EXAMINING THE TIME COURSE OF ATTENTION IN MONOLINGUALS AND BILINGUALS

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Abstract

There is converging evidence demonstrating that lifelong experience managing multiple languages on a regular basis has consequences for both language and cognition. Across the lifespan, bilinguals tend to outperform monolinguals on tasks that require selective attention. Compared to studies on children and older adults, these effects are less consistently observed in young adults. The majority of the research with young adults use relatively simple tasks that yield fast reaction times and accuracy rates at ceiling. In addition, these measures capture the endpoint of a chain of dynamic cognitive processes. Hence, the goal of the dissertation was to integrate two time-sensitive methodologies, mouse-tracking and eye-tracking, to examine whether monolinguals and bilinguals differ in the processes engaged between the time a response is initiated to when a response is selected. To assess cognitive performance, young adult and older adult monolinguals and bilinguals were administered the global-local task and oculomotor Stroop task while their eye-movements and mouse-movements were recorded. Both tasks involved focusing on one feature of the stimulus, while ignoring the other feature. When standard analyses of mean reaction time and accuracy were performed, no differences between language groups were observed in either age group. The mouse-tracking measures revealed that similar to experts, young adult bilinguals were slower to initiate a response than young adult monolinguals, while older adult bilinguals had a higher maximum velocity than older adult monolinguals. By using time-sensitive methodologies, we gain a deeper understanding of the cognitive processes associated with attention that are impacted by bilingualism during decision-making.

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I dedicate my dissertation to my grandfather, Joseph Foo-Kong-Kioung. Je t'aime beaucoup Koung Koung. Mo pu mette mo chapeau carré bientot.

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Introduction

For every waking moment of our lives, we are constantly surrounded by language. Not only do we actively use language to communicate our thoughts and feelings, to read a book, or listen to someone speak, but we are also passively using language every time we attach a label and representation to an object. Within a single language, words that share a phonological-onset (*book* and *boot*; Allopenna, Magnuson, & Tanenhaus, 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) or a semantic relationship (*dog* and *cat*; Schriefers, Meyer, & Levelt, 1990) with an incoming word are activated and competing for attention. For more than half of the world's population (Grosjean, 2010), this rich linguistic experience extends to multiple languages. In Canada specifically, the prevalence of bilingualism has increased by 13.3% since 2011, such that the linguistic diversity has expanded to over 200 languages in the home with almost 7.7 million Canadians speaking another language aside from English or French on a regular basis (Statistics Canada, 2016). It is important to understand how this form of mental exercise (i.e., the act of learning and speaking two languages on a regular basis) impacts cognition throughout the lifespan.

From birth to young adulthood, there is rapid growth in neural synapses and connections. Over time, the brain engages in a continuous process of synaptic pruning by deleting neural connections that are no longer necessary, while strengthening new pathways to increase neural efficiency for learning, memory formation, and other forms of adaptation. A wide range of experiences have been implicated as factors that can boost cognition through neuroplasticity, including formal education (Kramer, Bherer, Colcombe, Dong, & Greenough, 2004), aerobic exercise (Colcombe & Kramer, 2003), and musical training (Gaser & Schlaug, 2003; Münte, Altenmüller, & Jäncke, 2002). It has been argued that bilingualism is another experience that has the potential to modify brain structure (Baum & Titone, 2014; Bialystok, 2017). Several anatomical studies have shown that bilinguals tend to have greater grey matter density and increased white matter connectivity than monolinguals (see Grundy, Anderson, & Bialystok, 2017 and Li, Legault, & Litcofsky, 2014 for reviews). But unlike other experiences that can only be undertaken during a finite number of hours per day, language is unique due to its intensity and whole-brain involvement. Language processing recruits an extensive set of brain regions, including the frontal, temporal, and parietal lobes (Arana, Marquand, Hultén, Hagoort, & Schoffelen, 2020; Ardila, Bernal, & Rosselli, 2016); these areas are routinely involved to perform other types of tasks beyond language. Thus, bilingualism potentially has profound consequences for both language and cognitive processing.

A substantial body of research has shown that even when only a single language is required, the two languages of a bilingual remain constantly active (see Kroll, Dussias, & Bogulski, Valdes Kroff, 2012 for a review). During bilingual speech planning, lexical candidates from the unintended language produce either competition or facilitation depending on the degree of overlap in phonology and semantic association. Evidence for cross-language competition in bilingual speech production comes from studies that use the picture-word interference paradigm to study lexical access. In this paradigm, a picture is presented along with a distractor word superimposed. The objective is to name the picture while ignoring the word. When the distractor word in the non-target language was semantically-related to the picture (i.e., word *chien* paired with the picture of a cat), bilinguals experienced interference in lexical retrieval with longer naming times (Costa & Caramazza, 1999; Hermans, Bongaerts, de Bot, & Schreuder, 1998). The degree of interference is similar in magnitude as the within-language semantic interference (i.e., word *dog* paired with the picture of a cat). However, when the distractor was phonologically-related in the non-target language [i.e., word *sheep* (mouton) paired with a picture of a moon;

Costa, Colomé, Gómez, & Sebastián-Gallés, 2003; Costa, Miozzo, & Caramazza, 1999; Hermans et al., 1998], a translation-equivalent (i.e., word *chien* with the picture of dog; Costa et al., 1999), or a cognate (i.e., word *tigre* with the picture of a tiger; Costa, Caramazza, & Sebastián-Gallés, 2000; Dijkstra, Grainger, & Van Heuven, 1999), facilitation in naming occurred for bilinguals. Such findings demonstrate that bilinguals are susceptible to both facilitation and interference from the non-target language, placing unique processing demands that are not found in monolinguals.

A similar situation occurs for comprehension. When bilinguals encounter a spoken word, the lexicons from both languages are simultaneously activated. Marian and Spivey (2003) used the visual-world paradigm to examine lexical competition in monolinguals and bilinguals. In the visual-world paradigm, eye-movements are recorded while participants look at a display consisting of a target amongst distractors. Russian-English bilinguals were presented with a display of four objects that included a target object (e.g., “marker”), an object whose name is phonologically similar in the same language (e.g., “marbles”), an object whose name is phonologically similar across languages (e.g., “stamp”, which is *marka* in Russian), and an unrelated object (e.g., “dog”). For example, participants were instructed to “Pick up the marker. Put the marker below the cross”. Russian-English bilinguals made brief looks to the cross-language competitor (“stamp”) even though the object was irrelevant to the task. Similarly, Thierry and Wu (2007) reported that Mandarin-English bilinguals unconsciously translated English words into Chinese characters. Participants were asked to indicate whether English word pairs were semantically related or not when presented visually and auditorily. The critical manipulation was that half of the English words when translated into Chinese contained a repeated Chinese character. Although no behavioral differences were observed between conditions, the electrophysiological data showed an attenuated N400 for the English words that had a repeated Chinese character illustrating that bilinguals automatically activated the irrelevant language when reading or listening to words in their second language. These results provide further evidence for language non-selective activation. However, in order to successfully communicate in the intended language, there needs to be a mechanism that allows for competition between languages to be resolved.

Resolution of within-language competitors has been carried out differently between monolinguals and bilinguals on tasks that manipulate phonological and semantic associations (Bialystok, Dey, Sullivan, & Sommers, 2020; Blumenfeld & Marian, 2011; Friesen, Chung-Fat-Yim, & Bialystok, 2016). For example, Bialystok et al. (2020) compared monolinguals and bilinguals on the Deese-Roediger-McDermott paradigm (DRM; Roediger & McDermott, 1995). In the semantic variant of the DRM, participants are provided a list of words that are semantically associated to a critical lure that is not shown on the list. They are then told to recall or recognize as many words as possible from the list without guessing. The typical finding is that due to the spreading activation of semantic networks, participants tend to falsely recall the critical lure. On this task, bilinguals were less likely to falsely recognize critical lures than monolinguals. Therefore, as a result of having to select between competing alternatives that exist within- and between-languages, bilinguals have become experts in selecting relevant from irrelevant information.

Parallel activation of multiple languages implies that a language control mechanism exists to avoid cross-language interference. Green (1998) proposed the inhibitory control model as a possible mechanism to account for the efficiency of language selection. According to Green, the mental representation for each word contains a language tag that specifies the language to which it belongs to. A supervisory attention system that is a domain-general resource inhibits the language tags at the lemma level of the non-target language while activating those of the target language. The experimental evidence supporting the inhibitory control model comes from language switching studies demonstrating that switching into the more dominant language (i.e., L2 to L1) is more costly than switching into the less dominant language (i.e., L1 to L2; Meuter & Allport, 1999). The asymmetrical switch cost occurs because naming in the weaker language requires active inhibition of the dominant language. When required to switch back to naming in the dominant language, naming times increase because bilinguals had previously actively inhibited this language. Given that bilinguals can speak in one language with very few intrusions from the other language (Gollan, Sandoval, & Salmon, 2011; Sandoval, Gollan, Ferreira, & Salmon, 2010), inhibition as a mechanism is an appealing proposal.

Neuroimaging (Abutalebi & Green, 2008; Anderson, Chung-Fat-Yim, Bellana, Luk, & Bialystok, 2018; Coderre, Smith, van Heuven, & Horwitz, 2016; De Baene, Duyck, Brass, & Carreiras, 2015; Luk, Green, Abutalebi, & Grady, 2011) and electrophysiological (Timmer, Grundy, & Bialystok, 2017) studies have shown that bilinguals recruit the same areas of the brain for language selection and domain-general executive control. The repeated engagement of these neural networks for language selection suggests that over time, bilinguals may develop a more efficient executive control system that could facilitate conflict resolution in other cognitive domains as well (Bialystok, Craik, Green, & Gollan, 2009). A large body of research has shown that across the lifespan, bilinguals typically outperform monolinguals on non-verbal executive control tasks (see Bialystok, 2017 for a review); however, this pattern of results is less consistently observed in young adults. Some studies find young adult bilinguals perform better than monolinguals (Costa, Hernández, & Sebastián-Gallés, 2008; Marzecova, Asanowicz, Kriva, & Wodniecka, 2013; Yang & Yang, 2016), while others find no differences between groups (Paap & Greenberg, 2013; Paap & Sawi, 2014; von Bastian, Souza, & Gade, 2016). Therefore, the conditions under which the effects of bilingualism are found and the mechanism responsible for these effects are still not fully understood.

Over the years, many researchers investigated the impact of bilingualism on one or all three components of the tripartite model of executive functions postulated by Miyake and colleagues (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). The model proposed by Miyake and colleagues includes inhibition (controlled suppression of prepotent responses), working memory (updating and monitoring of mental representations), and shifting (ability to flexibly switch between mental states). Studies tend to focus on inhibition based on the assumption that the non-target language is routinely inhibited (Green, 1998). However, in a review paper, Bialystok (2017) argued that an inhibitory account explaining the cognitive and linguistic outcomes of bilingualism is unlikely due to several pieces of evidence. First, pre-verbal infants raised in bilingual households show advantages in anticipating the location of a reward after it has switched locations compared to those raised in monolingual households (Comishen, Bialystok, & Adler, 2019; Kovacs & Mehler, 2009). Pre-verbal infants have yet to produce a language and have only rudimentary representations of either language. Therefore, inhibition is not yet required for language selection since the languages are likely not competing with one another. The more likely explanation is that the bilingual experience affords bilinguals with a different way to allocate attention to their rich linguistic environment (Bialystok, 2015). Bilingual infants are using attention to continuously monitor the incoming speech stream for phonemic variations between languages from multiple sources in their environment and to discriminate between them. Eye-tracking studies revealed that compared to infants raised in a single-language household, infants exposed to multiple languages in the home are able to discriminate between languages based on visual cues alone (Sebastián-Gallés, Albareda-Castellot, Weikum, & Werker, 2012; Weikum et al., 2007). These findings demonstrate that from an early age, bilingualism may modify the way attention is allocated in the presence of interfering linguistic and non-linguistic information.

Second, in a review of the empirical data across several non-verbal interference tasks, Hilchey and Klein (2011) reported that bilinguals typically outperform monolinguals on *both* congruent and incongruent trials. This is contrary to the inhibitory account which predicts that language group differences would emerge on trials that require conflict and selection (i.e., incongruent trials). Congruent trials do not require inhibition because the distracting or irrelevant information does not produce conflict. In fact, the "distracting" information in congruent trials is often faciliatory, such as in the flanker task where the surrounding arrows are pointing in the same direction as the target central arrow (← ← ← ← ←). The more likely explanation is that bilinguals adapt to the current task demands regardless of whether the trial is congruent or incongruent by flexibly increasing or decreasing attentional engagement (Hilchey & Klein, 2011; Zhou & Krott, 2018).

Finally, inhibition is not a single process. Bilinguals generally perform better than monolinguals on tasks proposed to measure inhibitory control, such as the flanker task (Chung-Fat-Yim, Himel, & Bialystok, 2019; Costa, Hernández, & Sebastián-Gallés, 2008; Emmorey, Luk, Pyers, & Bialystok, 2008). However, on tasks that require withholding a prepotent response (Martin-Rhee & Bialystok, 2008), delaying gratification (Barac, Moreno, & Bialystok, 2016; Carlson & Meltzoff, 2008), or controlling impulses (Carlson & Meltzoff, 2008), which are also considered to reflect inhibition, monolinguals and bilinguals perform equivalently. Hence, models based on inhibition alone cannot fully explain the research on bilingualism and cognition.

For these reasons, attention has been recently proposed as the mechanism responsible for performance differences between monolinguals and bilinguals on non-verbal executive control tasks (Bialystok, 2015; 2017). Prior to the inhibitory control model by Green (1998), earlier proposals included selective attention as the key explanation for how bilingual children exceled in problem-solving tasks compared to monolingual children (Bialystok, 1992; 1999). However, the term "attention" is quite broad, and several models of selective attention exist each making different predictions about the cognitive outcomes associated with bilingualism.

Selective Attention as a Model for Bilingualism

"Everyone knows what attention is…it implies withdrawal from some things in order to deal effectively with others" (James, 1890).

Selective attention is the process by which our brain directs awareness to relevant information in the face of distracting or competing information (Treisman, 1964). Although we are constantly bombarded with a rich array of information in our environment, only a fraction of it is captured by our attention. For example, as you read this passage, your mind is focusing on the words on the page, while activity in the background may be spilling into your conscious awareness. In order to stay fixed on the task of reading, there needs to be a filter that conveys to the brain which pieces of information require your immediate attention. The filter is especially important because attention is a limited resource and attending to several things at once can overload our cognitive system.

One of the most prominent theories of selective attention is Broadbent's (1958) stage-like filter theory. In this theory, physical attributes (e.g., color, tone, pitch, etc.) of all incoming information are extracted and held in a pre-attentive temporary store (Figure 1a). A filter then acts as a buffer on all incoming sensory information to select what information gains conscious awareness and what gets blocked. Inputs that are not selected for further processing remain briefly in a temporary sensory storage but then decay if they are no longer used. Therefore, unattended information is not processed beyond the extraction of physical attributes. Inputs that are selected for further processing are extracted for semantic features and stored in short term memory. In this view, attended information moves to short term memory and a response is executed, while unattended information is filtered out.

Treisman (1964) extended Broadbent's (1958) filter theory of selective attention based on several observations demonstrating that participants engaged in a single task were influenced by unrelated semantic information (Figure 1b). Rather than blocking irrelevant stimuli completely, Treisman (1968) proposed a filter that *attenuates* irrelevant signals based on physical characteristics. Unattended information still passes through all processing stages, but the difference is that the information is weakened. The input can gain conscious awareness if it passes a certain threshold, which was thought to be determined by contextual and semantic information. For example, important words, such as our name, have low thresholds and can easily access our conscious awareness; low frequency words have high thresholds and are less likely to be perceived. The attenuation theory can account for why individuals are still able to process the meaning of both attended and unattended messages. Using dichotic listening tasks, Treisman (1964) conducted a series of experiments where identical messages were presented to each ear. Bilingual participants were asked to shadow a message in English, while the same message was presented in French in the unattended ear. Bilingual participants noticed that the information in the unattended ear was identical to the one in the shadowed ear. This finding demonstrates that unattended information is processed rather than filtered out, and meaningful information can be extracted.

Broadbent's (1958) filter theory and Treisman's (1964) attenuation theory are viewed as early selection models of attention because they place the filter at the perceptual level and closer to the input stage. Deutsch and Deutsch (1963) proposed a late selection model of attention, in which all stimuli (attended and unattended) are processed in their entirety for their physical *and* semantic properties (Figure 1c). Thus, selection occurs closer to the response stage and information that is most pertinent to the context are selected. In other words, if the information is deemed to be meaningful or relevant to the task demands, then it will move to short term memory. All stimuli have an equal chance of selection, but only the response that best fits the requirements of the situation is selected. Solso (1979) criticized the model for being uneconomical: If all incoming information is analysed for meaning, we would need a rather large processing capacity. Specifically, the model by Deutsch and Deutsch would be very taxing for highly proficient bilinguals. If the signal from the target and non-target languages were equivalent in strength and processed to their full extent, the mechanism responsible for managing attention between languages would be highly taxed presumably leading to many instances of cross-language intrusions. However, such high degree of cross-language intrusions rarely occurs.

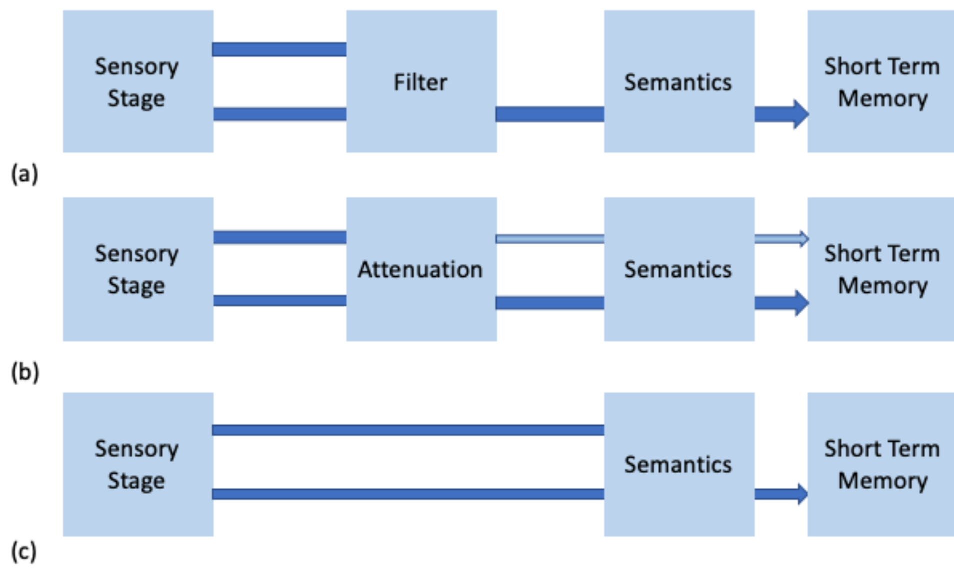

Figure 1. Models of selective attention. (a) Broadbent's (1958) filter theory. (b) Treisman's (1964) attenuation theory. (c) Deutsch and Deutsch's (1963) late-filter theory. The top arrow illustrates the processing stages of the unattended information, while the bottom arrow illustrates the processing stages of the attended information.

Broadbent's (1958) filter theory of attention as well as Deutsch and Deutsch's (1963) late filter theory, in which unattended information is blocked and not processed into short term memory, could both be perceived as inhibitory. Based on the evidence provided in the earlier section against the inhibitory account, Treisman's (1964) attenuation theory of selective attention appears to be a better fit than other alternative models of selective attention as a model for bilingualism.

To my knowledge, only one study has looked at the neural mechanisms of selective attention in monolinguals and bilinguals. Using a dichotic listening task, Olguin, Cekic, Bekinschtein, Katsos, and Bozic (2019) demonstrated that bilingualism modifies the neural mechanisms of auditory selective attention. The authors had bilinguals listen to a narrative in their native language while ignoring a competing narrative in the other ear. The information presented to the unattended ear was either a story in their native language (greatest degree of interference), a story in an unknown language, or non-verbal noise (i.e., musical rain; least amount of interference). The electrophysiological data revealed that bilinguals had similar levels of neural encoding across all interference conditions. In contrast, a separate study with English monolinguals tested under the same paradigm found that attentional encoding was modulated by the type of interference (Olguin, Bekinschtein, & Bozic, 2018), such that when the competing information was in their native language (i.e., English), the strongest neural encoding of the attended and unattended streams was found, followed by the unknown language (i.e., Spanish), and finally, the non-verbal noise. The authors interpreted these findings to suggest that early experience speaking multiple languages produces neurocognitive changes to the mechanisms underlying selective attention, such that years of experience ignoring irrelevant information has led to an enhanced or more efficient attentional control system in bilinguals. An alternative interpretation not mentioned by the authors is that bilinguals could be using *more* resources across all distractor types because both verbal and nonverbal information (i.e., cadence, pitch, tone, etc.) were useful to bilinguals during infancy to discriminate between languages. An examination of which interpretation is correct is beyond the scope of the dissertation.

Bilingualism and Executive Control: Controversial Findings

Across the lifespan, bilinguals tend to outperform monolinguals on non-verbal executive control tasks (Bialystok, 2017). Executive control involves the ability to carry out goal-directed behavior using a set of higher-order cognitive processes (Miller & Cohen, 2001). However, these effects are more consistently observed in children (see Barac, Bialystok, Castro, & Sanchez, 2014 for a review; Adesope, Lavin, Thompson, & Ungerleider, 2010 for a meta-analysis), adolescents (Christoffels, de Haan, Steenbergen, van den Wildenberg, & Colzato, 2014; Chung-Fat-Yim, Himel, & Bialystok, 2019), and older adults (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Craik, Luk, 2008; Gold, Kim, Johnson, Kriscio, & Smith, 2013) than in younger adults (e.g., Costa, Hernández, & Sebastián-Gallés, 2008; Marzecova, Asanowicz, Kriva, & Wodniecka, 2013; Yang & Yang, 2016; but see Paap & Greenberg, 2013; Paap & Sawi, 2014; von Bastian, Souza, & Gade, 2016).

In a cross-sectional study, Bialystok, Martin, and Viswanathan (2005) recruited children, young adults, middle-aged adults, and older adults who were monolingual or bilingual and compared their performance on the Simon task (Simon & Rudell, 1967). On the Simon task, participants are required to click right whenever they see one stimulus (e.g., circle) and click left whenever they see another stimulus (e.g., square). The stimulus could appear on either the left or right side of the screen. Incongruent trials occur when the stimulus and response key are on opposite sides, while congruent trials occur when the stimulus and response key are on the same side. To succeed on the task, one must overcome the irrelevant dimension, which is the spatial location of the stimulus. Bilinguals performed faster across all age groups, except in the young adult group, in which equivalent performance between groups was found. Other studies have also reported differences at each end of the lifespan, but rarely amongst young adults (Bialystok, Craik, Luk, 2008; Salvatierra & Rosselli, 2010). Bialystok and colleagues (2005) explained that for young adults, they are already operating at their developmental peak and as such bilingualism offers no additional boost in performance.

Within the last decade, the beneficial effects of bilingualism on cognitive performance have been called into question with some studies reporting no behavioral differences between monolinguals and bilinguals on various executive control tasks (e.g., Duñabeitia et al., 2013; Gathercole et al., 2014; Kirk, Fiala, Scott-Brown, & Kempe, 20114; Paap & Greenberg, 2013; Sörman, Hansson, & Ljungberg, 2019; von Bastian, Souza, & Gade, 2016; see Lehtonen et al., 2019 for a meta-analysis). In three experiments, Paap and Greenberg (2013) found that monolingual and bilingual university students performed equivalently on a variety of tasks that were meant to assess inhibitory control, monitoring, and switching. Furthermore, recent meta-analyses on the relationship between bilingualism and executive control report small or no bilingual advantages (Donnelly, Brooks, & Homer, 2019; Lehtonen, Soveri, Laine, Järvenpää, de Bruin, & Antfolk, 2018; Paap, Anders, Mulinksky, Mason, & Alvarado, 2017). It is important to note that the dependent variable included in these meta-analyses were a combination of the following subtraction scores or a composite score: 1) the interference effect (difference in reaction time between incongruent and neutral trials), 2) conflict effect (difference in reaction time between incongruent and congruent trials), or 3) overall reaction time (average reaction time across conditions). Draheim, Mashburn, Martin, and Engle (2019) explained that subtraction scores are problematic because they are based on means that are highly correlated with one another. When two variables correlate, they share a common amount of variance. Subtracting one of these variables from the other removes some of the systematic variance and increases the proportion of error. This is the reason why cost scores or difference scores tend to have low reliability and do not strongly correlate with other measures. Therefore, meta-analyses based on difference scores should be interpreted with caution. Furthermore, conflicting findings may stem from several methodological issues that need to be considered, such as the participants' language profile, the tasks used, the amount of practice with the task, and lastly, the types of statistical analyses performed.

Bialystok (2017) noted several reasons why null results have been reported in the field, one of which is the operationalization of the term bilingualism. There is no single defining factor that differentiates a bilingual profile from a monolingual profile. The lack of a convergent definition for bilingualism can make comparisons across studies challenging. In the study by Paap and Greenberg (2013), the criterion used to classify participants into groups was based on a single self-report measure of proficiency. Participants were asked to rate their speaking and listening proficiency on a scale from 1 (Beginner) to 7 (Super Fluency) for all known languages. The authors classified individuals who rated their proficiency across all non-English languages 3 or less (3 = Intermediate – can converse with a native speaker on most everyday topics, but with some difficulty) as a monolingual. This arbitrary cut-off describes a low-proficiency bilingual rather than a monolingual. Including low-proficiency bilinguals into the monolingual group introduces noise and variability to the data. For the bilingual group, asking a single question as an assessment of bilingualism generates an incomplete language profile. There is the possibility that even though the participant is fluent in a second language, they may not be using that language on a regular basis. Frequency of second-language usage or degree of language switching has been shown to modulate performance on several non-verbal conflict tasks (Barbu, Orban, Gillet, & Poncelet, 2018; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016; Yang, Hartanto, & Yang, 2016). The use of a single question to capture bilingualism dismisses the interactivity of various experience-based language factors, such as age of acquisition, switching frequency, or the context of acquisition (de Bruin, 2019). A more detailed questionnaire should be used to capture the multidimensionality of bilingualism.

