & Nebes, 1975).

Similarities (Wechsler, 2008). Similarities is a subtest from the *Wechsler Adult Intelligence Scale – IV* (WAIS-IV) which measures abstract verbal reasoning and associative thinking. During this subtest, participants are presented with pairs of words (e.g., two and seven) and asked to explain how the two words are alike. The pairs steadily increase in difficulty, with the similarities becoming more abstract as the test progresses.

California Verbal Learning Test, 2nd edition (CVLT-II; Delis, Kramer, Kaplan, & Omer, 2000). The CVLT-II is a test of verbal memory and learning in which participants are instructed to memorize words from two different lists. The first list is read five times and participants are asked to recall as many words as they can after each reading. Following this, the second list is read to the participants and they are asked to recall words from this new list and then from the first list (without having the list read to them). Subsequently, participants are instructed to recall all the words from the first list that belong to specific categories, thereby informing them of a possible strategy to organize their learning. After a longer delay, participants have to recall words from the list without semantic cues first, and with the help of the cues second. Finally, participants are read one more list. For each item, they have to decide whether the word was on the first list.

The CVLT-II yields a host of information about participants' verbal memory, how they organize their learning, and how quickly they acquire new information.

Visual Reproduction (Wechsler, 2009). Visual Reproduction is a subtest from the *Wechsler Memory Scales – IV* (WMS-IV) which assesses visual memory abilities. Participants are shown simple figures for a short period of time. After this brief presentation, they are instructed to draw the figures from memory. After a delay, participants are asked to draw the figures again. Finally, participants are presented with more figures and have to choose which figure they have previously seen.

Matrix Reasoning (Wechsler, 2008). Matrix reasoning is a subtest from the WAIS-IV which is a non-timed measure of visuo-perceptual abilities. Participants are presented with logical series of figures from which one is missing. They then are instructed to select the appropriate figure from an array of possible answers.

Digit Span (Wechsler, 2008). Digit Span is another subtest from the WAIS-IV. It is a measure of focused of auditory attention involving brief storage and mental manipulation of information (i.e., working memory). Participants are presented with sets of digits that gradually increase in length. The test is divided into three sections with slightly different instructions. In the first part, participants are asked to simply repeat the sets of digits that are read to them. In the second part, they are instructed to repeat the sets of digits backwards. In the third and final section, participants have to sequence the digits in each set from lowest to largest. For each section, the sets increase in difficulty, thereby allowing to determine the exact span that can no longer be sequenced.

Letter-Number Sequencing (Wechsler, 2008). Letter-Number Sequencing is a subtest from the WAIS-IV which is used as an optional measure of working memory and mental manipulation of auditory information. In a fashion similar to the Digit Span, participants are presented with sets that increase in length from two to eight. However, the sets are now comprised of both letters and numbers. Participants are instructed to reorder each set so as to repeat the digits first, in numerical order, and the letters in alphabetical order. As with Digit Span, the sets increase in difficulty in order to determine the exact span that can no longer be sequenced.

Verbal Fluency (Delis, Kaplan, & Kramer, 2001). Verbal Fluency is a subtest from the *Delis-Kaplan Executive Function System* (D-KEFS). This test is divided into three sections. In the first section, participants are assigned a letter of the alphabet and are given 60 seconds to produce as many words that beginning with this letter as they can. This exercise is repeated with two additional letters. In the second section, participants are given categories rather than letters of the alphabet in order to guide their word production. In the final section, participants are asked to alternate between two different categories.

Color-Word Interference (Delis, Kaplan, & Kramer, 2001). Color-Word Interference is a subtest from the D-KEFS which measures speed of processing and resistance to interference. This task is comprised of four different conditions. In the two baseline conditions, participants are asked to name patches of colour or read words. In the two critical conditions, they are to ignore conflicting information (i.e., a mismatch between the name of the colour and the ink it was printed in) and name the color of ink the names of colours are printed in.

Trail-Making (Delis, Kaplan, & Kramer, 2001). Trail-Making is a measure of visuo-motor skills from the D-KEFS. It involves simple motor speed, visual scanning, sequencing of information (i.e., drawing lines between letters or numbers in ascending order), as well as alternating between sequencing letters and numbers.

Hayling & Brixton Sentence Completion Test (Burgess & Shallice, 1997). This test is a measure of response initiation and response suppression (i.e. inhibition) divided into two sections. In the first section, participants are read a series of sentences with the last word missing and are instructed to complete the sentence with the most appropriate word. In the second section, participants are asked to complete the sentences with a word that is completely unconnected to the sentence in every way possible. For both sections, participants are told that they should give their answer as fast as possible.

Appendix C

Presentation order

Participants	Presentation Order	Auditory block	AX key	Other key
1	AX-70, BX-70, AY-70	Before	z	/
2	AX-70, BX-70, AY-70	Before	/	z
3	AX-70, BX-70, AY-70	After	z	/
4	AX-70, BX-70, AY-70	After	/	z
5	AX-70, AY-70, BX-70	Before	z	/
6	AX-70, AY-70, BX-70	Before	/	z
7	AX-70, AY-70, BX-70	After	z	/
8	AX-70, AY-70, BX-70	After	/	z
9	BX-70, AX-70, AY-70	Before	z	/
10	BX-70, AX-70, AY-70	Before	/	z
11	BX-70, AX-70, AY-70	After	z	/
12	BX-70, AX-70, AY-70	After	/	z
13	BX-70, AY-70, AX-70	Before	z	/
14	BX-70, AY-70, AX-70	Before	/	z
15	BX-70, AY-70, AX-70	After	z	/
16	BX-70, AY-70, AX-70	After	/	z
17	AY-70, AX-70, BX-70	Before	z	/
18	AY-70, AX-70, BX-70	Before	/	z
19	AY-70, AX-70, BX-70	After	z	/
20	AY-70, AX-70, BX-70	After	/	z
21	AY-70, BX-70, AX-70	Before	z	/
22	AY-70, BX-70, AX-70	Before	/	z
23	AY-70, BX-70, AX-70	After	z	/
24	AY-70, BX-70, AX-70	After	/	z

Note: Only the first 15 presentation orders have been used to date.