A second possibility is that the tasks used to examine executive control (e.g., flanker, Simon, and Stroop) in young adults are relatively simple. Testing young adults, who are likely operating at the peak of their cognitive functioning, on tasks with low levels of difficulty limits the variability to detect group differences. Previous studies have shown that bilingualism provides a boost when task difficulty increased and required greater attentional resources. For example, Costa, Hernández, Costa-Faidella, and Sebastián-Gallés (2009) manipulated the proportion of congruent and incongruent trials on the flanker task in two conditions. In the low-monitoring condition, where most of the trials were of a single type, monolinguals and bilinguals performed equivalently. However, in the high-monitoring condition, where the breakdown was more evenly distributed, bilinguals were overall faster than monolinguals across both congruent and incongruent trials. In the high-monitoring condition, the upcoming trial is less predictable requiring participants to actively monitor for conflict. Costa et al. (2009) proposed that the bilingual advantage may stem from the need to monitor and keep track of which language to use with which person. In another study, Friesen, Calvo, Latman, and Bialystok (2015) compared young adult bilinguals and monolinguals on a visual search task. In the feature search, target shapes differed from distractors by only one feature (e.g., color) producing a pop-out effect. In the conjunction search, targets differed by two features (e.g., color and shape), requiring participants to search in a serial manner and use top-down control processes to successfully locate the target. The authors also manipulated discriminability by making distractors more or less similar in color to the target. A bilingual advantage emerged only on the most difficult condition (low discriminability, conjunction search). Therefore, complex tasks requiring a greater amount of attentional control are more likely to find a significant effect of bilingualism.

A third possibility is that extensive practice on a task may diminish differences between language groups. Bialystok, Craik, Klein, and Viswanathan (2004) had monolinguals and French-English middle-aged adults perform a Simon task over 10 consecutive blocks of 24 trials each. Although bilinguals maintained their performance across blocks, monolinguals gradually improved in overall reaction time and achieved similar levels in performance as bilinguals by block 7. The convergence in performance demonstrates that the largest difference in performance exists in the earlier blocks when participants are still adjusting to the task demands and greater attentional control is needed to perform the task. Once processes become automated, differences between monolinguals and bilinguals are reduced.

Lastly, to elucidate the null effects reported in the young adult population, researchers have begun using novel analytical approaches that go beyond standard analyses of reaction time (RT) and accuracy rates to compare behavioral performance between language groups. These novel statistical approaches include examining participant's RT distributions (ex-Gaussian analyses: Calabria, Hernández, Martin, & Costa, 2011; Tse & Altaribba, 2012; 2014; Zhou & Krott, 2018), decomposing RTs into several parameters of decision and non-decision time (drift-diffusion model: Hartanto & Yang, 2016; Ong, Sewell, Weekes, McKague, & Abutalebi, 2017), and looking at the impact of previous trial congruency on current trial congruency (sequential congruency effect: Grundy, Chung-Fat-Yim, Friesen, Mak, & Bialystok, 2017; but see Goldsmith & Morton, 2018). On a variety of executive control tasks, bilingualism impacts the shift in RT distribution between congruent and incongruent trials, as well as the tail end of the distribution, with fewer excessively long RTs for bilinguals than monolinguals (Calabria et al., 2011; Tse & Altarriba, 2014; Zhou & Krott, 2018). Zhou and Krott (2018) interpreted these findings to suggest that bilinguals have enhanced attentional control and goal maintenance than monolinguals. Furthermore, bilingual young adults are less impacted by the previous trial than monolingual young adults and are thus better at disengaging attention from old information, while directing their attention towards new task demands (Grundy et al., 2017). Moving away from conventional analyses allows for a more detailed understanding of how bilingualism impacts performance. Together, these findings provide insight into why some studies show differences while others do not.

The majority of behavioral studies investigating the effect of bilingualism on cognitive performance have relied primarily on mean reaction times (RTs) and accuracy rates as outcome variables. For young adults, these measures are typically at ceiling (approximately 500 ms and > 90% accuracy) and lack the variance needed for reliable group differences to emerge. Although traditional analyses on RTs and accuracy rates provide a good description of overall performance, they lack the sensitivity or precision to capture important underlying cognitive processes that occur between the time a stimulus is presented and the execution of a response. For these reasons, utilizing methodologies high in temporal resolution, such as mouse-tracking and eye-tracking, are advantageous because they measure the timing of the cognitive processes underlying planning, decision-making, stimulus evaluation, and response execution. What remains unknown is whether monolinguals and bilinguals differ in the time course of attentional processes when planning to execute a response. While previous research has used different analytical techniques to examine the role of language experience on selective attention, the present dissertation will combine two methodologies, mouse-tracking and eye-tracking, to compare younger and older adult monolinguals and bilinguals on two non-verbal cognitive tasks. By integrating and utilizing both methodologies, we gain a better understanding into how each language group deals with conflicting information and the type of strategies employed. For example, it is possible that bilinguals spend more time fixating on the stimulus to assess the entire field before making a response while monolinguals go straight to the response boxes. The current approach allows us to untangle not only the quantitative differences between groups, but also allows for more qualitative examinations of performance.

Performance was assessed using the global-local task and a non-verbal version of the Stroop task, known as the oculomotor Stroop task (refer to section on Eye-Tracking and Bilingualism for a description of the task). The global-local task uses hierarchical compound stimuli to assess the ability to focus attention on salient aspects of a perceptual display (Navon, 1977). The global feature is the larger overall image, while the local feature is the individual components that make up the larger image. Participants are required to identify the global feature (i.e., whole) while ignoring the identity of the local feature (i.e., parts), or vice versa. Therefore, individuals process both the overall as well as the components of the complex stimulus. The locus of attention and task demands shift between these two levels of processing. Congruent trials occur when the global and local features match. Incongruent trials are when the global and local features are in conflict. The primary measures are speed and accuracy of identifying the global and local stimuli, as well as the congruency or incongruency of the trials.

The typical finding for adults is that global information is processed faster and more accurately than local information due to a preference for grouping similar objects that are in close proximity to one another, a phenomenon known as the global precedence effect (GPE; May, Guttierez, & Harsin, 1995; Navon, 1977). The GPE is calculated as the additional time required to respond to local trials compared to global trials on incongruent trials. In research with children, bilinguals were overall more accurate (Cottini, Pieroni, Spataro, Devescovi, Longobardi, & Rossi-Arnaud, 2015), faster (Bialystok, 2010), and had a smaller GPE (Cottini et al., 2015) than their monolingual counterparts. The smaller GPE indicates that bilinguals are less readily impacted by the salient global characteristics than monolinguals and can flexibly switch between local and global features. However, it is important to note that the GPE is based on a subtraction score and should be interpreted cautiously due to its low reliability (Draheim, Mashburn, Martin, & Engle, 2019). No studies to date have compared monolinguals and bilinguals on the global-local task in young and older adults.

Time-Sensitive Methodologies and Bilingualism

Time-sensitive methodologies provide rich temporal information with millisecond precision regarding the time course of cognitive processes, even in the absence of behavioral differences. One such method that has been previously used to compare monolinguals and bilinguals on cognitive tasks is Event-Related Potentials (ERPs). ERPs provide a continuous measure of cognitive processing between the stimulus and response, making it possible to determine at which stage of processing monolinguals and bilinguals differ when presented with conflict. ERPs consist of a sequence of negative or positive voltage deflections and are named based on the direction of the peak and the time at which it occurs. For example, the N2 is a negative peak at around 200ms. A review of the electrophysiological literature by Grundy, Anderson, and Bialystok (2017) revealed that bilinguals have larger N2 and P3 amplitudes, ERP components associated with cognitive control and attentional resources, than monolinguals. In addition, these components appear earlier for bilinguals than monolinguals. Thus, bilingualism is associated with earlier and more efficient allocation of attentional resources. Two other methods that can measure high-level cognitive processes in real time, but that are less commonly used to examine bilingualism and selective attention, are mouse-tracking and eye-tracking.

Mouse-tracking and Bilingualism. A key advantage of mouse-tracking over traditional key press methods is that it allows responses and decisions to unfold over time by measuring the x- and y- coordinates of the cursor as an individual executes a response (Freeman & Ambady, 2010). As such, mouse-tracking captures multiple processes between the initiation and execution of a response that are not captured by RTs alone. It has been shown that movements of the hand are executed alongside cognitive processing (Magnuson, 2005), and that fine adjustments can be made midflight as information is processed (Goodale, Pelisson, & Prablanc, 1986; Song & Nakayama, 2008). In other words, individuals have the ability to course-correct at any time and the path can be conceptualized as a record of the gradual decision-making processes that converge on one of two (or multiple) options in two-dimensional space. Because mouse-tracking has two (or more) competing responses, it is possible to calculate the maximum absolute deviation (MAD), which is the largest perpendicular deviation between the actual and idealized trajectory, as illustrated in Figure 2. In addition, the rich output of data allows for the velocity profile of mouse movements to be measured, which is calculated as the distance in Euclidean space between subsequent co-ordinates at different time points. Initially, competition between response options is characterized by a decrease in velocity due to uncertainty in response selection, but once a decision is reached, velocity increases towards the correct response box.

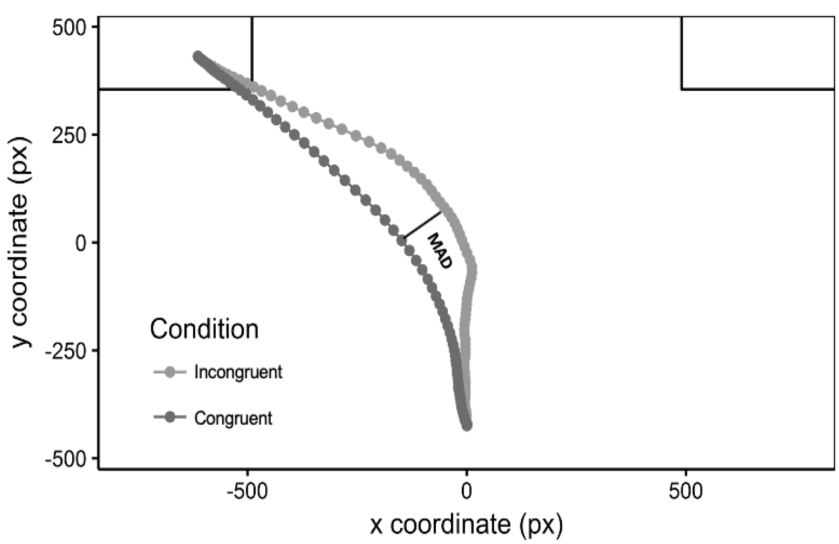

Figure 2. Illustration of the average time-normalized trajectories. Adapted from Kieslich and Henninger (2017). In this example, rightward trajectories have been horizontally re-mapped to the left response box. The trajectory for the incongruent condition (in light grey) shows a deflection towards the incorrect box compared to the congruent condition (in dark grey). The amount of deflection is known as the maximum absolute deviation (MAD).

Previous studies on bilingualism with mouse-tracking have focused on tasks assessing language processing (e.g., Bartolotti & Marian, 2012; Dale, Kehoe, & Spivey, 2007; Spivey, Grosjean, & Knoblich, 2005). Only a few studies have compared monolinguals and bilinguals on non-verbal tasks using this methodology. The first study to look at the relationship between bilingualism and executive control using mouse-tracking was conducted by Incera and McLennan (2016). The authors compared English monolinguals, low-proficiency Spanish-English bilinguals, and high-proficiency Spanish-English bilinguals on a Stroop task. Despite no behavioral differences, both groups of bilinguals showed longer initiation times and produced trajectories with steeper slopes (i.e., straighter paths to the correct response box) than monolinguals. The authors argued that prior to initiating a response, bilinguals scan their environment to determine the most efficient path to achieve their goal. The *Bilingual Expertise Hypothesis,* as termed by Incera and McLennan (2016), refers to bilinguals being experts at allocating their time and managing information. Rather than making a quick response, experts take a moment to assess the situation or scenario. However, one could argue that the bilinguals produced longer initiation times because the Stroop task is a verbal task. A number of studies have shown that on lexical retrieval tasks, bilinguals name fewer items and often name pictures more slowly than monolinguals (e.g., Bialystok, Craik, & Luk, 2008; Gollan, Montoya, Fennema-Notestine, & Morris, 2005; Ivanova & Costa, 2008), which could account for the delay in the initiation of a response for bilinguals. However, the "expertise" pattern of behavior has since been replicated in subsequent studies using non-verbal tasks, such as the Simon and Spatial Stroop tasks with Chinese-English bilinguals (Damian, Ye, Oh, & Yang, 2018) as well as the n-back and item-associative tasks when bilingualism was analyzed as a continuous measure (Capani, 2019). In addition to longer initiation times, Damien et al. (2018) observed smaller maximum absolute deviations for bilinguals compared to monolinguals on the Simon and Spatial

Stroop tasks, which is indicative of a more efficient trajectory in the bilingual group.

A follow-up study by Incera and McLennan (2018) examined bilingualism and age as continuous variables on both the Stroop and Flanker task. After controlling for baseline performance, the Stroop effect was independently impacted by degree of bilingualism and age, while the flanker effect was only impacted by age (see Draheim et al., 2019 for concerns on the reliability of subtraction scores). However, no differences in initiation time or maximum absolute deviation were observed. The authors speculated that the difference may be attributed to the change in task difficulty between studies. The Stroop task in the 2018 study had only two options, whereas the 2016 study had four. The amount of cognitive effort required to remember four alternatives rather than two may be the reason for the group differences on initiation time reinforcing the importance of taking into consideration task difficulty.

For the *Bilingual Expertise Hypothesis*, Incera and McLennan (2016) make the assumption that the delay in initiation time exists because bilinguals spend more time evaluating and scanning their environment. However, none of the abovementioned studies examined participants' gaze behaviour. One way to do this is to use eye-tracking in combination with mouse-tracking to study possible differences in mouse and gaze patterns. If differences in gaze behavior are found between monolinguals and bilinguals during the planning phase (i.e., time to initiate a response) and selection phase (i.e., response trajectory), then this would provide some validity to the *Bilingual Expertise Hypothesis.*

Eye-tracking and Bilingualism. Eye-tracking is a powerful tool for investigating the time course of perceptual and cognitive functions. It allows researchers to trace the location or movements of a participant's eyes in real time and can answer questions pertaining to where the observer is looking and for how long. While attention can be displaced without eye movements under certain laboratory conditions, the converse is not true; there is a shift in attention prior to every eye movement (Kowler, Anderson, Dosher, & Blaser, 1995). Shifts in gaze position thus closely follow and are guided by shifts in attentional focus.

Only a few eye-tracking studies have examined the relationship between bilingualism and cognition in adults (Bialystok, Craik, & Ryan, 2006; Blumenfeld & Marian, 2011; Mercier, Pivneva, & Titone, 2014; Blumenfeld, Schroeder, Bobb, Freeman, & Marian, 2016; Chabal, Schroeder, & Marian, 2015; Rubio-Fernandez & Glucksberg, 2011). Rubio-Fernandez and Glucksberg (2011) used eye-tracking to determine whether young adult bilinguals would be less influenced by egocentric bias on the Sally-Ann task measuring false belief than monolingual young adults. Both groups successfully performed the task, but bilinguals were more likely to make a first fixation towards the correct container than monolinguals. In another study, Chabal, Schroeder and Marian (2015) compared bilingual and monolingual young adults on a multi-modal visual search task that contained different audio-visual contexts. Prior to the start of the trial, the name of a target object (e.g., dog) was auditorily-presented. A display of eight objects was then shown along with an auditory sound that could be related (e.g., dog barking) or unrelated (e.g., piano keys) to the target object. Bilinguals made more fixations to the target and fewer fixations to the distractor, while monolinguals showed no differences between target and distractor. The authors concluded that monolinguals and bilinguals employed different search strategies based on the differences in eye movement patterns.

Lastly, Singh and Mishra compared low versus high proficiency Hindi-English bilinguals on an oculomotor Stroop task (2013) and a Traffic Lights Task (2016). In the oculomotor Stroop task, four color patches equidistant from each other and an arrow in the middle pointing towards one of them were presented to the participant. Participants had to select the color patch that matched the color of the arrow. Therefore, selective attention is recruited in order to focus on the color of the arrow while ignoring the direction of the arrow. In the Traffic Lights Task, participants were told to maintain fixation on the traffic light as it changed from red to amber and to only make a fixation to a target when the light changed to green. The duration of when the amber light remained on the screen varied making it difficult for the participant to anticipate when the light would change. In both studies, high proficiency bilinguals produced a faster saccadic latency to the target and committed fewer errors than low proficiency bilinguals.

Eye-tracking and Mouse-tracking. Combining several temporal techniques can provide a more comprehensive understanding of possible timing differences that may exist between language groups. Previous work has shown that eye and hand movements are typically co-ordinated, but that eye movements tend to precede motor activity (Gamble & Song, 2017; Prablanc, Echallier, Komilis, & Jeannerod, 1979). Using eye-tracking and mouse-tracking, Bartolloti and Marian (2012) had monolingual and bilingual participants trained in an artificial language that was designed to elicit cross-language competition in a new language (i.e., Colbertian). Participants were presented with two pictures, in which the target picture was always a word in Colbertian. The target was paired with either an unrelated picture or the picture of a word whose English name phonologically overlapped with the Colbertian name of the target. Monolinguals made more looks and had greater deviations in trajectory towards the competitor than bilinguals. The authors interpreted these findings to suggest that lifelong practice using multiple languages has honed the ability to manage between-language competition and enhances the processing of words in a novel language. However, no study to date has implemented both techniques in a non-verbal context and compared the results between methodologies to one another.

Current Dissertation

While electrophysiological and neuroimaging data have provided insight on the timing and location of the cognitive processes, it remains unknown whether monolinguals and bilinguals differ in "how" they process and resolve conflict. The goal of the proposed dissertation is to combine mouse-tracking and eye-tracking, which provides the x- and y- co-ordinates of the cursor and gaze on a millisecond by millisecond basis, to allow for a more detailed look at decision-making processes as they occur in real time in monolinguals and bilinguals. The output will provide a rich set of data that includes information on planning, stimulus evaluation, and response execution in the unfolding of responses. These data will be used to resolve conflicting findings in the literature. Performance will be assessed using two computer-based tasks that vary in level of difficulty and the amount of attentional control required. The dissertation adds to the growing body of literature by taking a methodological approach to examine the role of bilingualism on attention in younger and older adults.

Behaviorally, it is hypothesized that on measures of reaction time and accuracy, bilingual older adults will perform better than monolingual older adults on both cognitive tasks, with little relationship between bilingualism and attention in younger adults (see Bialystok, Craik, Luk, 2008; Salvatierra & Rosselli, 2010). For mouse-tracking, it is hypothesized that trajectories will differ between monolinguals and bilinguals, with bilinguals exhibiting less deflection towards the incorrect response than monolinguals (i.e., smaller deviations in trajectory for bilinguals). Furthermore, consistent with the findings by Incera and McLennan (2016), Damian, Ye, Oh, and Yang (2018), and Capani (2019), it is hypothesized that bilinguals will delay the initiation of their response (i.e., slower initiation times for bilinguals) but execute more efficient trajectories towards the target (i.e., higher maximum velocities for bilinguals), consistent with more skilled performance. For the eye-tracking data, it is hypothesized that bilinguals will spend more time fixating on the stimulus than monolinguals, accounting in part for the longer initiation times. Furthermore, bilinguals will be faster to make a correct first look towards the correct response box (Chabal, Schroeder, & Marian, 2015), consistent with the efficient trajectory revealed by mouse-tracking.

Chapter 2

Methodology

Participants

The sample consisted of two age-groups: young adults and older adults. Within each age group, approximately half of the sample was monolingual, and the other half was bilingual. The young adult sample consisted of 42 monolinguals and 44 bilinguals between the ages of 17 and 35 (M = 20.48, SD = 3.17). Participants were recruited through the Undergraduate Research Participant Pool or posters around campus and received academic credits or a $5 Tim Hortons gift card for their time. Young adult participants were categorized as monolinguals or bilinguals based on their responses on the young adult version of the Language and Social Background Questionnaire (LSBQ; Anderson, Mak, Keyvani Chahi, & Bialystok, 2018). In the older adult sample, 43 monolinguals and 41 bilinguals between the ages of 60 and 78 (M = 70.20, SD = 4.73) were recruited through York University's Centre for Aging Research and Education participant pool. Participants were characterized as monolingual or bilingual based on their responses on the older adult version of the LSBQ (Anderson, Hawrylewicz, & Bialystok, in press). Older adult participants received $20 for their time. All participants were right-handed, with no history of color blindness or neurological impairments. All participants had normal or corrected-to-normal vision.

Instruments

Language and Social Background Questionnaire (LSBQ; Anderson, Mak, Keyvani Chahi, & Bialystok, 2018; Anderson, Hawrylewicz, & Bialystok, in press). The young adult version of the LSBQ (Anderson, Mak, Keyvani Chahi, & Bialystok, 2018) was used to obtain information about each participant's language history and experience. Participants answered questions about their language use and proficiency for all known languages. Level of proficiency in speaking, understanding, reading, and writing for each language was rated on a scale from 0 (No proficiency) to 10 (High proficiency). Participants indicated their judgment by placing a vertical line along each horizontal scale. For usage, participants indicated the degree to which they use their non-English language when interacting with specific individuals (e.g., parents, siblings, grandparents), contexts (e.g., home, school, work), or activities (e.g., banking, texting, reading) on a scale from 0 (Always English) to 10 (Always Other language). Additionally, participants answered questions regarding their date of birth, gender, handedness, country of birth, as well as any history of vision problems, hearing problems, neurological impairments, and psychoactive medication use. The older adult version of the LSBQ (Anderson, Hawrylewicz, & Bialystok, in press) is similar to the young adult version. In addition to the demographic questions listed, older adults reported their highest level of education and occupation, while younger adults reported each parents' highest level of education and occupation. The last question on the older adult version was a global self-assessment rating of their level of bilingualism on a scale from "Monolingual" to "Bilingual". See Appendix A for the young adult version of the LSBQ and Appendix B for the older adult version of the LSBQ.

Shipley-2 Institute of Living Scale (Shipley, Gruber, Martin, & Klein, 2009). Vocabulary and nonverbal reasoning were assessed using Vocabulary scale (Appendix C) and Blocks Pattern scale (Appendix D), respectively. Both scales were administered in paper-and-pencil format. In the Vocabulary scale, participants are presented with a list of 40 capitalized words. For each capitalized word, participants had to circle the word that was closest in meaning to the target word. In the Blocks Pattern scale, participants are presented with 12 multiple-choice items based on Kohs block designs (Kohs, 1920). For each item, participants are presented a design with a missing tile as well as six tiles that could complete the pattern. Participants indicated their answer by bubbling in the letter corresponding to the tile they believed completed the pattern. Participants had 10 minutes to complete each scale. Raw scores were obtained and converted to standard scores (μ = 100, *SD* = 15) using an age-based norming table. Internal consistencies for the Vocabulary and Blocks Pattern scale ranges from .85 to .92 and .88 to .94, respectively. The inter-scale correlation between Vocabulary and Blocks Pattern is r = .38 in adults (Kaya, Delen, & Bulut, 2012).

Experimental Tasks

All experimental tasks were programmed in OpenSesame version 3.2 (Mathôt, Schreij, & Theeuwes, 2012) and presented on a 22-inch Dell monitor (screen resolution: 1024 x 768) at a viewing distance of 60 cm. For all tasks, a trial began with a blank white screen that had a "START" button (192 x 108 pixels) at the bottom. Participants were instructed to first click "START" and then select the correct response box as fast as possible. In OpenSesame, the mousetrap plugin (Kieslich & Henninger, 2017) recorded the x- and y-coordinates of the mouse trajectory every 10 ms, while the PyGaze plugin (Dalmaijer, Mathôt, Van der Stigchel, 2014) recorded the x- and y-coordinates of the gaze position every 33 ms. The speed and acceleration of the mouse was set to the default setting.

For each trial, participants had up to 1000 ms to initiate a response and up to 3000 ms to select a response box. If participants took longer than 1000 ms to initiate a response, a warning appeared on the screen that said: "Please start moving earlier on even if you are not fully certain of a response yet!" If the participant did not respond within 3000 ms, the stimulus disappeared and replaced with a new trial.

Baseline Task. Similar to Incera and McLennan (2017), a baseline task was used to control for individual differences in motor movements. On each trial, participants were presented with an initiation screen (Figure 3a) followed by a stimulus screen (Figure 3b). As soon as participants clicked "START", a pineapple appeared in one of two response boxes (96 x 192 pixels in size). Participants were instructed to click on the pineapple. The pineapple appeared in the top left response box 50% of the time and in the top right response box for the remaining half. There was a total of 12 trials.

(a)

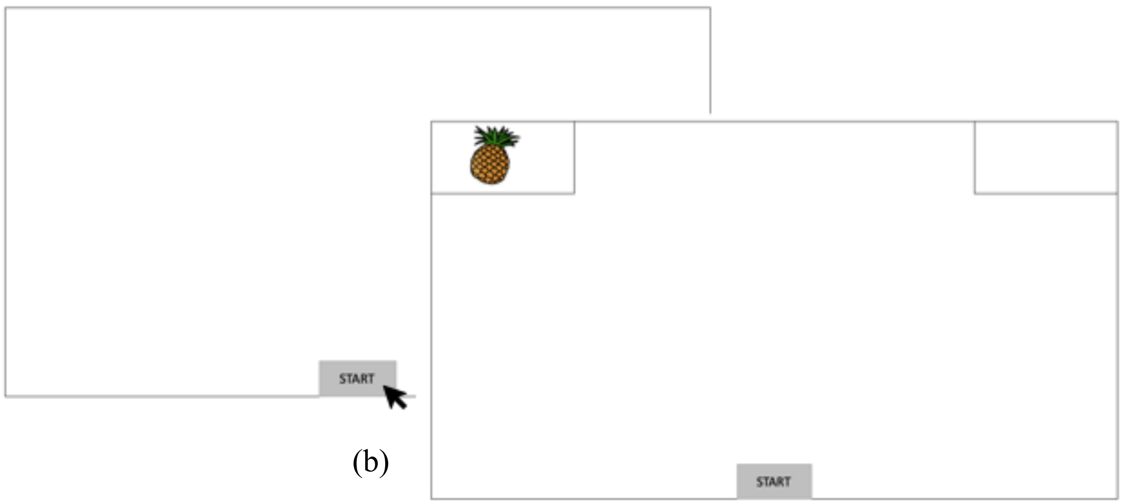

Figure 3. Baseline Task. (a) Initiation screen marks the beginning of a trial. Participants begin a trial by clicking "START". (b) Stimulus screen where the x- and y- coordinates are measured. All trajectories were rescaled to the top left response box and time-normalized into a standard coordinate space.

Global-local task (Navon, 1977). The global-local task was used as a measure of selective attention by assessing one's ability to focus on a specific feature, either global or local/congruent or incongruent, while resisting distraction from the other feature. The task consisted of three blocks: 1) global-neutral, 2) local-neutral, and 3) mixed. The order of presentation for the global-neutral and local-neutral blocks was counterbalanced across participants. The stimuli were adapted from Mills and Dodd's (2014) global-local paradigm that embedded smaller arrows within the shape of a larger arrow. The authors reasoned that rather than using letters, symbolic stimuli like arrows influence attentional control since attention is involuntarily oriented in the direction of the arrow.

For the global-neutral block, a large arrow pointing to the left or right was composed of smaller rectangles (Figure 4a). Participants were instructed to click on the response box corresponding to the direction of the large arrow. For the local-neutral block, a rectangle composed of smaller arrows that all point to the left or right in a 4 x 6 array appeared in the center of the screen (Figure 4b). Participants were instructed to click on the response box corresponding to the direction of the smaller arrows. The global-neutral and local-neutral blocks each consisted of 32 trials.

In the mixed block, a large arrow was composed of smaller arrows pointing in either the same direction (congruent trial; Figures 4c and 4d) or opposite direction (incongruent trial; Figures 4e and 4f) as the larger arrow. A rectangular cue surrounded the larger arrow to indicate which feature of the stimulus to attend to. If the cue was a solid line, participants responded to the global feature (i.e., larger arrow; Figures 4c and 4e). If the cue was a dashed line, participants responded to the local features (i.e., smaller arrows; Figures 4d and 4f). All trial types, including the neutral trials, were randomly intermixed in the mixed block. Each condition was presented 32 times for a total of 192 trials (6 conditions x 32 trials = 192 trials). A break was provided halfway through the mixed block. Participants were provided with 12 practice trials at the start of each block.

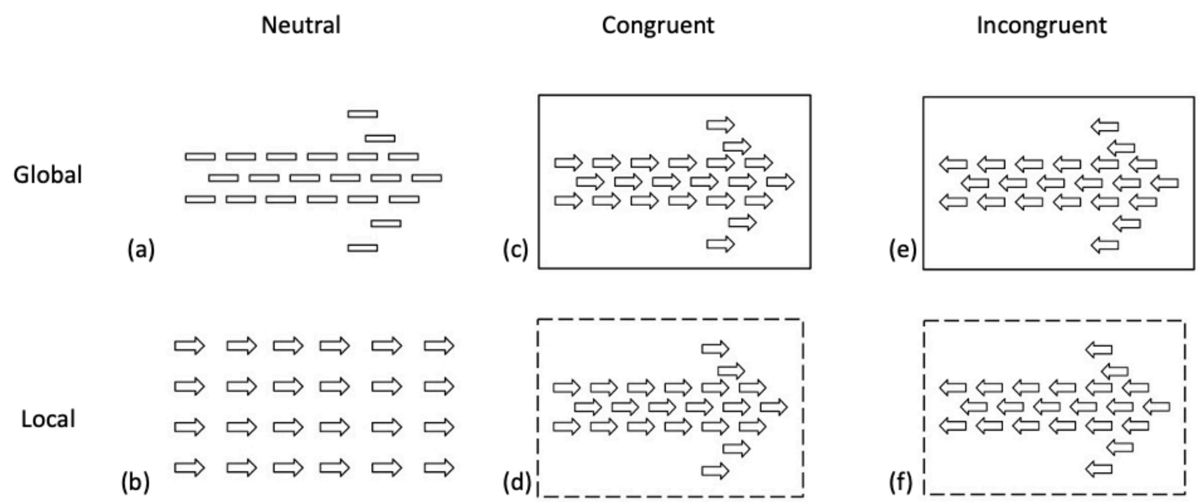

Figure 4. Conditions of the global-local task. (a) Global-neutral and (b) Local-neutral conditions. A solid line surrounded the compound arrow when participants had to respond to the global feature for congruent (c) and incongruent (e) trials. A dash line surrounded the compound arrow when participants had to respond to the local features for congruent (d) and incongruent (f) trials.

Each trial began by clicking the “START” button at the bottom of the screen (Figure 5a). A fixation cross then appeared in the middle of the screen for 500 ms (Figure 5b) followed by the stimulus (384 x 248 pixels) in the centre of the screen and two response boxes (96 x 192 pixels; Figure 5c). One response box was located in the top left corner of the screen with the word "LEFT", while the other was located in the top right corner of the screen with the word "RIGHT" (Figure 5). Once a response box was selected, the initiation screen appeared prompting the new trial.

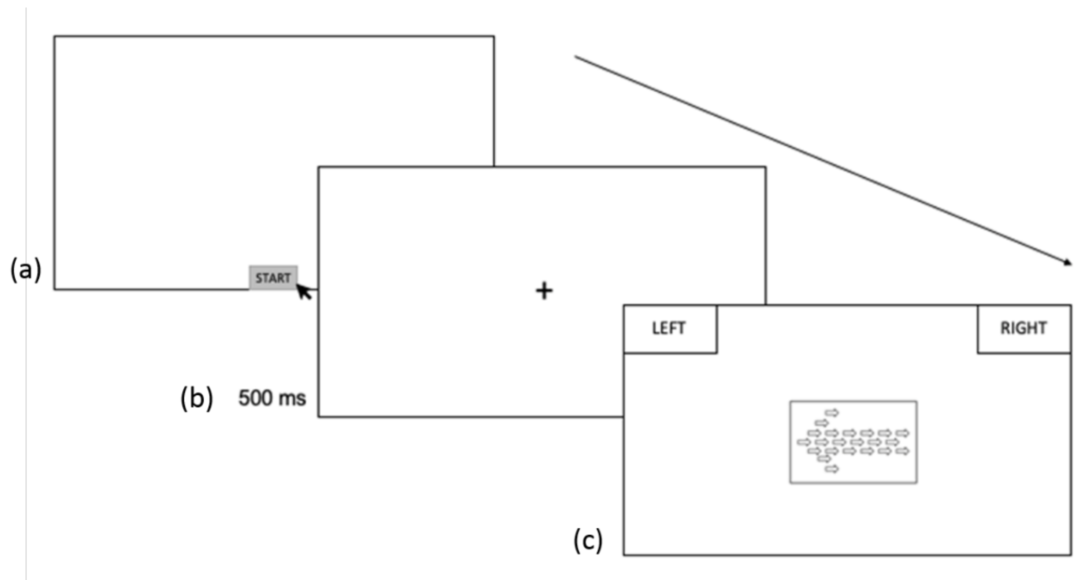

Figure 5. Example of a trial sequence on the global-local task. (a) Initiation screen where the participant clicks on the START button. (b) A fixation cross is displayed in the middle of the screen for 500ms. (c) Stimulus screen where the participant selects a response box. In this example, the global incongruent trial is displayed.

Oculomotor Stroop Task (Singh & Mishra, 2012). The oculomotor Stroop task was used as a measure of selective attention that required participants to respond to the color of the arrow while resisting interference from the direction of the arrow. Each trial began with the initiation screen (Figure 6a) followed by a fixation cross for 500ms (Figure 6b). A display then appeared containing a square (128 x 128 pixels) in each of the four corners of the screen, each in a different color (red, green, blue, and orange), along with a central arrow (150 x 150 pixels) in the centre of the screen (Figure 6c). The color patches were fixed at their locations for all trials. The arrow could point to any square in any of the four locations. In the congruent condition, the colored arrow pointed towards the correct color patch (e.g., green arrow pointing towards the green square). In the incongruent condition, the arrow pointed towards a color patch that did not match the color of the arrow (e.g., green arrow pointing to blue square, see Figure 6c).

Participants were instructed to click on the response box that was associated with the color of the arrow. There were 48 congruent and 48 incongruent trials randomly intermixed for a total of 96 trials. A break was provided halfway through the task.

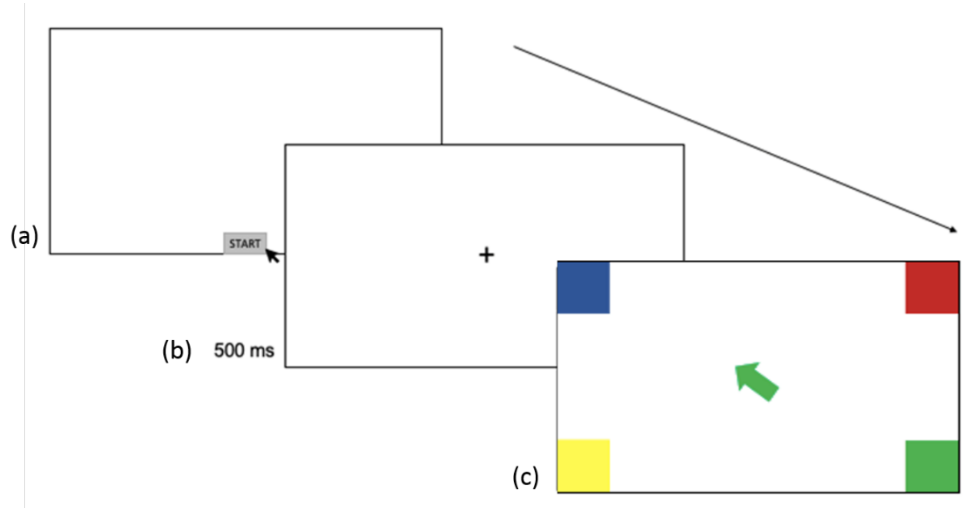

Figure 6. Example of a trial sequence on the oculomotor Stroop task. (a) Initiation screen where participants click on the START button. (b) Fixation cross displayed in the middle of the screen for 500ms. (c) Stimulus screen where participants select a response. In this example, the incongruent trial is displayed.

Procedure

Upon arrival at the laboratory, participants were provided an informed consent to read and sign (Appendix E). Once the participant consented to participate in the experiment, the experimenter administered the Language and Social Background Questionnaire (Anderson, Mak, Keyvani Chahi, Bialystok, 2018; Anderson, Hawrylewicz, & Bialystok, in press) in the form of an interview. The LSBQ was reviewed by the experimenter to ensure eligibility. Participants were then administered the Vocabulary scale followed by the Blocks Pattern scale of Shipley-2 Institute of Living Scale (Shipley, Gruber, Martin, & Klein, 2009).

Following the background measures, participants were seated in front of a computer and completed the baseline task followed by the EyeTribe calibration process (see section on EyeTracker Setup and Calibration). The order of the remaining experimental tasks was counterbalanced across participants between the oculomotor Stroop task and the global-local task. In addition, the two versions of the global-local task were also counterbalanced across participants.

The entire testing session took approximately 1 hour to complete. All participants were debriefed about the purpose of the study (Appendix F) and compensated for their time.

Eye-Tracker Apparatus and Calibration Process

The EyeTribe eye tracker (The Eye Tribe, Copenhagen, Denmark) uses a camera and a high-resolution infrared LED to track user's eye movements. The EyeTribe is a mobile eye-tracker that has a sampling rate of 30 Hz (i.e., 33 ms) and an average accuracy of 0.5 degree of visual angle.

Using the Eye Tribe user interface software, the first step was to ensure that the participant's head was in the eye tracker's field of view. If the eye-tracker successfully detected the participant's eyes, a green schematic face appeared that mimicked the participant's face. Every time the participant made a head movement or blinked; the schematic face also made similar movements. If the eyes were not successfully detected, the screen turned red, and the participant was instructed to adjust their head's position to be either closer to or further away from the eye tracker. Any changes in head position was recorded by the experimenter.

Prior to collecting eye-tracking data, participants completed a calibration process that estimated the geometric characteristics of the participant's eyes. The eye-tracking software models these characteristics to estimate gaze accurately. EyeTribe uses a 9-point calibration system, in which a target was displayed in 9 different locations of the screen on a black background. The target remained on the screen for 2 seconds with an intertrial interval of 1 second. Participants were instructed to follow the target with their eyes while remaining as still as possible. At the end of calibration, participants received a score from 1 (Poor) to 5 (Perfect). Every effort was made to achieve a score of at least 4 by either adjusting the seat or re-assuring participants to keep their head still.

OpenSesame PyGaze Calibration

OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) uses an open-source toolbox for eye-tracking in Python called PyGaze (Dalmaijer, Mathôt, & Van der Stigchel, 2014). In addition to initial calibration by Eye Tribe (The Eye Tribe, Copenhagen, Denmark), at the start of each experimental task, participants had to complete a 9-point calibration routine from PyGaze. The calibration routine is similar to that of EyeTribe. The only difference is that at the end of the calibration routine by PyGaze, a report is generated with the location of the target in green and the location of the participant's fixations in blue with the average degree of error between these two locations displayed. If the overall degree of error was less than 1.5, participants proceeded to the instructions of the experimental task. If the degree of error was larger than 1.5, participants were asked to perform the calibration routine again. After five failed attempts, the experimenter calibrated with their eyes and the participants' eye-tracking data was not be used in the eye-tracking analysis.

The output for the eye-tracking data maps the top left corner as (0, 0) and the bottom right corner as (1024, 768). Using an R-script (R Core Team, 2016), areas of interests (AOIs) were computed in pixels at every time point, such that the location of the participant's eye co-ordinates was coded as being either on the stimulus, target, distractor, or null (see Figure 7 for the oculomotor Stroop task). Incorrect trials were removed from the data. For the eye-tracking analyses, there were three measures of interest: 1) time spent looking at each of these AOIs per condition, 2) proportion of time looking at the stimulus, target, or distractor, and 3) time of first look to the target. Because the global-local task had response boxes that contained the words "LEFT" or "RIGHT", participants inherently did not need to look at the response boxes to make a response. As such, for the global-local task, the analyses were restricted to time spent looking at the stimulus.

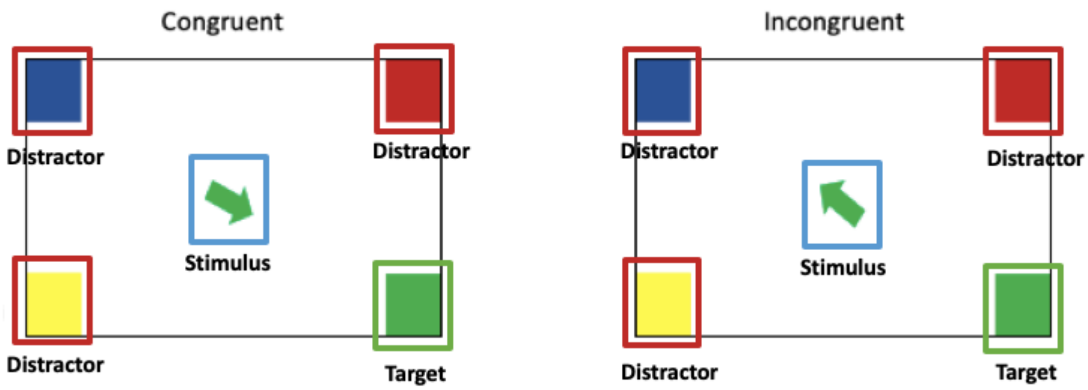

Figure 7. Areas of interest for the oculomotor Stroop task. The areas highlighted in blue, green, and red are the area of interests computed for the stimulus, target, and distractor, respectively.

Mouse-tracking Data Processing

Mouse-tracking data was acquired using the MouseTrap plugin in OpenSesame's experiment builder (Mathôt, Schreij, & Theeuwes, 2012). Data processing and analyses were performed using the mousetrap package (Kieslich & Henninger, 2017) in R (R Core Team, 2016), which allows users to process, analyze, and visualize mouse-tracking data. Mousetrap records the x- and y-positions of the cursor every 10ms. For each trial, three pieces of information were recorded: raw time (how many ms have elapsed), the x-coordinate of the mouse (in pixels), and the y-coordinate of the mouse (in pixels). In order to compare individual trajectories between conditions, all trajectories were rescaled and re-mapped into a standard co-ordinate space to ensure that every trajectory began at the START location with initial co-ordinates (0,0) and ended in the top left corner. Trajectories were then time-normalized so that each trajectory contained the same number of recorded co-ordinates regardless of response time (101 steps). Mousetrap also allows for the computation of maximum velocity based on the raw times prior to normalization.

The dependent variables of interests were initiation times, maximum absolute deviation, and maximum velocity. Initiation times were defined as the time between clicking START and the first mouse movement. Maximum absolute deviation was calculated as the maximum perpendicular deviation of the actual trajectory from the idealized trajectory, which is a straight line from coordinates (0, 0) to the end point (top left corner). Maximum velocity is calculated as the Euclidean distance (in co-ordinates) traveled from the previous set of recorded co-ordinates.

Chapter 3: Results

Background Measures

Young Adults. Background measures by language group are reported in Table 1. One-way ANOVAs revealed that young adult monolinguals and bilinguals were equivalent on age in years[1], socioeconomic status (as measured by maternal level of education), English vocabulary (as measured by the Shipley Vocabulary subscale), and non-verbal reasoning (as measured by the Shipley Blocks subscale), *Fs* < 1. Monolinguals rated their English proficiency higher than bilinguals in speaking, $F(1, 85) = 4.87$, $p = .030$, $\eta_p^2 = .054$, but not in understanding, $F(1, 85) = 1.21$, $p = .28$, $\eta_p^2 = .014$. The proficiency rating for English speaking in the bilingual group is greater than 9.2 out of 10, suggesting that the bilinguals are rating their proficiency in English quite high. Furthermore, all participants are enrolled and immersed in an anglophone community. Therefore, the lower proficiency rating in English speaking for bilinguals is not a concern. As expected, monolinguals reported that they used English more than bilinguals did for speaking, $F(1, 85) = 136.74$, $p < .001$, $\eta_p^2 = .62$, and listening, $F(1, 85) = 90.63$, $p < .001$, $\eta_p^2 = .52$. This is not surprising considering that bilinguals divide their time between languages and may be using their non-English language exclusively at home. Young adult bilinguals were fluent in English and one of the following languages: Albanian (1), Arabic (1), Assyrian (1), Bengali (2), Cantonese (1), Dari (1), Farsi (4), French (2), Ga (1), Gujarati (2), Hebrew (3), Hiligaynon (1), Hindi (2), Mandarin (2), Persian (1), Pidgin (1), Polish (1), Punjabi (4), Russian (1), Spanish (2), Tamil (2), Teochew (1), Urdu (5), and Vietnamese (2).

Older Adults. Demographic and language background information are presented by language group in Table 1. One-way ANOVAs revealed that older adult monolinguals and bilinguals were matched on age in years, level of education, English vocabulary, and non-verbal reasoning, all *ps* > .075. It should be noted that the level of education as at least some post-secondary education is expected considering the older adult participant pool at York University often consists of retired professors, teachers, or professionals. No differences were observed between older adult monolinguals and bilinguals on their self-rated proficiency in English for speaking and understanding, *F*s < 1. Older adult monolinguals reported that they used English more than older adult bilinguals did for speaking, $F(1, 82) = 12.31$, $p = .001$, $\eta_p^2 = .13$, and listening, $F(1, 82) = 17.08$, $p < .001$, $\eta_p^2 = .17$. Older adult bilinguals were fluent in English and one of the following languages: Afrikaans (3), Cantonese (2), Croatian (1), Dutch (1), French (14), German (4), Hebrew (1), Hungarian (1), Italian (3), Maltese (1), Portuguese (1), Romanian (1), Russian (1), Tagalog (2), Tamil (1), Ukrainian (5), and Yiddish (1). During the LSBQ interview, a number of older adult bilinguals revealed that they are no longer actively using their second language to the same extent as they did before, which may account for the low rating in proficiency and usage in their second language compared to the young adults.

Table 1

Background Information by Language Group and Age Group

	Younger Adults		Older Adults	
	Monolingual N = 43	Bilingual N = 44	Monolingual N = 41	Bilingual N = 43
Sex	26 F, 17 M	31 F, 13 M	26 F, 15 M	28 F, 15 M
Age (years)	20.35 (3.46)	20.62 (2.90)	69.90 (5.16)	70.49 (4.33)
Mother's Education (/5)	3.26 (1.25)	3.27 (1.28)	.	.
Level of Education (/5)	.	.	4.00 (.81)	3.93 (.86)
English Proficiency				
Speaking (/10)	9.67 (.70)	9.21 (1.20)	9.40 (.88)	9.36 (.94)
Understanding (/10)	9.58 (.77)	9.33 (1.30)	9.35 (1.13)	9.56 (.74)
English Usage				
Speaking (/10)	9.97 (.19)	7.04 (1.63)	10.00 (0.00)	9.07 (1.70)
Listening (/10)	9.96 (.20)	7.20 (1.89)	10.00 (0.00)	9.27 (1.13)
Other Language*				
Speaking (/10)	0.58 (1.66)	8.51 (1.58)	0.57 (1.13)	7.49 (2.01)
Understanding (/10)	0.51(1.33)	8.72 (1.46)	0.67 (1.22)	7.94 (1.79)
Other Language Usage*				
Speaking (/10)	0.22 (.82)	4.66 (2.64)	0.05 (.22)	2.74 (2.40)
Listening (/10)	0.29 (.90)	5.00 (2.74)	0.15 (.53)	3.05 (2.59)
Age of L2 Acquisition*	7.25 (4.73)	2.65 (3.89)	11.42 (7.09)	6.32 (9.67)
English Vocabulary	102.77 (8.92)	102.34 (11.47)	110.80 (6.95)	108.88 (8.13)
Nonverbal Reasoning	100.69 (11.42)	102.89 (13.38)	102.56 (12.42)	98.02 (10.64)

Note. Self-report ratings of proficiency range from 0 = "No Proficiency" to 10 = "High Proficiency" and usage from 0 = "Never this Language" to 10 = "Always this Language". A score of 5 for usage means that the participant uses both languages equally. Mother's education and level of education ranged from 1 to 5 (1 = No high school diploma, 2 = High school diploma, 3 = Some post-secondary education, 4 = Post-secondary degree or diploma, 5 = Graduate or professional degree). English vocabulary and nonverbal reasoning were measured using the standard scores from the Shipley-2 Institute of Living Scale Vocabulary and Block Patterns Scales, respectively. *12 young adult monolinguals listed a second language and 11 older adult monolinguals listed a second language.

Baseline Task

In order to account for individual differences in motor movements between groups, a baseline task was included in the study. Mean scores and standard deviations on the baseline task by language group and age group are shown in Table 2. Two-way ANOVAs with language group (monolingual versus bilingual) and age group (younger versus older adults) as between-subject variables were conducted on reaction time, maximum absolute deviation, initiation time, and maximum velocity of correct trials. Mean accuracy for clicking on the response box with the pineapple was at ceiling (above 95%). Due to the lack of variance, accuracy will not be analyzed further.

Across all dependent variables of the baseline task, monolinguals and bilinguals used the mouse in similar ways, ps > .21. In addition, the interactions between language and age were not significant, all ps > .16. No differences between younger and older adults were observed on maximum absolute deviation, $F < 1$, and maximum velocity, $F(1, 167) = 1.87$, $p = .17$, $\eta_p^2 = .011$, indicating that both age groups made similar movements in mouse trajectories. However, older adults were slower than younger adults to initiate a response, $F(1, 167) = 16.83$, $p < .001$, $\eta_p^2 = .094$, and make a response, $F(1, 167) = 310.15$, $p < .001$, $\eta_p^2 = .66$. Due to the longer initiation times (approx. 55 ms slower) and response times (approx. 580 ms slower) exhibited by older adults, the two age groups will be analyzed separately for the experimental tasks. Considering the task involved simply clicking on the response box with a stimulus, these differences in mouse movements indicate that older adults are less proficient in using the mouse than younger adults.

Table 2

Mean Scores (Standard Deviations) on the Baseline Task by Language Group and Age Group

	Younger Adult		Older Adult	
	Monolingual N = 41	Bilingual N = 44	Monolingual N = 41	Bilingual N = 43
Reaction Time (ms)	932 (160)	956 (144)	1499 (266)	1558 (259)
Accuracy Rate (%)	97.29 (14.54)	99.81 (1.26)	95.13 (10.20)	95.92 (8.51)
MAD (pxl)	-1.16 (137)	-33.99 (79.20)	-33.13 (108.34)	-32.66 (91.05)
Initiation Time (ms)	125 (67)	133 (74)	202 (115)	170 (95)
Velocity (co-ordinates)	11.63 (4.84)	17.32 (37.19)	9.60 (2.42)	11.09 (3.32)

Oculomotor Stroop Task

Younger Adults

Standard Analyses. Mean scores and standard deviations for the oculomotor Stroop task are shown in Table 3. Consistent with the protocol by Damian, Ye, Oh, and Yang (2019), no trimming procedures were conducted on mean reaction times (RTs). A three-way repeated-measures ANOVA was performed on the mean RTs of correct trials with congruency (congruent versus incongruent) and block half (first half versus second half) as within-subject variables and group (monolingual versus bilingual) as a between-subject variable. There was a main effect of congruency, $F(1, 85) = 44.52$, $p < .0001$, $\eta_p^2 = .34$, with faster responses on congruent ($M = 834$, $SE = 12$) than incongruent ($M = 866$, $SE = 13$) trials. In addition, the main effect of block half was significant, $F(1, 85) = 177.10$, $p < .0001$, $\eta_p^2 = .68$. Young adults were faster in the second half ($M = 823$, $SE = 12$) than the first half ($M = 882$, $SE = 12$) of the task. There was no main effect of group, $F < 1$, and no interaction effects, *p*s > .14.

Overall accuracy across conditions and language group was greater than 95%. Due to the lack of variance, accuracy rates were not analyzed further. To summarize, on standard behavioral measures of RT and accuracy, young adult monolinguals and bilinguals performed equivalently on the oculomotor Stroop task. As expected, the incongruent trial produced longer reaction times than congruent trials and participants were quicker to respond in the second half of the task compared to the first half.

Table 3

Mean Reaction Times and Accuracy Rates (Standard Deviations) on the Oculomotor Stroop Task in Young Adults by Language Group and Block Half

	First Half		Second Half	
	Monolingual N = 43	Bilingual N = 44	Monolingual N = 43	Bilingual N = 44
Reaction Time (ms)				
Congruent	872 (113)	870 (119)	803 (115)	810 (115)
Incongruent	898 (116)	887 (126)	842 (116)	836 (123)
Accuracy (%)				
Congruent	96.03 (7.49)	97.44 (2.73)	96.47 (7.91)	97.91 (2.20)
Incongruent	95.15 (12.66)	97.44 (2.58)	95.44 (12.67)	97.36 (2.43)

Mouse-Tracking Analyses. Means and standard deviations of the mouse-tracking measures for the oculomotor Stroop task are shown in Table 4. Trajectories were re-mapped to the top left response box. Mean maximum absolute deviation (MAD), initiation times (IT), and maximum velocity of correct trials were each subjected to a three-way ANOVA with congruency (congruent versus incongruent) and block half (first half versus second half) as within-subject variables and group (monolingual versus bilingual) as the between-subject variable.

For maximum absolute deviation (MAD), there was a significant main effect of congruency, $F(1, 85) = 93.23$, $p < .0001$, $\eta_p^2 = .52$, such that incongruent trials ($M = -27.44$, $SE = 2.37$) produced a larger and more negative deviation than congruent trials ($M = 18.23$, $SE = 3.30$). The main effect of block half, $F(1, 85) = 2.72$, $p = .10$, $\eta_p^2 = .031$, and group, $F < 1$, were not significant, however their interaction was, $F(1, 85) = 4.05$, $p = .047$, $\eta_p^2 = .045$ (Figure 8). Bonferroni corrected post-hoc pairwise comparisons revealed that the monolingual group had a more negative deviation in the second half compared to the first half of the task, p = .012. In contrast, there were no changes in deviation from the first to the second half of the task for the bilingual group, p = .80. All other interactions were not significant, ps < .27.

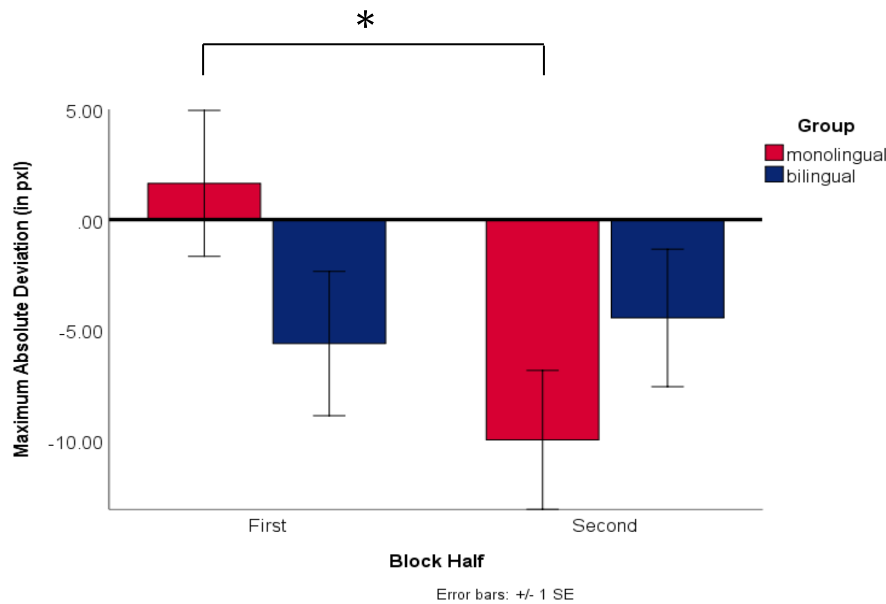

Figure 8. The means and standard error bars for the block half by group interaction on maximum absolute deviation (in pixel). *$p < .05$

The analysis performed on initiation time revealed a significant main effect of block half, $F(1, 85) = 15.77$, $p < .0001$, $\eta_p^2 = .16$, such that young adults were faster to initiate a response in the second half (M = 156, SE = 9) than the first half (M = 179, SE = 10). The main effect of group, $F(1,85) = 2.94$, $p = .090$, $\eta_p^2 = .030$, and the main effect of congruency, $F(1,85) = 1.38$, $p = .24$, $\eta_p^2 = .016$, were not significant. Finally, the three-way interaction of block half by congruency by group was significant, $F(1, 85) = 12.70$, $p = .001$, $\eta_p^2 = .13$. To breakdown the interaction, separate two-way ANOVAs were performed with block half as the within-subject variable and group as the between-subject variable on congruent and incongruent trials (Figure 9). For the congruent trials, the block half by group interaction was not significant, F(1, 85) =

1.14, p = .29, η_p^2 = .013; however, for the incongruent trials, the block half by group interaction was significant, $F(1, 85) = 3.97$, p = .05, η_p^2 = .045. In the second half of the task, bilinguals had significantly longer initiation times compared to monolinguals, p = .029, but no differences emerged between groups on the first half, p = .43. All other interactions did not reach significance, Fs < 1.

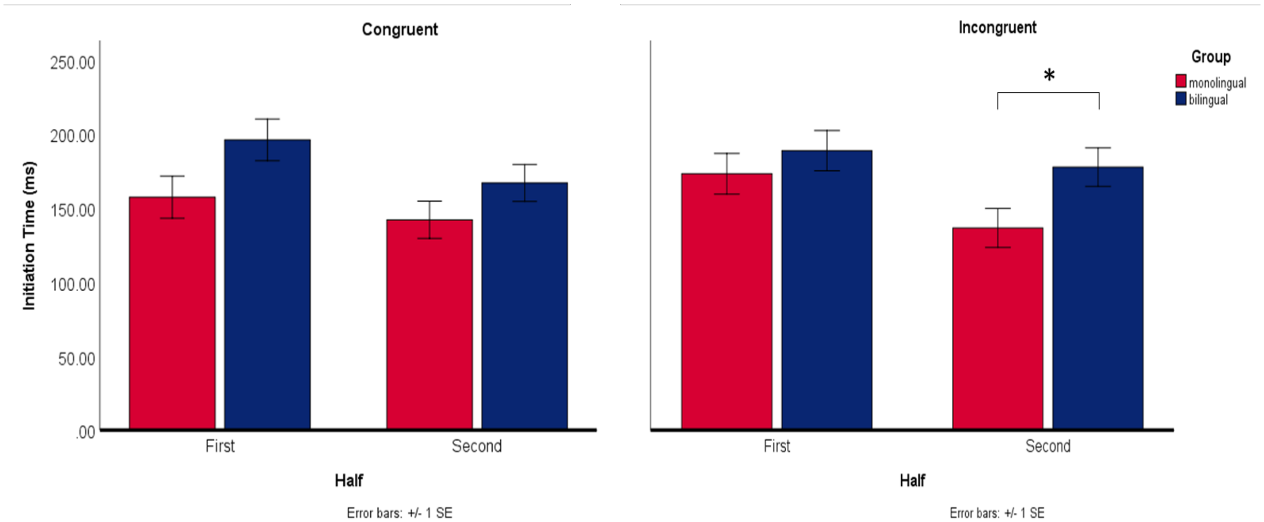

Figure 9. The means and standard error bars for the three-way interaction of congruency by block half by group on initiation time (ms). *p < .05

The analysis on maximum velocity revealed a significant main effect of congruency, $F(1, 85) = 19.05$, $p < .0001$, η_p^2 = .18, in which young adults reached a higher maximum velocity for the incongruent trials (M = 9.02, SE = .19) than congruent trials (M = 8.76, SE = .18). The main effect of group, F < 1, block half, $F(1, 85) = 3.58$, p = .062, η_p^2 = .04, and the interaction effects, ps > .23, were not significant.

To summarize the mouse-tracking results, young adults had a longer initiation time coupled with a higher maximum velocity for the incongruent trials compared to the congruent trials. Counter to our predictions, the incongruent trial did not produce a significantly larger deviation than congruent trials. Furthermore, participants were faster to initiate a response in the second half of the task than the first half of the task. When taking a closer look at the effect of bilingualism on mouse-tracking performance, monolinguals had an overall larger deviation in the second half of the task compared to the first half, while bilinguals exhibited similar mouse movements across both halves. Lastly, for incongruent trials, bilinguals had significantly longer initiation times than monolinguals but only on the second half of the task.

Table 4

Mean Scores (Standard Deviations) of the Mouse-Tracking Measures on the Oculomotor Stroop Task in Young Adults by Language Group and Block Half

	First Half		Second Half	
	Monolingual N = 43	Bilingual N = 44	Monolingual N = 43	Bilingual N = 44
Maximum Absolute Deviation (pxl)				
Congruent	25.87 (35.01)	17.38 (38.19)	9.26 (34.74)	20.40 (41.13)
Incongruent	-22.59 (31.42)	-28.62 (26.99)	-29.24 (33.24)	-29.32 (27.55)
Initiation Time (ms)				
Congruent	157 (92)	196 (94)	142 (84)	167 (82)
Incongruent	173 (94)	189 (86)	136 (85)	178 (88)
Maximum Velocity				
Congruent	8.57 (1.79)	8.81 (1.65)	8.62 (1.93)	9.02 (1.72)
Incongruent	8.75 (1.85)	9.10 (1.64)	8.99 (1.81)	9.22 (1.89)

Eye-Tracking Analyses. Seven monolingual and four bilingual young adults had calibration errors and were therefore removed from the eye-tracking analyses. Errors included degree of visual angle larger than 1.5 degrees and instances when the calibration failed more than five times and the eye-tracker was calibrated using the experimenter's eyes. The final sample for the eye-tracking analyses consisted of 36 monolingual and 40 bilingual young adults. Degrees of error in eye-tracking calibration for the monolingual group and bilingual group were 0.66° (1.27) and 0.34° (.23), respectively. Amount of time spent looking at the stimulus, target, and distractor as well as the proportion of looks made to the stimulus, target, and distractor were each analyzed in a three-way repeated-measures ANOVA with congruency (congruent versus incongruent) and block half (first half versus second half) as within-subject variables, while group (monolingual versus bilingual) was treated as the between-subject variable. Means and standard deviations for the eye-tracking measures on the oculomotor Stroop task are presented in Table 5.

The amount of time spent looking at the stimulus had a main effect of block half, $F(1, 74) = 29.09$, $p < .001$, $\eta_p^2 = .28$, and congruency, $F(1, 74) = 6.47$, $p = .013$, $\eta_p^2 = .080$. Participants spent more time looking at the stimulus in the first half ($M = 354$, $SE = 17$) than the second half ($M = 300$, $SE = 18$), as well as for the incongruent condition ($M = 333$, $SE = 17$) compared to the congruent condition ($M = 320$, $SE = 17$). In addition, the group by congruency interaction was significant, $F(1, 74) = 4.34$, $p = .041$, $\eta_p^2 = .055$, such that monolinguals spent more time looking at the stimulus for the incongruent trials ($M = 319$, $SE = 25$) than congruent trials ($M = 295$, $SE = 25$), $p = .002$, while bilinguals spent an equal amount of time looking at the stimulus when the trial was congruent ($M = 346$, $SE = 23.34$) and incongruent ($M = 348$, $SE = 24$), $p = .74$. The main effect of group, $F(1, 74) = 1.36$, $p = .25$, $\eta_p^2 = .018$, and all other interactions were not significant, ps > .084.

A main effect of block half emerged for time spent looking at the target, $F(1, 72) = 7.02$, $p = .010$, $\eta_p^2 = .089$, in which young adults spent more time looking at the target in the first half ($M = 240$, $SE = 10$) compared to the second half ($M = 220$, $SE = 10$). There was also a marginal effect of block half for proportion of looks to the target, $F(1, 74) = 3.73$, $p = .057$, $\eta_p^2 = .044$. More looks were made to the target in the second half ($M = .39$, $SE = .026$) compared to the first half ($M = .36$, $SE = .23$). There was no main effect of congruency, ps > .14, group, Fs < 1, or interaction effects, ps > .091.

No main effects or interactions were significant for time spent looking at the distractor, *p*s > .093, proportion of looks to the distractor, *p*s > .094, and proportion of looks to the stimulus, *p*s > .11.

Finally, the time to look at the target response box was recorded. The three-way ANOVA revealed a main effect of block half, $F(1, 71) = 20.05$, $p < .001$, $\eta_p^2 = .22$, and congruency, $F(1, 71) = 6.29$, $p = .014$, $\eta_p^2 = .081$. Young adults were faster to look at the target in the second half ($M = 553$, $SE = 12$) than first half ($M = 592$, $SE = 11$) and for the congruent condition ($M = 560$, $SE = 14$) compared to the incongruent condition ($M = 586$, $SE = 10$). In addition, the group by block half interaction was significant, $F(1, 71) = 4.90$, $p = .030$, $\eta_p^2 = .065$, in which monolinguals took longer to look at the correct response box in the first half than the second half, $p < .001$, while the bilinguals took the same amount of time to look at the correct response box in both halves, $p = .11$ (Figure 10). The main effect of group, $F(1, 71) = 3.18$, $p = .079$, $\eta_p^2 = .043$, and all interaction effects did not reach significance, *p*s > .076.

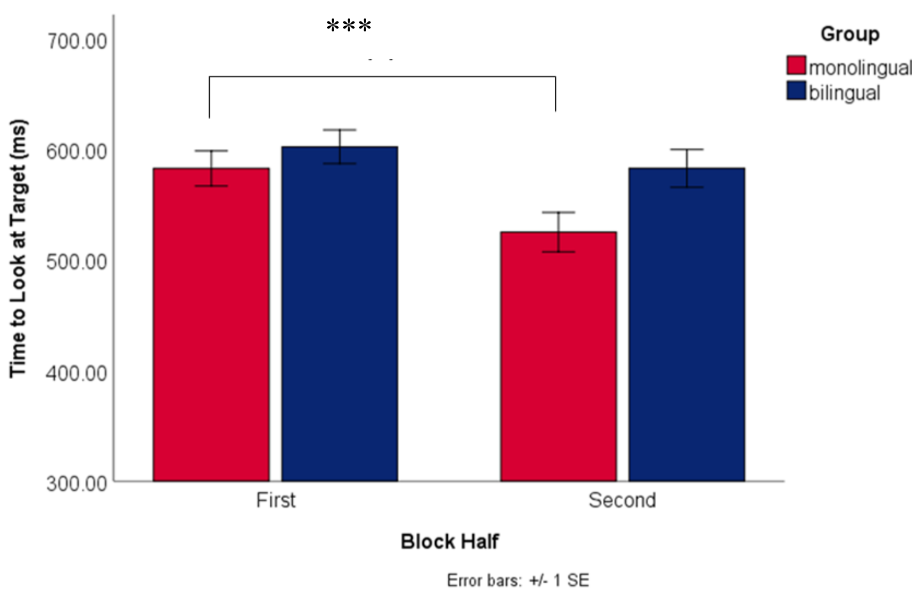

Figure 10. The means and standard error bars for the interaction between group and block half on the time it took to look at the target (ms). ***$p < .001$

The eye-tracking results revealed that young adults spent significantly more time looking at the stimulus when the color of the arrow did not match the color patch that the arrow was pointing to. Participants also took longer to make a correct first look towards the target response box when the stimulus was incongruent. Participants spent less time looking at the stimulus and were faster to look at the target response box in the second half of the task than the first half. The analyses on the proportion of looks broken down by each area of interest was not impacted by bilingualism, congruency, or half (except for the proportion of looks to the target and congruency). The amount of time spent looking at the distractor was very short, suggesting that the distractor produced minimal conflict and was relatively easy to resolve. Bilinguals differed from monolinguals on the amount of time spent looking at the stimulus as well as the time it took to make a first look towards the target. Bilinguals do not change the pattern in their eye-movements by trial type or between the first half and second half, whereas the monolinguals do. Figure 11 contains a plot and summary of the time components from the standard, mouse-tracking, and eye-tracking analyses.

Table 5

Mean Scores (Standard Deviations) of the Eye-Tracking Measures on the Oculomotor Stroop Task in Young Adults by Language Group and Block Half

	First Half		Second Half	
	Monolingual N = 36	Bilingual N = 40	Monolingual N = 36	Bilingual N = 40
Time Spent Looking at Stimulus				
Congruent	315 (159)	379 (138)	276 (141)	312 (176)
Incongruent	346 (161)	375 (146)	292 (146)	321 (181)
Time Spent Looking at Target				
Congruent	239 (100)	243 (72)	229 (117)	212 (66)
Incongruent	241 (101)	237 (70)	233 (108)	207 (69)
Time Spent Looking at Distractor				
Congruent	125 (89)	136 (84)	106 (73)	126 (76)
Incongruent	122 (69)	127 (37)	95 (50)	99 (64)
Proportion of Fixations on Stimulus				
Congruent	.57 (.24)	.60 (.24)	.52 (.28)	.59 (.27)
Incongruent	.55 (.26)	.61 (.24)	.53 (.27)	.59 (.56)
Proportion of Fixations on Target				
Congruent	.37 (.24)	.36 (.22)	.41 (.27)	.38 (.24)
Incongruent	.38 (.26)	.32 (.19)	.41 (.26)	.34 (.20)
Proportion of Fixations on Distractor				
Congruent	.066 (.18)	.040 (.088)	.066 (.17)	.024 (.056)
Incongruent	.067 (.18)	.079 (.21)	.069 (.19)	.069 (.17)
Time to Look at Target				
Congruent	559 (109)	587 (111)	510 (95)	582 (167)
Incongruent	605 (108)	616 (101)	539 (70)	582 (108)

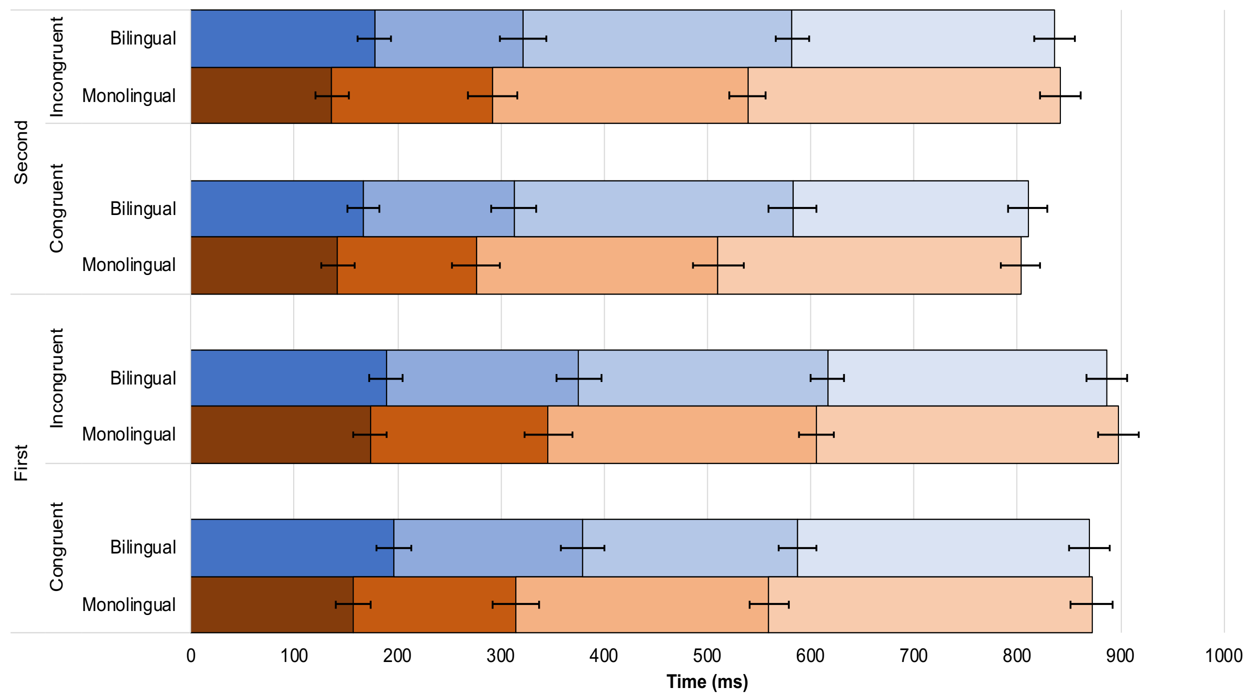

Figure 11. Summary of the time components from the standard (RT), mouse-tracking (initiation time), and eye-tracking (time spent looking at stimulus and time of first look to target) analyses on the oculomotor Stroop task in young adults.

Older Adults

Standard Analyses. Similar analyses to the young adult data were also conducted on the older adult sample. Means and standard deviations for reaction time (RTs) and accuracy on the oculomotor Stroop task in older adults are shown in Table 6. A three-way repeated-measures ANOVA was conducted on the mean RTs of correct trials. Congruency (congruent versus incongruent) and block half (first half versus second half) were treated as within-subject variables, while group (monolingual versus bilingual) was treated as a between-subject variable. There was a main effect of congruency, $F(1, 82) = 151.58$, $p < .0001$, $\eta_p^2 = .65$, such that participants were faster to respond to congruent trials ($M = 1255$, $SE = 15$) than incongruent trials ($M = 1300$, $SE = 15$). Furthermore, the main effect of block half was significant, $F(1, 82) = 106.57$, $p < .001$, $\eta_p^2 = .57$, in which the second half ($M = 1243$, $SE = 15$) produced faster responses than the first half (*M* = 1312, *SE* = 15) of the task. The main effect of group, $F < 1$, and the interaction effects were not significant, *p*s > .19. Overall accuracy across conditions were at ceiling (> 90%). Due to the lack of variance, accuracy rate was not analyzed further.

To summarize, on standard behavioral measures of RT and accuracy rate, older adult monolinguals and bilinguals performed equivalently on the oculomotor Stroop task. As expected, the incongruent trial produced longer reaction times than congruent trials and participants were quicker to respond in the second half of the task compared to the first half.

Table 6

Mean (Standard Deviations) Reaction Times and Accuracy Rates on the Oculomotor Stroop Task in Older Adults by Language Group and Block Half

	First Half		Second Half	
	Monolingual N = 41	Bilingual N = 43	Monolingual N = 41	Bilingual N = 43
Reaction Time (ms)				
Congruent	1288 (134)	1292 (151)	1213 (126)	1229 (140)
Incongruent	1330 (132)	1340 (142)	1252 (130)	1281 (147)
Accuracy Rate (%)				
Congruent	91.56 (8.76)	91.08 (8.46)	96.59 (3.75)	94.98 (9.08)
Incongruent	93.19 (7.38)	90.79 (9.25)	95.71 (4.23)	94.23 (7.16)

Mouse-Tracking Analyses. Means and standard deviations for the mouse-tracking measures on the oculomotor Stroop task in older adults are shown in Table 7. All trajectories were re-mapped to the top left response box. Separate three-way repeated-measures ANOVAs were performed on mean maximum absolute deviation, initiation time, and maximum velocity of correct trials with congruency (congruent versus incongruent) and block half (first half versus second half) as the within-subject variables and group (monolingual versus bilingual) as the between-subject variable.

The three-way ANOVA on maximum absolute deviation produced a main effect of congruency, $F(1, 82) = 109.05$, $p < .001$, $\eta_p^2 = .57$, with larger and more negative deviations observed for incongruent trials ($M = -35.38$, $SE = 3.35$) compared to congruent trials ($M = 11.65$, $SE = 3.24$). The main effect of block half, $F < 1$, group, $F(1, 82) = 2.85$, $p = .095$, $\eta_p^2 = .034$, and the interaction effects, all *p*s > .16, were not significant.

The repeated-measures ANOVA on initiation time revealed a main effect of block half, $F(1, 82) = 14.91$, $p < .001$, $\eta_p^2 = .15$. Older adults were faster to initiate a response in the second half ($M = 223$, $SE = 13$) than first half ($M = 246$, $SE = 14$). Furthermore, the interaction between congruency and block half was significant, $F(1,82) = 8.53$, $p = .005$, $\eta_p^2 = .094$. Bonferroni-corrected post-hoc pairwise comparisons revealed significantly longer initiation times for congruent ($M = 251$, $SE = 14$) than incongruent trials ($M = 241$, $SE = 14$) in the first half, $p = .059$. However, in the second half, the pattern was reversed, such that incongruent ($M = 227$, $SE = 13$) had longer initiation times than congruent trials ($M = 219$, $SE = 13$), but the difference was not significant, $p = .10$. The main effect of group, $F(1,82) = 2.15$, $p = .15$, $\eta_p^2 = .026$, congruency, $F < 1$, and the interaction effects, all *p*s > .16, were not significant.

The repeated-measures ANOVA on maximum velocity revealed a main effect of block half, $F(1, 81) = 10.36$, $p = .002$, $\eta_p^2 = .11$. Older adults had a higher maximum velocity in the first half ($M = 7.92$, $SE = .22$) than second half ($M = 7.59$, $SE = .18$). There was also a main effect of group, $F(1, 81) = 7.77$, $p = .007$, $\eta_p^2 = .088$, in which bilinguals ($M = 8.29$, $SE = .27$) had an overall higher maximum velocity than monolinguals ($M = 7.22$, $SE = .28$). The main effect of congruency, $F(1, 81) = 2.52$, $p = .12$, $\eta_p^2 = .030$, and all interactions, *F*s < 1, were not significant.

As a summary of the mouse-tracking results for the older adults, incongruent trials produced larger deviations than congruent trials. Furthermore, older adults were faster to initiate a response, coupled with a smaller maximum velocity, in the second half compared to the first half of the task. The only difference between language groups was found in maximum velocity. Bilingual older adults reached a higher maximum velocity than monolingual older adults.

Table 7

Mean Scores (Standard Deviations) on the Mouse-Tracking Measures of the Oculomotor Stroop Task in Older Adults by Language Group and Block Half

	First Half		Second Half	
	Monolingual N = 41	Bilingual N = 43	Monolingual N = 41	Bilingual N = 43
Maximum Absolute Deviation (pxl)				
Congruent	20.59 (36.81)	8.09 (35.95)	12.60 (26.07)	5.32 (40.58)
Incongruent	-35.15 (40.79)	-40.23 (44.63)	-29.22 (26.24)	-36.89 (37.74)
Initiation Time (ms)				
Congruent	273 (135)	229 (124)	241 (124)	197 (117)
Incongruent	260 (133)	222 (122)	241 (127)	214 (115)
Maximum Velocity				
Congruent	7.29 (2.02)	8.43 (1.92)	7.03 (1.67)	8.04 (1.69)
Incongruent	7.43 (2.07)	8.54 (2.15)	7.11 (1.77)	8.16 (1.60)

Eye-Tracking Analyses. Eleven monolingual older adults and fifteen bilingual older adults had errors in calibration. Thus, these participants were removed from the eye-tracking analyses leading to a final sample of 30 monolingual and 28 bilingual older adults. Degree of errors in eye-tracking calibration for the remaining monolingual and bilingual participants were 0.71° (0.57) and 0.67° (0.45), respectively. Amount of time spent looking at the stimulus, target, and distractor as well as the proportion of looks made to the stimulus, target, and distractor were each subjected to a three-way ANOVA with congruency (congruent versus incongruent) and block half (first half versus second half) as the within-subject factors and group (monolingual versus bilingual) as the between-subject factor. Means and standard deviations for the eye-tracking measures on the oculomotor Stroop task are presented in Table 8.

There was a significant main effect of block half for time spent looking at the stimulus, $F(1, 56) = 21.84$, $p < .001$, $\eta_p^2 = .28$, time spent looking at the distractor, $F(1, 46) = 3.78$, $p = .058$, $\eta_p^2 = .076$, and proportion of looks to the stimulus, $F(1, 74) = 5.20$, $p = .025$, $\eta_p^2 = .066$. Participants spent more time looking at the stimulus in the first half ($M = 268$, $SE = 15$) than the second half ($M = 215$, $SE = 13$), and also had a greater proportion of looks made to the stimulus in the first half ($M = .37$, $SE = .025$) than the second half ($M = .33$, $SE = .027$). Similarly, participants spent more time looking at the distractor in the first half ($M = 132$, $SE = 10$) than the second half ($M = 112$, $SE = 9$). The main effect of group, *ps* > .063, congruency, *F*s < 1, and the interaction effects, *p*s > .13, were not significant.

For time spent looking at the target, there was a main effect of block half, $F(1, 64) = 12.88$, $p < .001$, $\eta_p^2 = .17$. Participants spent more time fixating on the target in the first half ($M = 350$, $SE = 17$) than the second half ($M = 311$, $SE = 17$). The congruency by group interaction was significant, $F(1, 64) = 6.31$, $p = .015$, $\eta_p^2 = .090$, in which bilinguals spent more time looking at the target for the incongruent trial ($M = 354$, $SE = 24$) compared to the congruent trials ($M = 332$, $SE = 23$), $p = .044$, while monolinguals looked equally long at the target for the congruent ($M = 327$, $SE = 23$) and incongruent ($M = 311$, $SE = 24$) trials, $p = .14$. The main effect of group, congruency, and the other interactions were not significant, all *F*s < 1.

All main effects and interactions were not significant for proportion of looks to the target, *p*s > .25, and proportion of looks to the distractor, *p*s > .069.

The three-way ANOVA for time to make a first look to the target revealed a main effect of congruency, $F(1, 64) = 6.90$, $p = .011$, $\eta_p^2 = .097$. Participants took longer to look at the target for the incongruent trial ($M = 739$, $SE = 11$) than the congruent trial ($M = 709$, $SE = 14$). The main effect of block half, $F(1, 64) = 3.14$, $p = .081$, $\eta_p^2 = .047$, group, $F < 1$, and interaction effects, all *p*s > .073, were not significant.

The eye-tracking results for the oculomotor Stroop task revealed that older adults spent more time looking at the stimulus, distractor, and target in the first half compared to the second half of the task. Only the time of the first look to the target response box was impacted by congruency. As expected, older adults took longer to look at the correct response box when the stimulus was incongruent than congruent. Language group differences only emerged on the time spent looking at the target. Bilinguals spent more time looking at the target when it was an incongruent trial than congruent trial, while monolinguals spent an equal amount of time looking at the target for both trial types. It should be noted that the eye-tracking pattern of results for the older adults is different from the younger adults. Older adults spent less time looking at the stimulus and more time on the target (proportion of looks to target is also greater than the proportion of looks to stimulus), which is the reverse of what is observed amongst young adults. See Figure 12 for a summary of the time components from the standard, mouse-tracking, and eye-tracking analyses.

Table 8

Mean Scores (Standard Deviations) for the Eye-Tracking Measures on the Oculomotor Stroop Task in Older Adults by Language Group and Block Half

	First Half		Second Half	
	Monolingual N = 33	Bilingual N = 33	Monolingual N = 33	Bilingual N = 33
Time Spent Looking at Stimulus				
Congruent	276 (116)	262 (123)	196 (87)	224 (119)
Incongruent	270 (111)	265 (125)	210 (80)	231 (125)
Time Spent Looking at Target				
Congruent	340 (137)	359 (146)	314 (140)	304 (161)
Incongruent	327 (145)	374 (148)	294 (133)	335 (160)
Time Spent Looking at Distractor				
Congruent	120 (69)	134 (82)	100 (63)	121 (77)
Incongruent	113 (77)	160 (90)	94 (43)	134 (101)
Proportion of Fixations on Stimulus				
Congruent	.37 (.24)	.37 (.24)	.35 (.23)	.32 (.26)
Incongruent	.39 (.23)	.36 (.21)	.33 (.23)	.31 (.25)
Proportion of Fixations on Target				
Congruent	.47 (.23)	.49 (.23)	.49 (.25)	.48 (.28)
Incongruent	.45 (.22)	.49 (.19)	.48 (.24)	.47 (.28)
Proportion of Fixations on Distractor				
Congruent	.15 (.28)	.14 (.20)	.16 (.31)	.19 (.32)
Incongruent	.16 (.30)	.15 (.18)	.18 (.32)	.23 (.32)
Time to Look at Target				
Congruent	736 (123)	704 (108)	690 (98)	705 (190)
Incongruent	760 (95)	733 (89)	731 (93)	732 (132)

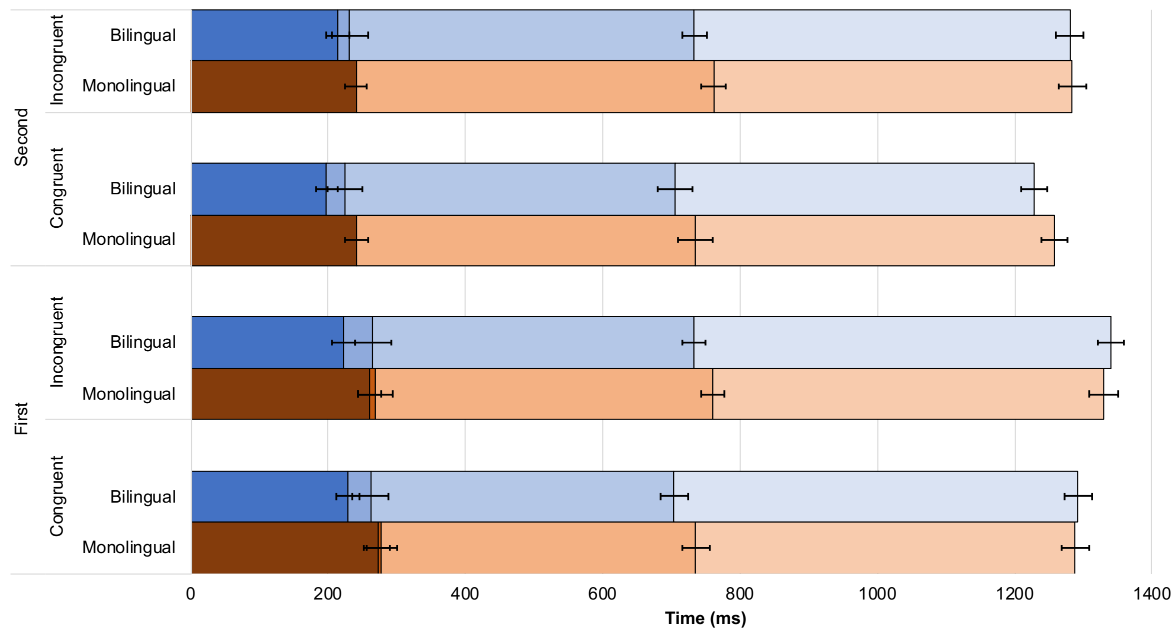

Figure 12. Summary of the time components from the standard (RT), mouse-tracking (initiation time), and eye-tracking (time spent looking at stimulus and time of first look to target) analyses on the oculomotor Stroop task in older adults.

Global-Local Task

Young Adults

Two monolingual and two bilingual young adults could not remember the rule for the global information in the mixed block. Their accuracy on the global incongruent trial was 0% despite completing twelve practice trials. In addition, the instructions for the task, and specifically the cue for the local and global stimuli, were repeated to all participants during the break. This may be indicative of a local precedence effect for these participants. One bilingual participant had reaction times that were 3 standard deviations above the group's mean on four conditions of the global-local task. As such, these participants were removed from all analyses. The final sample for the global-local task consisted of 41 monolinguals and 41 bilinguals.

Standard Analyses. Mean scores and standard deviations from the mixed block of the global-local task are presented on Table 9. Accuracy on the global-local task was near ceiling performance. As a result, accuracy rates were not analyzed further. Consistent with the study by Damian, Ye, Oh, and Yang (2019), no trimming procedures were conducted on mean reaction times (RTs). The comparison between first half and second half was not done for this task due to the low number of trials per condition (17 trials per condition if broken down by block half). A three-way repeated-measures ANOVA was conducted on mean RTs of correct trials only. Trial type (congruent, incongruent, versus neutral) and level (global versus local) were treated as within-subject variables, while group (monolingual versus bilingual) was treated as a between-subject variable. There was a main effect of level, $F(1, 79) = 9.72$, $p = .003$, $\eta_p^2 = .11$, and a main effect of trial type, $F(2, 158) = 544.42$, $p < .001$, $\eta_p^2 = .87$. Overall, young adults were faster to respond to the global information ($M = 1173$, $SE = 21$) than the local information ($M = 1199$, $SE = 21$). In addition, neutral trials ($M = 927$, $SE = 14$) produced the fastest responses, followed by the congruent trials ($M = 1154$, $SE = 23$) and then the incongruent trials ($M = 1477$, $SE = 29$). However, these main effects were qualified by a significant level by trial type interaction, $F(2, 158) = 57.42$, $p < .001$, $\eta_p^2 = .42$ (Figure 13). Participants were faster to respond to the global information than the local information on congruent trials, $p < .001$, but the reversed was found for incongruent trials, $p = .002$. There were no differences between global or local level of processing on neutral trials $p = .24$. The main effect of group, $F < 1$, and all other interaction effects with group, ps > .31, were not significant.

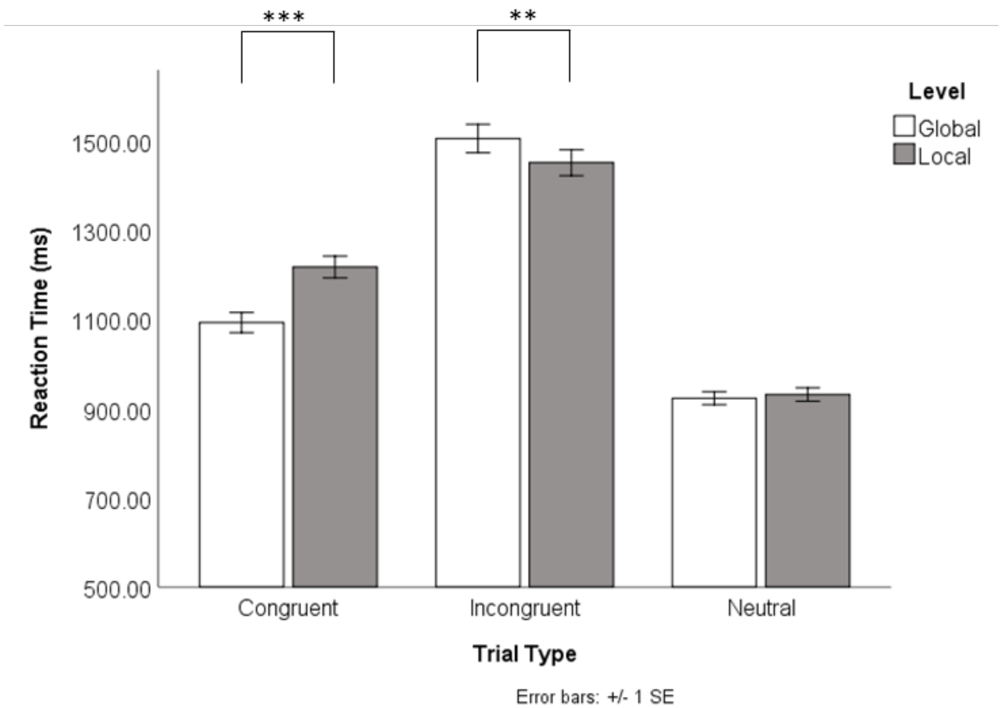

Figure 13. The means and standard error bars for the two-way interaction of trial type by level on reaction time (ms). $**p < .01$, $***p < .001$

On the global-local task, young adults were the slowest on trials in which the compound stimulus had global and local features that were incompatible. For the incongruent trials, we were expecting a global precedence effect, in which the global aspect (image as a whole), would slow down the reaction time when responding to local features (individual elements). Instead, a local precedence effect was found, which will be discussed in more detail in the discussion section. Bilingual and monolingual young adults had equivalent reaction times and accuracy rates on the global-local task.

Table 9

Mean Reaction Times and Accuracy Rates (Standard Deviations) on the Global-Local Task from the Mixed Block in Young Adults

	Monolingual *N = 40*	Bilingual *N = 41*
Reaction Time (ms)		
Global Congruent	1097 (231)	1087 (173)
Global Incongruent	1488 (285)	1521 (287)
Local Congruent	1216 (217)	1217 (223)
Local Incongruent	1454 (273)	1447 (253)
Global Neutral	930 (137)	914 (123)
Local Neutral	940 (146)	921 (125)
Accuracy Rate (%)		
Global Congruent	99.06 (1.76)	99.01 (1.63)
Global Incongruent	90.39 (9.35)	89.03 (13.49)
Local Congruent	98.75 (2.21)	97.79 (3.29)
Local Incongruent	93.28 (7.37)	93.83 (9.59)
Global Neutral	99.30 (1.50)	99.54 (1.32)
Local Neutral	99.38 (1.90)	99.54 (1.12)

Mouse-Tracking Analyses. Means and standard deviations from the mouse-tracking measures for the global-local task in the mixed block are presented in Table 10. Trajectories were re-mapped to the top left response box. Mean maximum absolute deviation, initiation time, and maximum velocity of correct trials were each subjected to a three-way ANOVA with trial type (congruent, incongruent, versus neutral) and level (global versus local) treated as the within-subject variables and group (monolingual versus bilingual) as the between-subject variable.

For maximum absolute deviation, a main effect of trial type was found, $F(2, 158) = 533.55$, $p < .001$, $\eta_p^2 = .87$, in which participants had significantly larger deviations for the incongruent ($M = 350.00$, $SE = 13.50$), followed by the congruent ($M = 109.62$, $SE = 7.43$), and then the neutral trials ($M = 74.43$, $SE = 6.23$), all $ps < .001$. There was also a level by trial type interaction, $F(2, 158) = 25.15$, $p < .001$, $\eta_p^2 = .24$ (Figure 14). Bonferroni-corrected pairwise post-hoc comparisons revealed that young adults had a smaller deviation when responding to global information than local information on congruent trials, $p < .001$, but a larger deviation when responding to global than local information for incongruent trials, $p < .001$. The difference between global and local level of processing on neutral trials was significant, but to a lesser extent, $p = .046$. The main effect of group, level, and all other interaction effects did not reach significance, all *Fs* < 1.

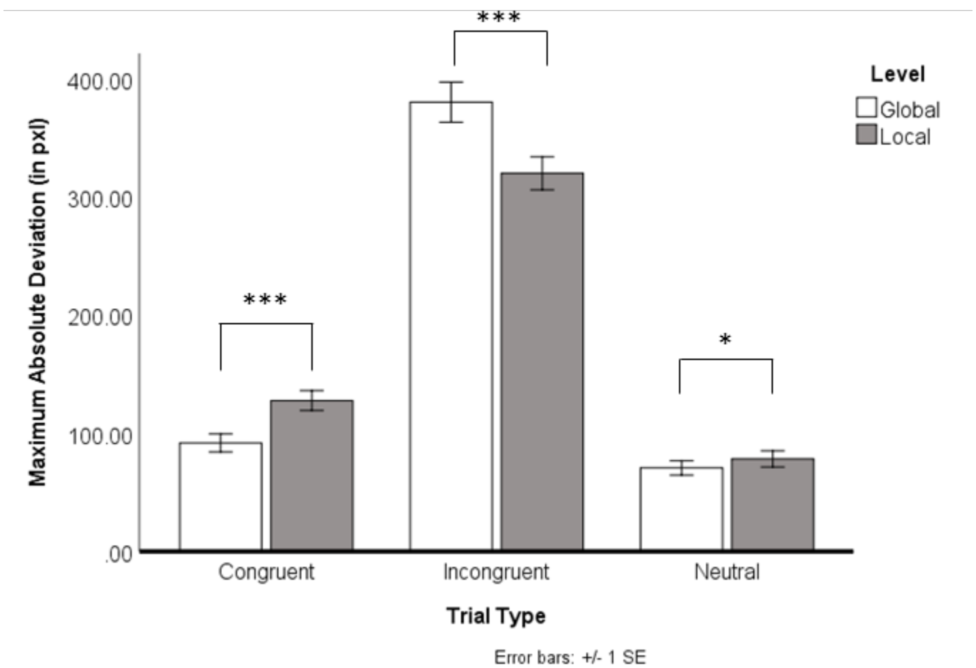

Figure 14. The means and standard error bars for the two-way interaction of trial type by level on maximum absolute deviation (in pixels). $^*p < .05$, $^{**}p < .01$, $^{***}p < .001$

For initiation time, there was a main effect of trial type, $F(2, 158) = 15.94$, $p < .001$, $\eta_p^2 = .17$, level, $F(1, 79) = 4.81$, $p = .031$, $\eta_p^2 = .057$, and their interaction, $F(2, 158) = 12.90$, $p < .001$, $\eta_p^2 = .14$. Making judgments based on the global information ($M = 130$, $SE = 9$) produced longer initiation times than the local information ($M = 124$, $SE = 9$). The neutral trial ($M = 113$, $SE = 8$) produced faster initiation times than the congruent ($M = 131$, $SE = 10$) and incongruent trials ($M = 136$, $SE = 10$), which did not differ from each other. The global information ($M = 128$, $SE =$

10) produced longer initiation times than the local information (*M* = 98, *SE* = 7) only on the neutral trials, $p < .001$. No differences in initiation time were found between global and local information for the congruent and incongruent trials, *p*s > .12. The type by group interaction was significant, $F(2, 158) = 3.87$, $p = .028$, $\eta_p^2 = .047$ (Figure 15). Bilinguals took longer than monolinguals to initiate a response on congruent, $p = .043$, and incongruent trials, $p = .015$, but not for neutral trials, $p = .069$. The three-way level by type by group interaction was significant, $F(2, 158) = 12.90$, $p < .001$, $\eta_p^2 = .14$. When the monolingual group was analyzed separately, the level by type interaction was not significant, $F < 1$. However, for the bilingual group, the level by type interaction was significant, $F(2, 80) = 16.80$, $p < .001$, $\eta_p^2 = .30$. Bilinguals took longer to initiate a response when responding to global information (*M* = 152, *SE* = 16) than local information (*M* = 102, *SE* = 11), but only on the neutral trials, $p < .001$. No differences between global and local level of processing was found for congruent and incongruent trials, *ps* > .14. Lastly, the main effect of group was significant, $F(1, 79) = 4.95$, $p = .029$, $\eta_p^2 = .059$. Bilinguals (*M* = 147, *SE* = 12) had an overall longer initiation time than monolinguals (*M* = 107, *SE* = 13). The level by group interaction was not significant, $F(1, 79) = 2.97$, $p = .089$, $\eta_p^2 = .036$.

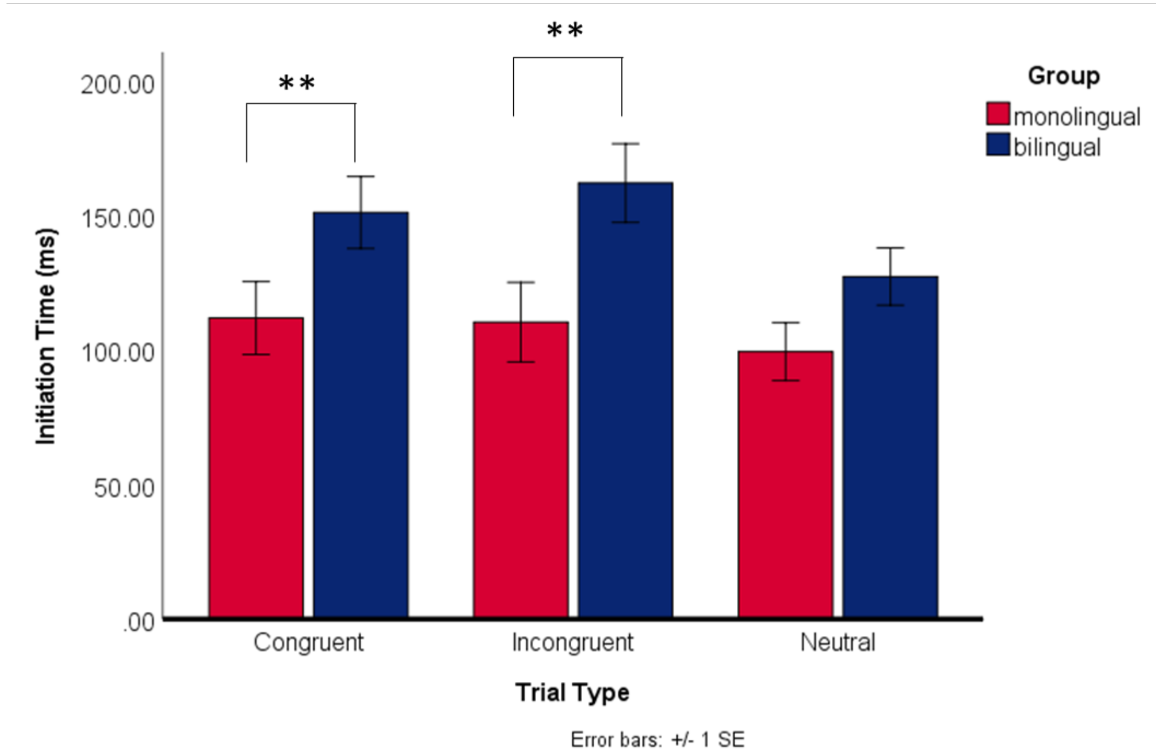

Figure 15. The means and standard error bars for the two-way interaction of trial type by group on initiation time (in ms). **$p < .01$

For maximum velocity, a main effect of level, $F(1, 79) = 10.43$, $p = .002$, $\eta_p^2 = .12$, type, $F(2, 158) = 19.55$, $p < .001$, $\eta_p^2 = .20$, and their interaction, $F(2, 158) = 4.73$, $p = .013$, $\eta_p^2 = .057$, were found. Overall, participants had a higher maximum velocity when responding to global information ($M = 9.94$, $SE = .24$) than local information ($M = 9.77$, $SE = .24$). Furthermore, participants had higher maximum velocities on incongruent ($M = 10.05$, $SE = .25$) and neutral ($M = 10.07$, $SE = .25$) trials compared to congruent trials ($M = 9.44$, $SE = .24$), both *p*s < .001. The incongruent and neutral trials did not differ from each other, $p = 1.00$. Furthermore, the level by trial type interaction was significant, $F(2, 158) = 4.73$, $p = .013$, $\eta_p^2 = .057$, such that participants had a higher maximum velocity for the global than the local information on incongruent trials only, $p = .001$ (Figure 16). No differences between global and local information were found for the neutral and congruent trials, *p*s > .13. The main effect of group, *F* < 1, and all other interaction effects with group, *p*s > .073, were not significant.

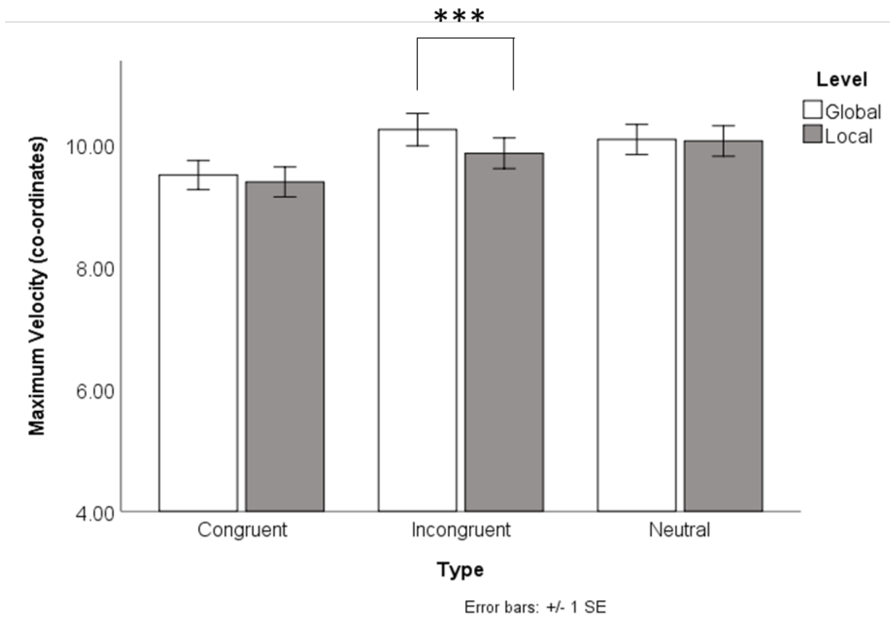

Figure 16. The means and standard error bars for the two-way interaction of trial type by level on maximum velocity (in co-ordinates). ****p* < .001

The mouse-tracking findings of the global-local task revealed that young adults produced the largest deviation and longest initiation times on trials in which the compound stimulus had global and local features that were incompatible. Similar to the RT results, the incongruent trials produced a local precedence effect. When the individual arrows pointed in the same direction as the larger arrow, deviations were smaller when asked to respond to the global feature. However, when the individual arrows pointed in the opposite direction, producing a discrepancy between local and global features, the local features interfered with the processing of global features, as can be seen in the differences in maximum absolute deviation. Bilinguals on average took longer to initiate a response than monolinguals across all trial types.

Table 10

Means (Standard Deviations) of the Mouse-Tracking Measures on the Global-Local Task from the Mixed Block in Young Adults

	Monolingual *N = 40*	Bilingual *N = 41*
Maximum Absolute Deviation (pxl)		
Global Congruent	94.07 (60.12)	89.38 (77.17)
Global Incongruent	390.98 (140.90)	368.56 (163.22)
Local Congruent	134.30 (65.29)	120.75 (85.06)
Local Incongruent	337.43 (109.18)	301.87 (140.00)
Global Neutral	71.47 (47.23)	69.77 (61.89)
Local Neutral	82.49 (57.27)	73.97 (65.83)
Initiation Time (ms)		
Global Congruent	110 (67)	146 (98)
Global Incongruent	110 (77)	159 (108)
Local Congruent	114 (78)	156 (104)
Local Incongruent	111 (76)	165 (113)
Global Neutral	104 (63)	152 (102)
Local Neutral	95 (55)	102 (73)
Maximum Velocity (co-ordinates)		
Global Congruent	9.15 (2.31)	9.85 (1.95)
Global Incongruent	10.25 (2.81)	10.23 (1.89)
Local Congruent	9.14 (2.41)	9.63 (1.98)
Local Incongruent	9.70 (2.61)	10.01 (1.86)
Global Neutral	9.76 (2.25)	10.40 (2.18)
Local Neutral	9.78 (2.38)	10.33 (2.10)

Eye-Tracking Analyses. Due to errors in calibration, in which the degree of error was larger than 1.5, two young adult monolinguals and one young adult bilingual were removed from the eye-tracking analyses. The remaining participants had a degree of error of 0.35 (0.24) and 0.32 (0.25) for the monolingual and bilingual group, respectively. Means and standard deviations for time spent looking at the stimulus by trial type, level, and group are presented on Table 11. Time spent looking at the stimulus was subjected to a three-way ANOVA with trial type (congruent, incongruent, versus neutral) and level (global versus local) as the within-subject variables, and group (monolingual versus bilingual) as the between-subject variable. There was a main effect of trial type, $F(2, 152) = 268.92$, $p < .001$, $\eta_p^2 = .78$, in which participants spent more time looking at the stimulus in incongruent trials ($M = 868$, $SE = 39$), followed by congruent trials ($M = 657$, $SE = 27$), and then neutral trials ($M = 470$, $SE = 20$), all *ps* < .001. In addition, there was a main effect of level, $F(2, 152) = 13.97$, $p < .001$, $\eta_p^2 = .15$, in which participants spent more time looking at the stimulus when asked to respond to the local features ($M = 677$, $SE = 28$) than the global feature ($M = 653$, $SE = 28$), $p < .001$. Lastly, the level by trial type interaction was significant, $F(2, 152) = 33.03$, $p < .001$, $\eta_p^2 = .30$ (Figure 17). In the congruent trial, participants spent more time looking at the stimulus for the local information than global information, $p < .001$. No differences between the local and global level of information was found for the incongruent and neutral trials, *p*s > .25. The main effect of group, $F < 1$, and all interaction effects with group, *F*s < 1, did not reach significance. The eye-tracking results confirm that incongruent trials and having to attend to local features produced the greatest amount of interference and stimulus evaluation. See Figure 18 for a summary of the time components from the standard, mouse-tracking, and eye-tracking analyses from the younger adults on the global-local task.

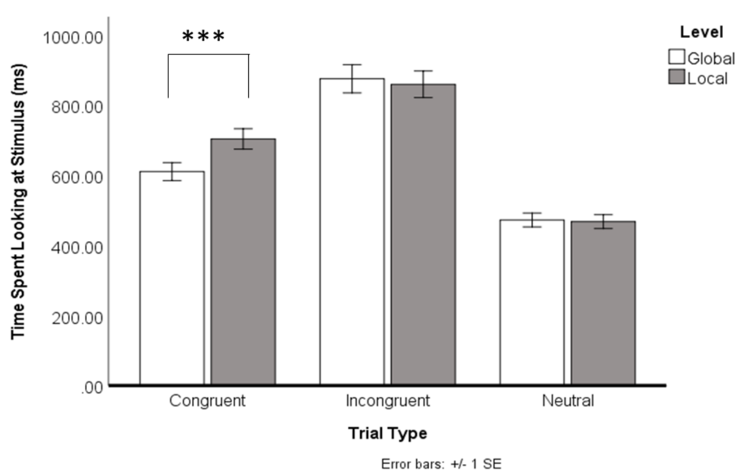

Figure 17. The means and standard error bars for the trial type by level interaction on time spent looking at the stimulus (in ms). ***$p < .001$

Table 11

Mean Time Spent Looking at Stimulus (Standard Deviations) on the Global-Local Task from the Mixed Block in Young Adults

	Monolingual N = 38	Bilingual N = 40
Time Spent Looking at Stimulus		
Global Congruent	604 (227)	618 (225)
Global Incongruent	863 (366)	888 (345)
Local Congruent	689 (274)	718 (242)
Local Incongruent	850 (358)	869 (314)
Global Neutral	472 (178)	473 (172)
Local Neutral	464 (166)	471 (180)

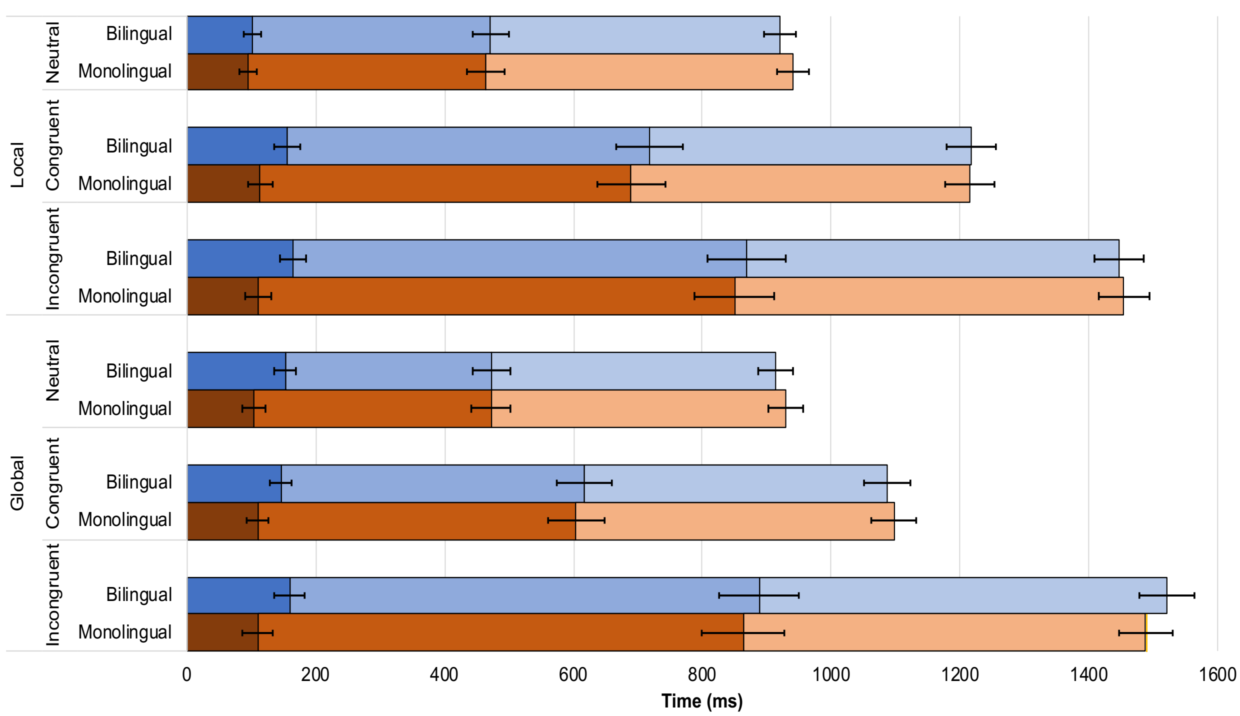

Figure 18. Summary of the time components from the standard (RT), mouse-tracking (initiation time), and eye-tracking (time spent looking at stimulus) analyses on the global-local task in young adults.

Pure Block Analysis. Mean and standard deviations from the pure block are presented in Table 12. The trials from the pure blocks were analyzed in a two-way repeated-measures ANOVA. Level (global versus local) was treated as the within-subject variable and group (monolingual versus bilingual) as the between-group variable. All dependent variables (i.e., RT, accuracy, maximum absolute deviation, maximum velocity, and time spent looking at the stimulus) yielded no main effect of group, *p*s > .14*,* level, *p*s > .17, or group by level interactions, *p*s > .14. However, for initiation time, there was a significant group by level interaction, $F(1, 79) = 5.01$, $p = .028$, $\eta_p^2 = .060$, in which bilinguals had a longer initiation time than monolinguals when responding to local features, $p = .055$, but not for global features, $p = .61$ (Figure 19).

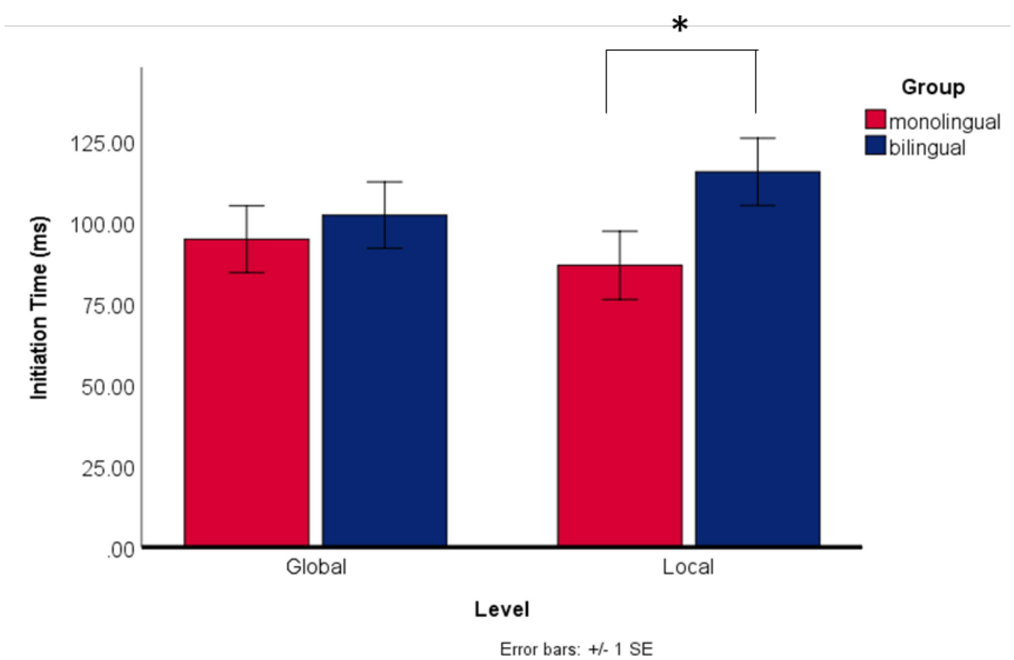

Figure 19. The means and standard error bars for the two-way interaction of group by level on initiation time (ms) from the pure blocks. *$p = .05$

Table 12

Means (Standard Deviations) on the Global-Local Task of the Trials from the Pure Block in Young Adults

		Monolingual N = 40	Bilingual N = 41
Standard Measures	Reaction Time (ms)		
	Global Neutral	842 (132)	846 (122)
	Local Neutral	854 (135)	846 (135)
	Accuracy Rate (%)		
	Global Neutral	99.77 (.83)	99.77 (.82)
	Local Neutral	99.84 (.69)	98.55 (8.79)
Mouse-Tracking Measures	Maximum Absolute Deviation (pxl)		
	Global Neutral	114.11 (58.85)	120.10 (65.97)
	Local Neutral	110.58 (60.64)	109.90 (67.17)
	Initiation Time (ms)		
	Global Neutral	95 (56)	102 (73)
	Local Neutral	87 (57)	115 (74)
	Maximum Velocity (co-ordinates)		
	Global Neutral	10.51 (2.84)	10.66 (1.83)
	Local Neutral	10.31 (2.28)	10.95 (2.32)
Eye-Tracking Measures	Time Spent Looking at Stimulus		
	Global Neutral	367 (134)	379 (104)
	Local Neutral	374 (151)	405 (137)

Older Adults

Three older adult monolinguals and two older adult bilinguals could not remember the global cue in the mixed block. Their accuracy on the global incongruent trial was 0% despite completing twelve practice trials. The rules for the local and global information were also repeated to all participants halfway through the task during the break. In addition, one monolingual and three bilingual participants did not want to continue with the task during the break. Hence, the final sample for the global-local task consisted of 36 monolinguals and 38 bilinguals.

Standard Analyses. Mean scores and standard deviations from the global-local task in the mixed block are presented in Table 13. Similar to the young adult data, no trimming procedures were applied to the reaction time data. A three-way repeated-measures ANOVA was conducted on mean RTs of correct trials only. Trial type (congruent, incongruent, versus neutral) and level (global versus local) were treated as within-subject variables, while group (monolingual versus bilingual) was treated as a between-subject variable. There was a main effect of level, $F(1, 72) = 8.77$, $p = .004$, $\eta_p^2 = .11$, and a main effect of trial type, $F(2, 144) = 687.57$, $p < .001$, $\eta_p^2 = .91$. Overall, older adults made faster responses to global information ($M = 1783$, $SE = 23$) than local information ($M = 1818$, $SE = 23$), and were faster to respond to neutral trials ($M = 1413$, $SE = 22$) followed by congruent trial ($M = 1824$, $SE = 28$) and then incongruent trials ($M = 2165$, $SE = 25$). However, these main effects were qualified by an interaction between trial type and level, $F(2, 144) = 63.33$, $p < .001$, $\eta_p^2 = .47$ (Figure 20). Older adults were faster to respond to the global information than local information on congruent trials, $p < .001$, but slower to respond to the global information than local information on incongruent trials, $p = .002$. No differences between local or global information were observed on neutral trials, $p = .17$. The main effect of group, $F < 1$, and the interaction effects with group were not significant, ps > .35.

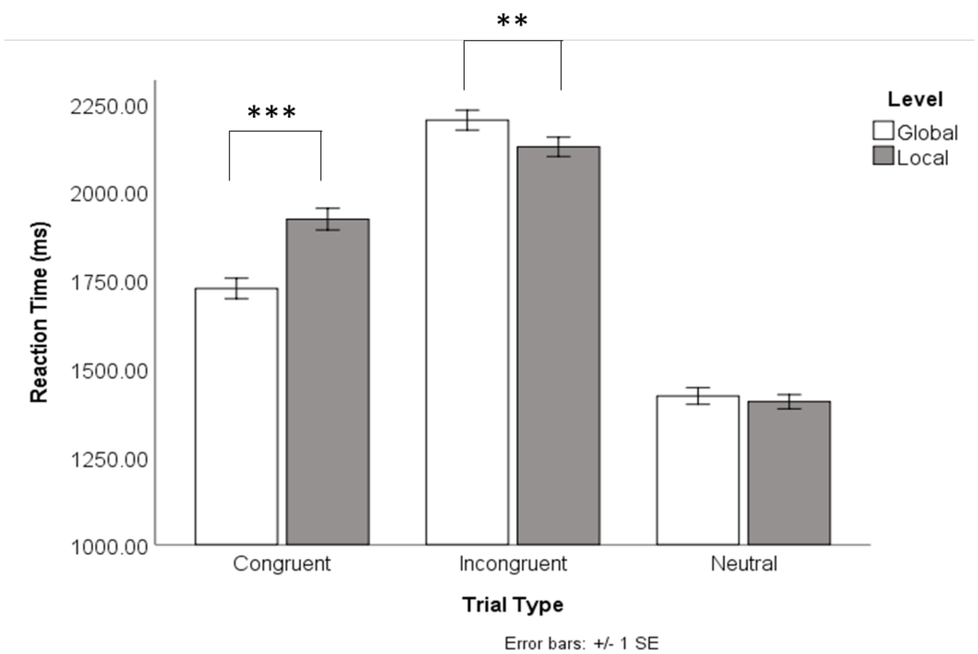

Figure 20. The means and standard error bars for the two-way interaction of trial type by level on reaction time (ms). $^{**}p < .01$, $^{***}p < .001$

For accuracy, there was a main effect of trial type, $F(2, 144) = 110.43$, $p < .001$, $\eta_p^2 = .61$, such that older adults were more accurate on the neutral trials ($M = 96.43$, $SE = .97$), followed by the congruent trials ($M = 89.71$, $SE = 1.56$), and lastly the incongruent trials ($M = 68.29$, $SE = 2.90$), $ps < .001$. Furthermore, the level by trial type interaction was significant, $F(2, 144) = 17.89$, $p < .001$, $\eta_p^2 = .20$ (Figure 21). Older adults were more accurate when responding to the global feature than the local features on the congruent, $p < .001$, but more accurate on the local features than global feature on incongruent trials, $p = .007$. On the neutral trials, there was no difference between global or local information, $p = .72$. The main effect of group, $F(1, 72) = 1.39$, $p = .24$, $\eta_p^2 = .019$, level, $F < 1$, and the interaction terms with group were not significant, Fs < 1.

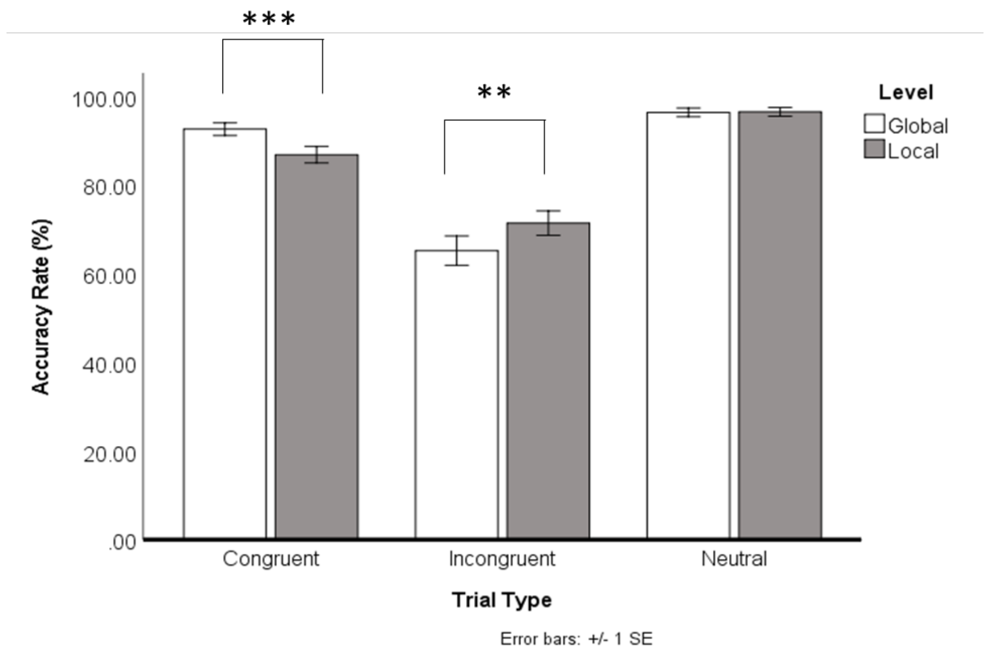

Figure 21. The means and standard error bars for the two-way interaction of trial type by level on accuracy (%). $^{**}p < .01$, $^{***}p < .001$

On the global-local task, older adults were the slowest on trials in which the compound stimulus had global and local features that were incompatible. Consistent with the young adult data, a local precedence effect was found. Bilingual and monolingual older adults had equivalent reaction times and accuracy rates on the global-local task.

Table 13

Mean Reaction Times and Accuracy Rates (Standard Deviations) on the Global-Local Task in the Mixed Block for Older Adults

	Monolingual N = 36	Bilingual N = 38
Reaction Time (ms)		
Global Congruent	1753 (245)	1698 (253)
Global Incongruent	2198 (246)	2207 (242)
Local Congruent	1926 (253)	1918 (272)
Local Incongruent	2134 (236)	2120 (234)
Global Neutral	1431 (178)	1411 (226)
Local Neutral	1419 (153)	1390 (192)
Accuracy Rate (%)		
Global Congruent	93.75 (8.93)	91.45 (14.82)
Global Incongruent	67.54 (27.13)	62.83 (29.68)
Local Congruent	89.50 (12.92)	84.13 (18.46)
Local Incongruent	73.79 (24.52)	69.00 (23.12)
Global Neutral	97.66 (3.91)	95.07 (11.06)
Local Neutral	97.83 (4.15)	95.15 (11.29)

Mouse-Tracking Analyses. The means and standard deviations of the mouse-tracking measures from the global-local task in the mixed block are shown in Table 14. Mean maximum absolute deviation, initiation time, and maximum velocity were each subjected to a three-way repeated-measures ANOVA with trial type (congruent, incongruent, versus neutral) and level (global versus local) as within-subject variables, and group (monolingual versus bilingual) as the between-subject variable.

For maximum absolute deviation, there was a main effect of trial type, $F(2, 144) = 215.32$, $p < .001$, $\eta_p^2 = .74$, in which participants had a significantly greater deviations for the incongruent trials ($M = 208.61$, $SE = 12.20$), followed by the congruent trials ($M = 82.33$, $SE = 7.25$), and then the neutral trials ($M = 21.59$, $SE = 5.10$), all *ps* < .001. There was also a main effect of level, $F(1, 72) = 9.77$, $p = .003$, $\eta_p^2 = .12$, in which older adults had larger deviations when responding to global features (M = 114.32, SE = 7.86) than local features (M = 94.04, SE = 7.34). The main effects were qualified by a significant interaction between level and trial type, $F(2, 144) = 45.31$, $p < .001$, $\eta_p^2 = .39$ (Figure 22). Older adults produced a smaller deviation when responding to the global feature than local features on the congruent trial, $p < .001$, but a larger deviation for the global feature than local features on incongruent trials, $p < .001$. On the neutral trials, there was no difference between global or local information, $p = .35$. The main effect of group, $F(1, 72) = 2.11$, $p = .15$, $\eta_p^2 = .028$, and the interaction effects with group did not reach significance, $Fs < 1$.

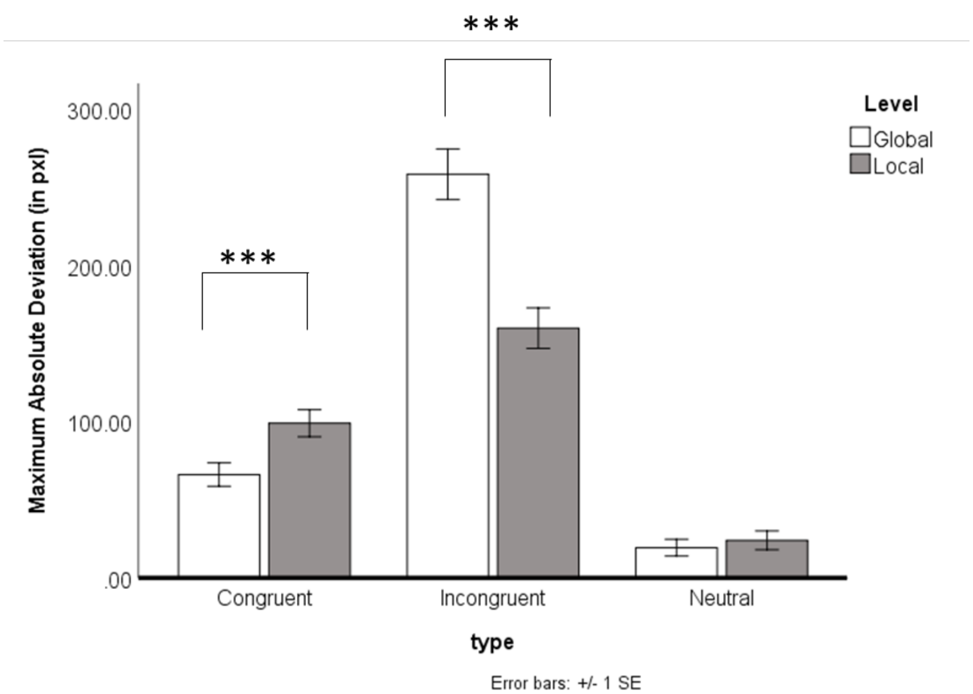

Figure 22. The means and standard error bars for the trial type by level interaction on maximum absolute deviation (pxl). ***$p < .001$

For the initiation time, a main effect of level, $F(1, 72) = 8.77$, $p = .004$, $\eta_p^2 = .11$, and a main effect of trial type, $F(2, 144) = 17.98$, $p < .001$, $\eta_p^2 = .20$, were found. Older adults were faster to initiate a response to local (M = 199, SE = 15) than global (M = 216, SE = 17) features.

Neutral trials (*M* = 181, *SE* = 13) produced the fastest initiation time, followed by congruent trials (*M* = 204, *SE* = 16) and then incongruent trials (*M* = 237, *SE* = 20), *ps* < .014. The main effects were qualified by a significant level by trial type interaction, $F(2, 144) = 5.91$, $p = .005$, $\eta_p^2 = .076$ (Figure 23). On neutral trials, older adults were faster to initiate a response when responding to local information than global information, $p < .001$. No difference between global and local information was found for congruent, $p = .40$, and incongruent trials, $p = .13$. The main effect of group, $F < 1$, and the interaction effects with group were not significant, *F*s < 1.

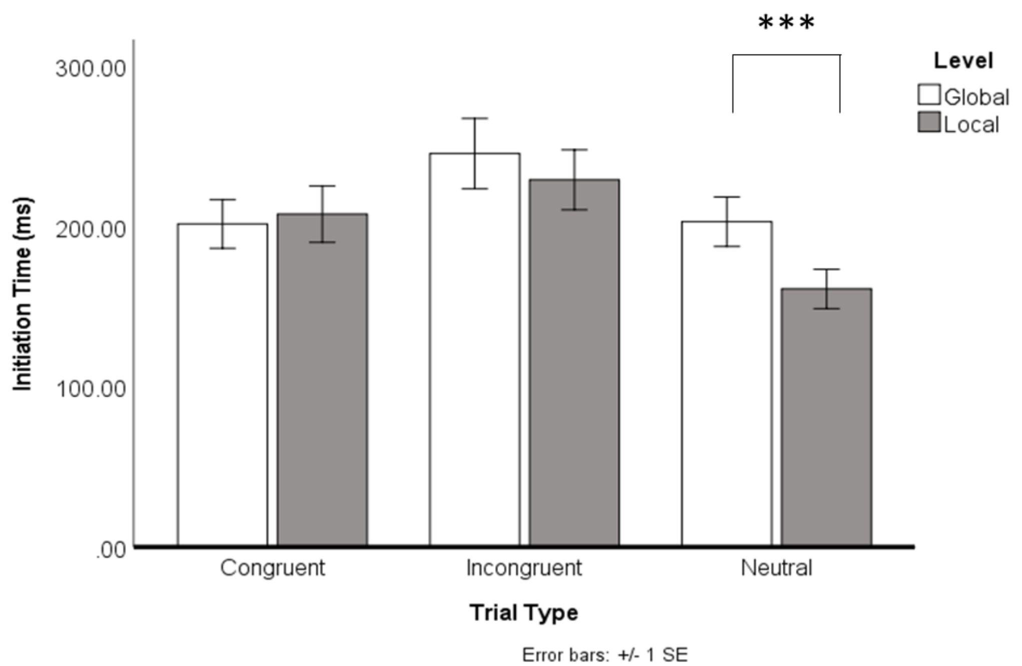

Figure 23. The means and standard error bars for the two-way interaction of trial type by level on initiation time (ms). ****p* < .001

For maximum velocity, there was a main effect of trial type, $F(2, 138) = 46.84$, $p < .001$, $\eta_p^2 = .40$. Incongruent (*M* = 8.45, *SE* = .24) and neutral trials (*M* = 8.27, *SE* = .27) had a higher maximum velocity than congruent trials (*M* = 7.32, *SE* = .22), *p*s < .001. Incongruent trials and neutral trials did not differ from each other, $p = .76$. Furthermore, the level by trial type interaction was significant, $F(2, 138) = 9.85$, $p = .001$, $\eta_p^2 = .13$ (Figure 24). Participants had a higher maximum velocity for the global information than the local information on the incongruent trials, $p = .013$, but a higher maximum velocity for the local information than global information for the neutral trial, $p < .001$. No differences between global and local information were found for the congruent trials, $p = .68$. Lastly, there was a main effect of group, $F(1, 69) = 7.34$, $p = .008$, $\eta_p^2 = .096$. Bilinguals ($M = 8.64$, $SE = .32$) had a significantly higher maximum velocity than monolinguals ($M = 7.38$, $SE = .34$), $p = .008$. The main effect of level, $F < 1$, and all other interactions with group, ps > .26, were not significant.

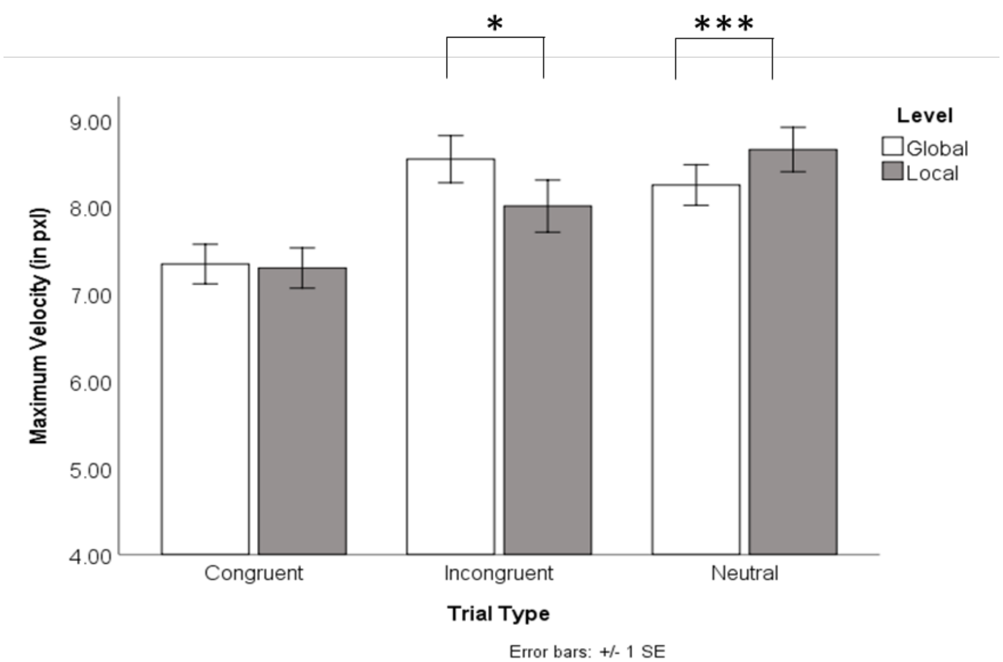

Figure 24. The means and standard error bars for the two-way interaction of trial type by level on maximum velocity (pxl). *$p < .05$, ***$p < .001$

The mouse-tracking data for the older adults corroborates the reaction time and accuracy findings. When the compound stimulus consisted of incompatible global and local features, responding to the global feature was more challenging. This is made evident by the larger deviation and higher maximum velocities when responding to the global feature than the local features on incongruent trials. Bilingual older adults had an overall higher maximum velocity than monolingual older adults.

Table 14

Means Scores (Standard Deviations) on the Mouse-Tracking Measures of the Global-Local Task in the Mixed Block with Older Adults

	Monolingual N = 36	Bilingual N = 38
Maximum Absolute Deviation (pxl)		
Global Congruent	57.53 (65.33)	74.31 (63.43)
Global Incongruent	248.78 (138.06)	266.81 (138.80)
Local Congruent	97.24 (80.87)	100.25 (67.57)
Local Incongruent	141.32 (103.75)	177.55 (118.54)
Global Neutral	4.56 (45.83)	33.94 (46.48)
Local Neutral	15.58 (57.85)	32.29 (44.33)
Initiation Time (ms)		
Global Congruent	199 (122)	203 (138)
Global Incongruent	241 (178)	249 (197)
Local Congruent	197 (133)	218 (166)
Local Incongruent	233 (168)	224 (168)
Global Neutral	205 (130)	199 (135)
Local Neutral	161 (108)	160 (103)
Maximum Velocity (co-ordinates)		
Global Congruent	6.73 (2.00)	7.94 (1.86)
Global Incongruent	7.79 (1.93)	9.30 (2.55)
Local Congruent	6.73 (1.88)	7.85 (2.02)
Local Incongruent	7.26 (2.19)	8.74 (2.79)
Global Neutral	7.80 (2.08)	8.70 (1.84)
Local Neutral	7.99 (2.29)	9.32 (2.02)

Eye-Tracking Analyses. Six monolingual older adults and 14 bilingual older adults were removed from the analyses due to errors in calibration. For the remaining participants, the mean calibration error for the monolingual and bilingual group were 0.72 (0.61) and 0.79 (0.54), respectively. As such, the final sample consists of 30 monolinguals and 24 bilinguals. Means and standard deviations for time spent looking at the stimulus by trial type and language group are shown in Table 15.

Time spent looking at the stimulus was subjected to a three-way repeated-measures ANOVA with trial type (congruent, incongruent, versus neutral) and level (global versus local) as within-subject variables, and group (monolingual versus bilingual) as the between-subject variable. There was a main effect of trial type, $F(2, 104) = 109.35$, $p < .001$, $\eta_p^2 = .68$, in which older adults spent more time looking at the stimulus in the incongruent trials ($M = 932$, $SE = 59$), followed by the congruent trials ($M = 754$, $SE = 48$), and then the neutral trials ($M = 483$, $SE = 27$), all $ps < .001$. There was also a level by trial type interaction, $F(2, 104) = 21.08$, $p < .001$, $\eta_p^2 = .29$ (Figure 25). On congruent trials, older adults spent more time looking at the stimulus for the local information than global information, $p < .001$. On incongruent trials, older adults spent more time looking at the stimulus for the global information than the local information, $p = .007$. There was no difference between the local and global information on the neutral trials, $p = .085$. The main effect of group, $F(1, 52) = 2.50$, $p = .12$, $\eta_p^2 = .046$, and the interaction effects with group, ps > .072, did not reach significance.

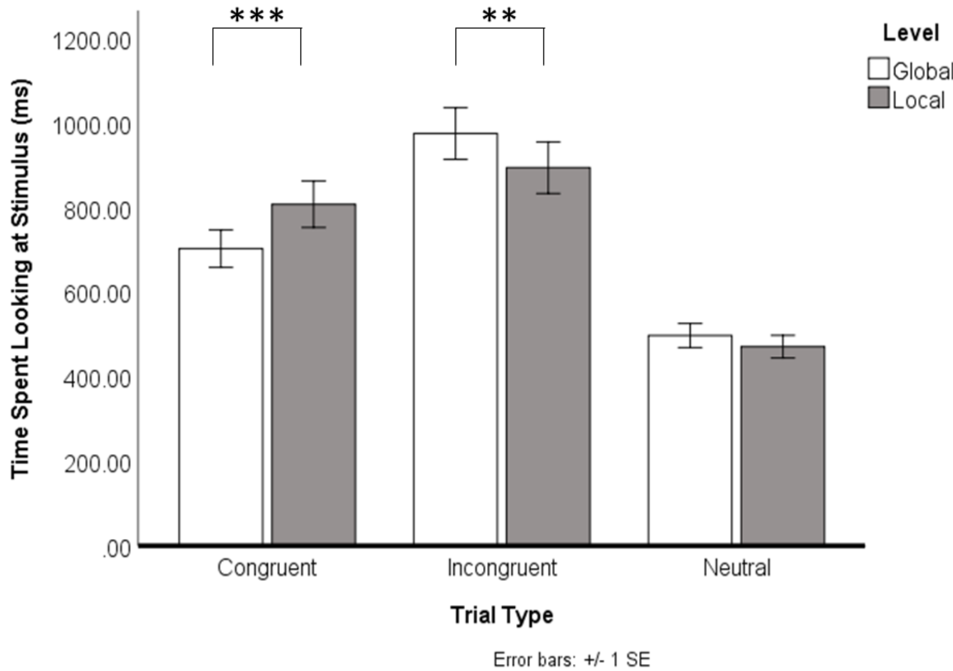

Figure 25. The means and standard error bars for the trial type by level interaction on time spent looking at stimulus (ms). $^{**}p < .01$, $^{***}p < .001$

Table 15

Mean Time Spent Looking at Stimulus (Standard Deviations) on the Global-Local Task in the Mixed Block for Older Adults

	Monolingual N = 30	Bilingual N = 24
Time Spent Looking at Stimulus		
Global Congruent	786 (326)	616 (317)
Global Incongruent	1052 (430)	893 (461)
Local Congruent	886 (391)	726 (411)
Local Incongruent	1011 (433)	774 (460)
Global Neutral	513 (160)	479 (255)
Local Neutral	500 (174)	440 (220)

The eye-tracking results in the older adult sample coincides with the mouse-tracking findings as well as the results from the reaction time and accuracy analyses. When the compound stimulus consisted of incompatible global and local features, participants spent more time looking at the stimulus when asked to attend to the global feature than local feature. Figure 26 contains a plot summarizing the time components from the standard, mouse-tracking, and eye-tracking analyses from the older adults on the global-local task.

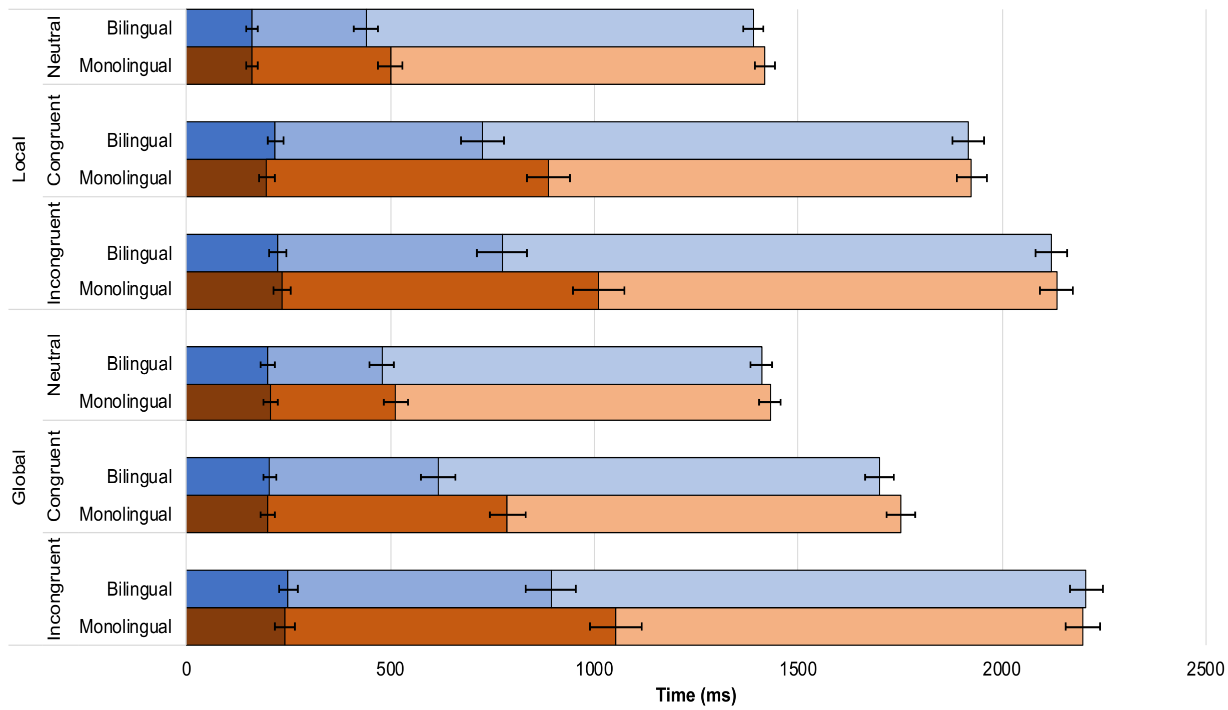

Figure 26. Summary of the time components from the standard (RT), mouse-tracking (initiation time), and eye-tracking (time spent looking at stimulus) analyses on the global-local task in older adults.

Pure Block Analysis. Results from the pure block are presented in Table 16. Pure blocks were analyzed in a two-way mixed factorial ANOVA. Level (global versus local) was treated as the within-subject variable and group (monolingual versus bilingual) as the between-group variable. All dependent variables (i.e., RT, accuracy, maximum absolute deviation, initiation time, maximum velocity, and time spent on stimulus) yielded no main effect of group, *F*s < 1, no main effect of level, *p*s > .14, and no group by level interaction, *p*s > .25.

Table 16

Means (Standard Deviations) on the Global-Local Task from the Trials in the Pure Block for Older Adults

		Monolingual N =36	Bilingual N = 38
Standard Measures	Reaction Time (ms)		
	Global Neutral	1294 (165)	1252 (158)
	Local Neutral	1285 (154)	1278 (182)
	Accuracy Rate (%)		
	Global Neutral	97.83 (8.35)	99.01 (2.07)
	Local Neutral	97.92 (8.32)	99.01 (2.31)
Mouse-Tracking Measures	Maximum Absolute Deviation (pxl)		
	Global Neutral	36 (57)	49 (60)
	Local Neutral	40 (74)	53 (64)
	Initiation Time (ms)		
	Global Neutral	161 (108)	160 (103)
	Local Neutral	167 (97)	148 (88)
	Maximum Velocity (co-ordinates)		
	Global Neutral	8.06 (2.30)	9.39 (2.37)
	Local Neutral	8.24 (2.18)	9.49 (2.61)
Eye-Tracking Measures	N	38	40
	Time Spent Looking at Stimulus		
	Global Neutral	403 (124)	352 (163)
	Local Neutral	397 (124)	327 (138)

Chapter 4: Discussion

The present dissertation combined eye-tracking and mouse-tracking to compare the timing of various cognitive processes related to selective attention in monolingual and bilingual younger and older adults. The combined methodologies provided a rich set of data to examine how bilingualism impacts decision-making, including the initiation, execution, and selection of a response. Four main findings emerged between language groups. First, standard analyses of mean reaction time and accuracy rate revealed no differences between monolinguals and bilinguals on both cognitive tasks within each age group. Second, young adult bilinguals took longer to initiate a response compared to young adult monolinguals on the global-local task, replicating previous mouse-tracking studies (Capani, 2019; Damian, Ye, Oh, & Yang, 2018; Incera & McLennan, 2016). On the oculomotor Stroop task, a similar pattern of longer initiation times for bilinguals is observed, but the effect is only marginal. Third, young adult bilinguals maintained the same level of performance throughout the task, whereas young adult monolinguals' performance changed from the first half to the second half of the oculomotor Stroop task. This finding is similar to the results by Bialystok, Craik, Klein, and Viswanathan (2004), where middle-aged bilinguals did not vary in their performance across the ten blocks. Finally, older adult bilinguals had an overall higher maximum velocity than older adult monolinguals when executing a response on both tasks, but both language groups had equivalent initiation times and reaction times.

Standard behavioral measures of central tendency (i.e., mean reaction time and accuracy) failed to capture group differences between monolinguals and bilinguals in young adults and older adults on each task. In the young adult group, this finding is not surprising given that undergraduate students are performing at their peak efficiency (Bialystok, 2006). Such high levels of performance by monolinguals and bilinguals reduces the amount of variability to detect reliable group differences. Therefore, tasks need to be more effortful and recruit greater attentional resources for the effects of bilingualism to emerge (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Friesen, Latman, Calvo, & Bialystok, 2015). It is possible that the cognitive tasks used in the dissertation were not sufficiently challenging for the younger adults, as made evident by the high accuracy rates. However, performance on the global-local task for the older adults was not at ceiling. When collapsing across conditions and language group, the overall reaction time and accuracy rate for older adults was 1800ms and 84.18%, respectively. Yet, equivalent behavioral performance was observed between monolinguals and bilinguals in the older age group. This finding is similar to that of Incera and McLennan (2018), who also reported no interaction between bilingualism and age on several measures, including reaction time and initiation time. Changes in motor skills along with reduced familiarity using a computer mouse may have obscured the effects of bilingualism in older adults. An alternative explanation is that the task was overly challenging for both groups since the incongruent trials elicited RTs longer than two seconds and accuracy rates less than 75%. As such, the requirements to use a computer mouse along with high demands placed on the cognitive system by the task could have depleted both groups of their attentional resources.

Reaction time and accuracy rates are only a summary of all cognitive operations. Recent studies examining the relationship between bilingualism and cognition using novel analytical techniques (e.g., Grundy, Chung-Fat-Yim, Friesen, Mak, & Bialystok, 2017; Ong, Sewell, Weekes, McKague, & Abutalebi, 2018; Zhou & Krott, 2018) have all converged on the important role of attention as the underlying mechanism for bilingualism in the interpretation of their results. For example, Ong et al. (2018) reported a shorter “non-decision time” for bilinguals than monolinguals, which encompasses all non-task-related processes that occur prior to a decision being made, such as perceptual encoding and attentional shifts. The authors concluded that bilinguals are better at “filtering out” distracting information, suggesting more advanced attentional control. The present dissertation expanded on these results by taking a methodological approach that combines two time-sensitive methodologies. The results from the mouse-tracking and eye-tracking measures similarly demonstrate that bilingualism impacts attention during decision-making.

The mouse-tracking results revealed that bilingualism impacted *both* congruent and incongruent trials. In young adults, there was a main effect of group on initiation time for the global-local task; whereas in older adults, there was a main effect of velocity on the global-local and oculomotor Stroop tasks. These findings reinforce the argument that inhibition is not the mechanism since congruent trials elicit no conflict. Bilinguals outperforming monolinguals on congruent trials is not all that surprising given that congruent trials simulate a communicative context that bilinguals also encounter. Depending on the degree of overlap between language systems, bilinguals are often processing cognates and translation-equivalents. In such instances, activation of the unwanted language actually facilitates performance. Therefore, congruent and incongruent trials on cognitive tasks, albeit non-verbal, are situations that bilinguals deal with during language processing. As such, bilinguals are more efficient at processing conflict and non-conflict trials than monolinguals due to their lifelong experience managing multiple languages.

Other researchers have proposed that language experience impacts cognitive processes involved in conflict monitoring (Abutalebi, Della Rosa, Green, Hernandez, Scifo, Keim, Cappa, & Costa, 2012; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Hilchey & Klein, 2011; Teubner-Rhodes, Bolger, & Novick, 2019) and the disengagement of attention (Grundy, Chung-Fat-Yim, Friesen, Mak, & Bialystok, 2017; Grundy & Bialystok, 2018); both of which can account for why bilinguals outperform monolinguals on all trial types. Both accounts are not mutually exclusive. Conflict monitoring theory posits that bilinguals are better at adapting to conflict and require fewer resources to outperform monolinguals (Abutalebi et al., 2012). Better adaptation to conflict may be because bilinguals are more rapid to disengage attention from previous trial information (i.e., task irrelevant information) since this information is no longer necessary (Grundy et al., 2017; Grundy & Bialystok, 2018). Bilinguals are thus able to direct attention to new task relevant information regardless of the trial type. Similarly, Zhou and Krott (2018) conducted ex-Gaussian analyses on RT distributions and found that bilinguals had a smaller tau (i.e., shorter RT distribution tails) than monolinguals irrespective of the trial type or task. The authors interpreted this to indicate that bilinguals are better at actively sustaining or engaging attention throughout the task. Failing to sustain attention on the task would lead to temporary lapses in attention and excessively longer RTs.

The analysis by block half for the oculomotor Stroop task revealed that in general, bilinguals maintained the same level of performance throughout the task, while monolinguals did not. Following the interpretation by Zhou and Krott (2018), this finding may be due to the bilinguals' ability to maintain the same level of attentional engagement throughout the task. For example, monolinguals had larger deviations from an "ideal" trajectory in the second half compared to the first half, which could be because of temporary lapses in attention. Unlike the study by Bialystok, Craik, Klein, and Viswanathan (2004), performance between groups did not converge in the second half. We expected differences between language groups in the first half but not the second half of the task. Instead, the largest differences were observed in the second half (e.g., maximum absolute deviation and look to target). Future studies should examine performance by block half to see if performance remains stable for bilinguals and not monolinguals.

The Bilingual Expertise Hypothesis

The Bilingual Expertise Hypothesis coined by Incera and McLennan (2016) proposes that bilinguals have become experts in dealing with conflict from the accumulated experience in managing competition between two active language systems. Similar to experts in other domains, it has been hypothesized that bilinguals will wait longer to initiate a response but carry out a faster and/or more efficient trajectory towards the target. Incera and McLennan (2016) predicted that bilinguals will behave differently than monolinguals in how they allocate their time and attention. Mouse-tracking revealed that young adult bilinguals delayed the initiation of a response compared to young adult monolinguals and that older adult bilinguals had a higher maximum velocity during their trajectory towards the correct response box than older adult monolinguals. However, there were no group differences in the efficiency of the participants' responses aside from the larger deviation in the second half for the monolingual young adults compared to the bilingual young adults on the oculomotor Stroop task. Incera and McLennan (2016) argued that bilinguals may use this time to scan their environment prior to executing a response to determine the most efficient path to achieve their goal. Differences in the eye-tracking data between language groups emerged in the amount of time older adults took to make a correct first look to the target. Bilingual older adults took longer to look at the target compared to older adult monolinguals.

The mouse movements in initiation time showcased by bilinguals is consistent with the expertise literature in other domains. Previous studies comparing novices to experts generally finds that experts are faster at solving problems than novices, partly due to their skills becoming more automatized which reduces the amount of cognitive load and processing demands to perform the task (Murphy & Wright, 1984). Such ease in processing allows for new information to be examined or new parts of the problem to be tackled. With increasing experience, experts notice features and patterns in their environment that are not noticed by novices and are better at teasing apart relevant from irrelevant information (Dreyfus & Dreyfus, 1986; Ericsson & Smith, 1991). However, even though experts produce faster responses than novices, research has shown that they spend more time during the initial stages of problem-solving, such as when solving physics problems (Larkin, McDermott, Simon, & Simon, 1980) or when master chess players play chess (de Groot, 1965). This is because experts spend more time evaluating and trying to understand the problem at a deeper level. In contrast, novices approach a problem more superficially, and do not easily make connections to previously acquired information, leading to more biased and erroneous decisions. During the initial stages, experts not only plan their movements, but also set the parameters surrounding *how* the movement will be executed (i.e., velocity, force, and direction). A longer initiation time helps with the pre-planning of movement and the subsequent control of movement. Furthermore, research has shown that the expertise advantage can be found in visual anticipation, pattern recognition, and decision making (Panchuk & Vickers, 2013). However, on more mundane tasks, experts spend the same amount of time as novices to plan their behavior, which may be the reason why the oculomotor Stroop task yielded no differences in initiation time in either age group; although a trend in the right direction was observed for young adults.

Other examples of longer initiation times come from everyday applications of research. Experts develop an optimal gaze behavior that becomes more refined over time, which allows them to extract which areas of their environment are most relevant to the task goals, but also enables them to know *when* to attend to certain pieces of information. In other words, during this time, the motor system uses the information from the visual system to produce accurate and precise movements. For example, highly skilled golfers made longer and steadier fixations on the ball and the target just before, as well as during the motion of striking the golf ball (Vickers, 1992). Novice golfers spent the same amount of time focusing on different areas of the scene, such as the ball, club, target, and surface. In a study by Shank and Haywood (1987), novice baseball players focused on the pitcher's eyes and arm when preparing to bat, while expert baseball players fixated only on the pitcher's point of release. Longer duration during the planning stage of decision-making has been shown in across multiple sports, including basketball free throws, soccer goaltending, throwing darts, and so on (see Wilson, Causer, & Vickers, 2015 for a review). In another study, using a virtual command post environment, Kobus, Proctor, Bank, & Holste (2000) had highly experienced marines and beginner marines observe a tactile situation. The objective was to formulate a battle plan as quickly as possible. While marines in the high experience group spent more time assessing the situation than the marines in the low experience group, the selection for the course of action was significantly faster for the high experience group. Formulating a plan without properly evaluating and assessing all viable options can have dire consequences, such as in the example with the marines during combat.

In contrast to the young adult data, differences between language groups emerged in velocity for older adults rather than initiation time. Incera and McLennan (2016) described the expertise pattern of behavior as longer initiation time but more efficient execution towards the response box. The word "efficient" can be interpreted in multiple ways, including smaller curvature in trajectories (smaller slopes) or a higher velocity towards the correct response box to indicate a high degree of certainty in response selection. However, not only was a high maximum velocity reported for neutral trials, this was also observed for incongruent trials, which could suggest that older adult bilinguals are spending more time fixating on the stimulus and are delaying the initiation of their response than monolinguals. If this is the case, the results would coincide with the young adult findings. On the contrary, we find that older adult bilinguals generally had shorter initiation times and spent less time fixating on the stimulus compared to their monolingual counterparts, although not significant. Therefore, future studies should untangle why older adult bilinguals have a faster velocity. One possibility is that older adult bilinguals are less certain in their response. However, theoretically, there is no reason to assume that bilingualism would impact the degree of confidence in decision-making.

Although direct comparisons between ages were not made, the amount of time spent looking at each areas of interest in each age group were distinctive. Young adults spent more time looking at the stimulus than the target, while older adults spent more time looking at the target than the stimulus. Similar to what was proposed for the older adult bilinguals, there is the possibility that older adults are second guessing their response and as a result are spending more time looking at the target (and the distractor on the oculomotor Stroop task) compared to young adults. In addition, the older adults are looking at the distractor more often, as can be seen in the greater proportion of looks to the distractor in older adults compared to younger adults. The development of executive functions follows an inverted U-shaped pattern, such that they increase rapidly in early childhood, reach maturation in young adulthood, and then gradually decline in older adulthood (Mayr, Spieler, & Kliegl, 2001; McDowd, & Shaw, 2000; Zelazo & Müller, 2002 for a review). Older adults may be less efficient at filtering out unwanted distracting information because of the decline in selective attention.

Task Effects and Difficulty

The oculomotor Stroop task was used to assess cognitive performance and produced reaction times that were substantially faster than those observed in the global-local task. With a mean reaction time ranging from 800-898ms for young adults and 1200-1340ms for older adults as well as a mean accuracy rate for both age groups above 90%, one could argue that the oculomotor Stroop task does not elicit conflict since participants were essentially required to perform a color-matching task. Despite ceiling performance, the incongruent trials were more challenging than congruent trials. Participants took significantly longer to respond, had larger deviations, and made more looks to the stimulus on incongruent trials than congruent trials.

However, the proportion of looks to the distractor was very small, indicating that the distractor did not elicit a high degree of competition. The version of the oculomotor Stroop task used in the present study is similar to Singh and Mishra's (2013) version, except the response boxes were located in the corners rather than perpendically (up, down, left, or right). Although no button press responses were made by low-proficiency and high-proficiency bilinguals, Singh and Mishra (2013) reported a significant congruency effect of 34ms when examining the difference in "saccadic reaction time", which was calculated as the difference in time between stimulus onset and a saccade towards the correct color patch for incongruent and congruent trials. Furthermore, the reaction times obtained in this task were similar to the reaction times on the flanker task from the mouse-tracking study by Damian, Ye, Oh, and Yang (2018). However, it should be noted that Damian et al. (2018) found differences between language groups only on the Simon and non-verbal Stroop task, which had reaction times around 1300ms. Hence, modifying tasks to include competitors that automatically elicit conflict and require active engagement of attentional resources to resolve conflict are needed.

The global-local task was a more demanding task as seen in the longer response times generated by participants in both age groups (RTs ranged between 914–1521ms in young adults and 1390–2207ms in older adults). Consistent with previous studies on typically developing adults (Navon, 1977), participants in the present study were faster to perceive global features than local features when the trials were congruent and neutral. As expected, the incongruent trials produced longer RTs, longer initiation times, larger deviations, higher maximum velocities, and longer stimulus evaluation time compared to the congruent and neutral trials. The usual finding is that hierarchical or compound stimuli produces a "global advantage", such that global level features interfere with the identification of local level features (Love, Rouder, & Wisniewski, 1999; Navon, 1977). Thus, attention is typically directed towards the processing of holistic aspects of a stimulus rather than the discrete individual components of an object or scene. The present study found a local precedence effect in younger and older adults. Participants in both age groups performed better on incongruent trials when responding to the local features than the global feature. The local incongruent trial produced faster reaction times, smaller deviations from the ideal trajectory, more accurate responses, and lower maximum velocities than global incongruent trials.

The global advantage or global precedence effect can be impacted by participant characteristics, such as culture (Davidoff, Fonteneau, & Fagot, 2008) or age (Lux, Marshall, Thimm, & Fink, 2008; Müller-Oehring, Schulte, Raassi, Pfefferbaum, & Sullivan, 2007; Oken, Kishiyama, Kaye, & Jones, 1999). With increasing age, studies have reported that older adults show a local bias or local precedence effect (e.g., Polster & Rapcsak, 1994; but see Georgiou-Karistianis, Tang, Mehmedbegovic, Farrow, Bradshaw, & Sheppard, 2006; Roux & Ceccaldi, 2001 for a global precedence effect in older adults). Oken and colleagues (1999) attributed the decline in global-level processing to older adults' narrowing in attentional field. Furthermore, Müller-Oehring et al. (2007) reported that larger local precedence effects were correlated with age and smaller areas of the genu in the corpus callosum, which has been shown to mediate global and local processing through processes of inhibition and selective attention.

A local precedence effect was also observed for young adults. Previous studies have shown that stimulus parameters (i.e., ratio of global to local features; Kimchi, 1992; Yovel, Yovel, & Levy, 2001), visual angle (Kinchla & Wolfe, 1979), and stimulus presentation time (Navon, 1977; Mills & Dodd, 2014; 2016) can impact whether global features or local features will be more salient. The paradigm used for the global-local task had the stimuli on the screen until the participant made a response or for a maximum duration of 3000ms. The long stimulus onset asynchrony (SOA) was implemented to provide older adults sufficient amount of time to process the stimulus and execute a mouse movement. However, the additional time may have afforded participants the time to process beyond the global information. Processing at the global level tends to occur during early perceptual analysis and persists for a shorter duration than local level processing (Luna, 1993; Paquet & Merikle, 1984). Mills and Dodd (2014; 2016) manipulated the SOA from 250, 500, to 750ms. The authors reported a global cueing effect at short SOAs (250ms), consistent with a global bias, and a local cueing effect at longer SOAs (750ms), indicative of a local bias. Since the stimulus was presented on the screen for a long duration, it is likely that participants began shifting their attention towards the local features. Presenting the compound stimuli at varying SOAs but allowing for responses to be made after the stimulus is presented, provides insight into when the shift from global to local level processing occurs, and whether the shift is impacted by language experience. The occurrence of an earlier shift in bilinguals might explain the smaller global precedence effect found for bilingual children (Cottini, Pieroni, Spataro, Devescovi, Longobardi, & Rossi-Arnaud, 2015) and adolescents (Christoffels, de Haan, Steenbergen, van den Wildenberg, & Colzato, 2015).

Finally, the degree of saliency between local and global features can bias attention towards one feature. If the image is composed of few large elements, then the individual parts become more salient and observers are more likely to perceive the local features. Increasing the number of elements and decreasing their size increases the likelihood that a unified form is perceived (Kimchi & Palmer, 1982; Martin, 1979; Yovel, Yovel, & Levy, 2001). It is possible that the stimuli used for the local elements were not dense enough, making it difficult to perceive the holistic image.

Limitations and Considerations for Future Studies

Baseline Task. Incera and McLennan (2018) expressed the importance of including a baseline task for mouse-tracking in order to account for differences in motor movements between language groups. Equivalence in performance between monolinguals and bilinguals on the baseline task ensures that the results found on the cognitive tasks for the mouse-tracking measures is attributed to the cognitive processes elicited by the task and not due to difficulties using a mouse. The baseline task was particularly useful to screen older adult participants who expressed during the pre-screen phone interview that they were comfortable using a mouse, but upon performing the baseline task, it was clear that they had never used a mouse before. This occurred on two separate occasions. These participants were not tested further, and their data was discarded. We thanked them for their time, debriefed them about the purpose of the study, and they received financial compensation. Therefore, we agree with Incera's (2018) plea for a baseline measure in all future mouse-tracking studies. Through the baseline task, we were able to determine that older adults were in fact using the mouse differently than younger adults and thus the two age groups were analyzed separately.

In retrospect, the baseline task should have also included trials with four response options, similar to the oculomotor Stroop task. This could allow us to determine whether there are differences in mouse movements in a downward-left or downward-right motion, and not simply just an upward-left or upward-right motion. The four-option baseline task would have put into perspective whether the oculomotor Stroop task involves additional processing aside from simple selection or matching.

Mouse-Tracking. Research in the area of bilingualism using mouse-tracking is still novel. There are several factors that need to be considered prior to using mouse-tracking in bilingualism as well as aging research. One key observation is that mouse-tracking adds approximately 500ms to the response time due to the requirement to move the mouse towards a response box rather than simply pressing a button. Damian and colleagues (2018) found that the RTs were twice as long when mouse-tracking was used on the flanker, Stroop, and Simon task compared to the button-press RTs from the study by Zhou and Krott (2016). It is possible that the global-local and oculomotor Stroop tasks may also yield RTs double in duration. This remains unknown since neither task have been previously used within these age groups to compare monolinguals and bilinguals. James, Humphrey, Gati, Menon, and Goodale (2000) attempted to slow down processing of object recognition using an "unmasking" technique, in which the picture of an object is gradually revealed over a 46 second period. Combined with fMRI, the authors were able to separately examine pre- and post-recognition processing and found differences in level of activation at each stage. Although slowing down performance can provide important information about the stages of processing, it remains a possibility that using mouse-tracking may be the reason why no differences between language groups were found in overall RT.

Furthermore, because mouse-tracking is self-paced, there is less residual interference from the previous trial. Bilinguals have been shown to be better at disengaging from previous trial information (Grundy, Chung-Fat-Yim, Friesen, Mak, & Bialystok, 2017). Although not explicitly stated in the instructions, participants can take a break between trials when prompted to click the START button. For these reasons, the cognitive processes engaged are less automatic and the attentional system can reset in both language groups in order to efficiently deal with the upcoming trial.

In older adults, lack of fluency using a computer mouse may have contributed to the null findings between language groups. Incera (2018) noted that "older adults might take longer to initiate mouse movements regardless of their language background (p. 4)." To circumvent this issue in older adults, an alternative approach that provides similar output as mouse-tracking is reach-tracking or finger-tracking (Dotan, Pinheiro-Chagas, Al Roumi, & Dehaene, 2019). Reach-tracking has been used with children to examine dissociable processes underlying cognitive performance (e.g., Erb, Moher, Sobel, & Song, 2016; Erb, Moher, Song, & Sobel, 2017). Reach-tracking and finger-tracking both measure the path a participant's hand makes towards a target. Similar to mouse-tracking, the initiation of a response is often made prior to resolving conflict between alternatives and the degree of curvature indexes the extent to which competing responses are co-activated. Due to the increase use of touchpads among children and the elderly, finger-tracking may be a potential new avenue for future use.

When designing tasks for specific methodologies, it is important to be cognizant of how certain task parameters implemented for one methodology might influence the other. For example, for the global-local task, the response boxes contained the words *LEFT* and *RIGHT*. Because these labels never changed, participants did not have to look at the response boxes in order to make a response. Hence, participants only fixated on the stimulus. When combining mouse-tracking and eye-tracking, if the research question involves examining the amount of looks to the competitor for example, then including stimuli that compete with one another in each response box is vital. Future studies integrating both mouse-tracking and eye-tracking should avoid using tasks that involve a left or right response, such as the flanker task or Simon task, because in such cases the mouse-tracking measures will often take precedence over the eye-tracking measures.

Eye-Tracking. Individual differences in older adults impacted calibration and the quality of the eye-tracking data. The majority of older adults wore glasses. Research has shown that depending on the type of lens, glasses produce less precise data than no visual aids at all (Nystrom, Andersson, Holmqvist, & van de Weijer, 2012). The reason is that some glasses contain an anti-reflection or anti-scratch coating that absorbs some of the infrared light, which in turn produces a less distinct contrast between the pupil and iris. Therefore, the eye-tracker has a difficult time detecting the pupil. Accuracy also deteriorates with time as participants move their head or body over the course of the experiment. Some of the older adults were less comfortable using a mouse and looked at the mouse on some trials. Other individual differences in older adults that impact the quality of eye-tracking data include droopy eyelids, cataracts or watery eyes (Isaacowitz, Wadlinger, Goren, & Wilson, 2006). In a study that examined gaze behavior in older and younger adult looking at emotional faces, only 61% of the older adult participants were included in the analysis due to an excessive loss of eye-tracking data (excessive blinks or body movements; Chaby, Hupont, Avril, Boullay, & Chetouani, 2017).

Although the low-cost EyeTribe eye-tracker has been shown to perform well against other established and more expensive eye-trackers (Dalmajier, 2014; Titz, Scholz, & Sedlmeier, 2018), a limitation of the eye-tracker was the low-sampling rate. With a sampling rate of 30 Hz, the eye-tracker records gaze co-ordinates once every 33ms. A sampling rate of 30 Hz may have contributed towards the loss of data. In addition, Ooms, Dupont, Lapon, and Popelka (2015) found that the EyeTribe eye-tracker produced large deviations at the edge of the screen, in which the lower edge produced near zero recordings for the y-value and for the right edge, there were near zero recordings for the x-value. This is a concern for mouse-tracking studies since the response boxes are typically located close to the edge of the screen.

An eye-tracker with a higher sampling frequency opens up the possibility for eye-movements beyond fixation to be examined. For example, analyses on saccadic latency would enable questions regarding disengagement of attention to be examined more thoroughly. If bilinguals were faster to make a saccade towards the target than monolinguals, this would suggest that bilinguals are better at disengaging attention from the stimulus and re-directing their attention towards the correct response.

Triangulation of Time-Sensitive Methodologies

Incera (2018) proposed the possibility of integrating all three time-sensitive methodologies (i.e., eye-tracking, mouse-tracking, and event-related potentials) into one study because the rich set of data will further our understanding of how bilingualism shapes the allocation of attentional resources, the engagement and disengagement of attention, as well as the efficiency of selective attention. Beyond the issues previously discussed, it is important to understand how the electrophysiological signal is impacted by eye-movements, eye-blinks, and muscle activity. The eye consists of an electrical gradient that is positive at the front and negative at the back. When the eyelid moves, a voltage deflection occurs that modulates the electrical potentials of the surrounding region. An eyeblink is characterized by a 50-100 microvolt deflection that lasts around 200–400ms (Luck, 2014). Furthermore, when the eyes move, the voltage gradient across the scalp shifts, becoming more positive at sites that the eyes have move towards (Hillyard & Galambos, 1970). Some subjects cannot easily control their eye-blinks and eye-movements (such as children), making it difficult to obtain a sufficient number of artifact-free trials. Furthermore, some experimental paradigms have eye-movements as an integral measure (i.e., eye-tracking), and rejecting these artifacts would undermine the study. Muscle tension or head movements that may arise from having to continuously move a mouse for every trial can distort the EEG signal with high frequency noise or drift. Although sophisticated artifact rejection techniques have been developed over the years, such as independent components analysis (Jung et al., 2000), reducing the occurrence of an artifact is always better than rejecting trials or distorting the EEG signal. Therefore, careful consideration of these issues is important in order for comparisons between methodologies can be appropriately made.

How does the longer initiation time by bilinguals relate to the earlier N2 and P3 components in bilinguals that is commonly observed on executive control tasks (see Grundy, Anderson, & Bialystok, 2017)? Even though bilinguals have been shown to delay the initiation of their response, the delay occurs in the early stages of decision-making (between 100-250ms). The extra time taken to evaluate the stimulus (i.e., longer initiation time) could be contributing towards the earlier emergence of the processes related to conflict monitoring (N2: 200-400ms) and attentional control (P3: 300-600ms). Since mouse-tracking increases the amount of time required to select a response compared to button press, it is possible that even earlier ERP components that are related to attention may be observed. For example, the P2 is a positive-going peak that occurs at frontal or fronto-central electrode sites around 150-250ms post-stimulus onset. The P2 has been thought to reflect greater involvement of selective attention (Luck & Hillyard, 1994; Potts, 2004). Since selective attention has been proposed to serve as a model of bilingualism, combining ERP and mouse-tracking will shed some light on the earlier processes.

Conclusion

The present study provided a close examination into the effect of bilingualism on attention using conventional behavioral methods of reaction time and accuracy rates along with more time-sensitive methodologies, namely eye-tracking and mouse-tracking. To our knowledge, this is the first study to combine these methods in the non-verbal domain to assess how language experience impacts performance. Recently, the effects of bilingualism have been called into question leading to an on-going debate on the “bilingual advantage”. Some studies have reported better performance by bilinguals, but a substantial number of studies report no group differences. A number of factors may contribute to the mixed findings, including the categorization of participants, the tasks used, and the analyses performed. When tasks are too simple, group differences are unlikely to emerge because the attentional control system that underlies the bilingual advantage is not engaged. Relying solely on outcome measures like mean reaction times and accuracy rates overlooks the cognitive processes that occur between the time a stimulus is presented, and a response is selected. For this reason, the present study used mouse-tracking and eye-tracking to gain a detailed analysis of performance in real time. Young adult bilinguals delayed the initiation of a response on the global-local task; a behavior typically exhibited by experts in other domains. The delay in initiation time was proposed to occur because bilinguals allocate their attention differently than monolinguals. However, eye-tracking revealed similar gaze behavior across language groups. Amongst older adults, bilingualism impacted velocity, such that bilinguals reached a higher maximum velocity. Although this measure may be indirectly indicative of a more "efficient" trajectory towards the target, the lack of any differences in initiation time and fixation to the stimulus would suggest otherwise. More research is needed that combines these methodologies in order to understand the complex relationship between bilingualism and attention as revealed by the findings from mouse-tracking and eye-tracking.

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Footnote

[1] Due to the large age range in the young adult sample (17-35), an outlier analysis was performed. The analysis revealed that two monolinguals and one bilingual were 3 SDs above the young adult sample's mean age. Pearson correlations between age and all dependent variables (RT, accuracy, eye-tracking, and mouse-tracking) of the global-local and oculomotor Stroop task were performed. On the global-local task, age negatively correlated with accuracy on the local incongruent condition, $r(81) = -.22$, $p = .051$. No other correlations for the global-local task reached significance, all *p*s > .11. On the oculomotor Stroop task, age correlated positively with maximum absolute deviation for the incongruent trial in the second half of the task, $r(87) = .22$, $p = .042$. Furthermore, age correlated with proportion of time spent looking at the stimulus for the congruent trials in the first, $r(86) = -.29$, $p = .007$, and second half of the task, $r(86) = -.27$, $p = .012$. Lastly, age correlated with the proportion of time spent looking at the stimulus for the incongruent trials in the second half of the task, $r(86) = -.23$, $p = .032$. None of the other correlations reached significance, *p*s > .059.

Appendix

Appendix A: Young Adult Language and Social Background Questionnaire (Anderson, Mak, Keyvani Chahi, & Bialystok, 2018)

YAV Reference ID ____________________

Lifespan Cognition and Development Laboratory
Ellen Bialystok, Ph.D., Principal Investigator
Department of Psychology, York University

Language and Social Background Questionnaire

Today's Date: ____________________
Day Month Year

1. Sex: Male ☐ Female ☐
2. Occupation/Student Status (i.e. FT/PT, current year of study): ____________________
3. Handedness: Left ☐ Right ☐ 4. Date of Birth: ____________________
Day Month Year
5. Do you play first-person shooting (FPS)/action video games? **Yes** ☐ **No** ☐
   If **yes**, on average how many hours do you play per week? ____________________
6. Do you have hearing problems? **Yes** ☐ **No** ☐
   If **yes**, do you wear a hearing aid? **Yes** ☐ **No** ☐
7. Do you have vision problems? **Yes** ☐ **No** ☐
   If **yes**, do you wear glasses or contacts? **Yes** ☐ **No** ☐
   Is your vision corrected to normal with glasses or contacts? **Yes** ☐ **No** ☐
8. Are you colour blind? **Yes** ☐ **No** ☐
   If **yes**, what type? ____________________
9. Have you ever had a head injury **Yes** ☐ **No** ☐
   If **yes**, please explain: ____________________
10. Do you have any known neurological impairments? (e.g., epilepsy etc) **Yes** ☐ **No** ☐
    If **yes**, please indicate: ____________________
11. Are you currently taking any psychoactive medications? **Yes** ☐ **No** ☐
    If **yes**, please indicate: ____________________

YAV Reference ID ______________________

12. Please indicate the highest level of education and occupation for each parent:

Mother			Father		
1.	_____	No high school diploma	1.	_____	No high school diploma
2.	_____	High school diploma	2.	_____	High school diploma
3.	_____	Some post-secondary education	3.	_____	Some post-secondary education
4.	_____	Post-secondary degree or diploma	4.	_____	Post-secondary degree or diploma
5.	_____	Graduate or professional degree	5.	_____	Graduate or professional degree
Occupation:		______________________	Occupation:		______________________
First Language:		______________________	First Language:		______________________
Second Language:		______________________	Second Language:		______________________
Other Language:		______________________	Other Language:		______________________

13. Were you born in Canada? **Yes** ☐ **No** ☐

If **no**, where were you born? ______________________________

When did you move to Canada ______________________________

Year

14. Have you ever lived in a place where English is not the dominant communicating language? **Yes** ☐ **No** ☐

		From	**To**
If **yes**, where and for how long?	1. ______________________	__________	__________
	2. ______________________	__________	__________
	3. ______________________	__________	__________
		Year	**Year**

YAV Reference ID ____________________

Language Background

15. List all the language and dialects you can speak including English, ***in order of fluency***:

Language	Where did you learn it?	At what age did you learn it? (If learned from birth, write age "0")	Were there any periods in your life when you did not use this language? Indicate duration in months/years.
1.________	☐**Home** ☐**School** ☐**Community** ☐**Other:** ________		
2.________	☐**Home** ☐**School** ☐**Community** ☐**Other:** ________		
3.________	☐**Home** ☐**School** ☐**Community** ☐**Other:** ________		
4.________	☐**Home** ☐**School** ☐**Community** ☐**Other:** ________		
5.________	☐**Home** ☐**School** ☐**Community** ☐**Other:** ________		

16. Please indicate how often you heard or used a ***non-English language*** in the following life stages, both inside and outside of the home. If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

		Always English 0	5	Always non-English 10
16.1	Infancy			
16.2	Preschool age			
16.3	Primary School age			
16.4	High school age			
16.5	College/University age			

Relative to a highly proficient speaker's performance, rate your proficiency level on a scale of 0-10 for the following activities conducted in English and your other language(s).

17.1 **English**

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

17.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in English?

	Never English 0	5	Always English 10
Speaking			
Listening			
Reading			
Writing			

18.1 **Other Language:** ____________

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

18.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in this language?

	Never this language 0	5	Always this language 10
Speaking			
Listening			
Reading			
Writing			

19.1 **Other Language:** ____________

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

19.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in this language?

	Never this language 0	5	Always this language 10
Speaking			
Listening			
Reading			
Writing			

20.1 **Other Language:** ____________

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

20.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in this language?

	Never this language 0	5	Always this language 10
Speaking			
Listening			
Reading			
Writing			

YAV Reference ID ______________________

The following questions refer to the language you know best aside from English.
If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

21. How well are you able to engage in an informal conversation about daily routines and activies in your best non-English language?

No ability at all — Perfect Ability
0 5 10

22. How well are you able to talk about work/school in your best non-English language?

No ability at all — Perfect Ability
0 5 10

23. How well are you able to understand a TV show or movie in your best non-English language without subtitles?

No ability at all — Perfect Ability
0 5 10

24. How well are you able to understand the news on TV or the radio in your best non-English language?

No ability at all — Perfect Ability
0 5 10

25. How well are you able to talk about current events and items in the news in your best non-English language?

No ability at all — Perfect Ability
0 5 10

26. How well are you able to complete a banking or government transaction in your best non-English language?

No ability at all — Perfect Ability
0 5 10

27. During a debate or an emotional conversation in your best non-English language, how well are you able to express your opinions or emotions?

No ability at all — Perfect Ability

0 — 5 — 10

28. How well can you switch between formal (official) and informal (slang) styles of speech in your best non-English language?

No ability at all — Perfect Ability

0 — 5 — 10

29. How well are you able to act as an informal translator between English and your best non-English language for a new immigrant who speaks no English?

No ability at all — Perfect Ability

0 — 5 — 10

30. How well are you able to tell children's stories/fairy tales in your best non-English language?

No ability at all — Perfect Ability

0 — 5 — 10

YAV Reference ID ____________

Community Language Use Behaviour

31. Please indicate how often you use a non-English language with the following people. If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

		Always English 0		5		Always non-English 10	N/A
31.1	Parents						☐
31.2	Siblings						☐
31.3	Grandparents						☐
31.4	Other Relatives						☐
31.5	Partner						☐
31.6	Roommate(s)						☐
31.7	Neighbours						☐
31.8	Friends						☐

32. Please indicate how often you use a non-English language in the following situations. If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

		Always English 0		5		Always non-English 10	N/A
32.1	Home						☐
32.2	School						☐
32.3	Work						☐
32.4	Social activities (e.g. hanging out with friends, movies)						☐
32.5	Religious activities						☐
32.6	Extracurricular activities (e.g. hobbies, sports, volunteering, gaming)						☐
32.7	Shopping/ Restaurants/ Other commercial services						☐
32.8	Health care services/ Government/ Public offices/ Banks						☐

33. Please indicate how often you use a non-English language when performing the following activities. If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

		Always English 0	5	Always non-English 10	N/A
33.1	Reading				☐
33.2	Emailing				☐
33.3	Texting				☐
33.4	Social media (e.g. Facebook, Twitter etc.)				☐
33.5	Writing shopping lists, notes, etc.				☐
33.6	Watching TV/ listening to radio				☐
33.7	Watching movies				☐
33.8	Browsing on the Internet				☐
33.9	Praying				☐

34. Some people switch between the languages they know within a single conversation (i.e. while speaking in one language they may use sentences or words from the other language). This is known as "language-switching". Please indicate how often you engage in language-switching. If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

		Never language switch 0	5	Always language switch 10
34.1	With parents and family			
34.2	With friends			
34.3	On social media (e.g. Facebook, Twitter)			

35. Please indicate your agreement with the following statements regarding language use in your community.

		Strongly Disagree	Somewhat Disagree	Somewhat Agree	Strongly Agree
35.1	I mix my languages most of the time when interacting with people in my community.	☐	☐	☐	☐
35.2	I prefer to speak to people in English even if we speak a common non-English language.	☐	☐	☐	☐
35.3	I only use my other language(s) when it is necessary (i.e. with people who have difficulties understanding English.)	☐	☐	☐	☐
35.4	Using languages other than English is viewed positively in my community.	☐	☐	☐	☐
35.5	Mixing languages in the same conversation is viewed positively in my community.	☐	☐	☐	☐
35.6	I feel comfortable using my other language(s) in public.	☐	☐	☐	☐

Thank you for participating!

Appendix B: Older Adult Language and Social Background Questionnaire (Anderson, Hawrylewicz, & Bialystok, in press)

OAV Reference ID: ______________

YORK U UNIVERSITÉ UNIVERSITY

Lifespan Cognition and Development Laboratory
Ellen Bialystok, Ph.D., Principal Investigator
Department of Psychology, York University

Language and Social Background Questionnaire

Today's Date: ______________
Day Month Year

1. Date of Birth: ______________
Day Month Year

2. Sex: Male ☐ Female ☐ 3. Handedness: Left ☐ Right ☐

4. Do you have hearing problems? **Yes** ☐ **No** ☐
   If **yes**, do you wear a hearing aid? **Yes** ☐ **No** ☐
5. Do you have vision problems? **Yes** ☐ **No** ☐
   If **yes**, do you wear glasses or contacts? **Yes** ☐ **No** ☐
   Is your vision corrected to normal with glasses or contacts? **Yes** ☐ **No** ☐
6. Are you colour blind? **Yes** ☐ **No** ☐
   If **yes**, what type? ______________
7. Have you ever had a head injury **Yes** ☐ **No** ☐
   If **yes**, please explain: ______________
8. Do you have any known neurological impairments? (e.g., epilepsy etc) **Yes** ☐ **No** ☐
   If **yes**, please indicate: ______________
9. Are you currently taking any psychoactive medications? **Yes** ☐ **No** ☐
   If **yes**, please indicate: ______________
   Further Comments: ______________

OAV Reference ID: ______________

12. Please indicate your highest level of education and occupation:

No high school diploma	High school diploma	Some post-secondary education	Post-secondary degree or diploma	Graduate or professional degree
☐	☐	☐	☐	☐

Occupation: ____

13. Were you born in Canada? **Yes** ☐ **No** ☐

If **no**, where were you born? ______________________________

When did you move to Canada ______________________________

Year

14. Have you ever lived in a place where English is not the dominant communicating language? **Yes** ☐ **No** ☐

		From	**To**
If **yes**, where and for how long?	1. ______________________	____________	____________
	2. ______________________	____________	____________
	3. ______________________	____________	____________
		Year	**Year**

Language Background

15. List all the language and dialects you can speak including English, ***in order of fluency***:

Language	Where did you learn it?	Where did you use it?	At what age did you learn it? (If learned from birth, write age "0")	Were there any periods in your life when you did not use this language? Indicate duration in months/years.
1. ____________	☐Home ☐School ☐Community ☐Other: ____________	☐Home ☐School ☐Community ☐Other: ____________		
2. ____________	☐Home ☐School ☐Community ☐Other: ____________	☐Home ☐School ☐Community ☐Other: ____________		
3. ____________	☐Home ☐School ☐Community ☐Other: ____________	☐Home ☐School ☐Community ☐Other: ____________		
4. ____________	☐Home ☐School ☐Community ☐Other: ____________	☐Home ☐School ☐Community ☐Other: ____________		
5. ____________	☐Home ☐School ☐Community ☐Other: ____________	☐Home ☐School ☐Community ☐Other: ____________		

Relative to a highly proficient speaker's performance, rate your proficiency level on a scale of 0-10 for the following activities conducted in English and your other language(s).

16.1 **English**

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

16.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in English?

	Never English 0	5	Always English 10
Speaking			
Listening			
Reading			
Writing			

17.1 **Other Language:** ______________________________

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

17.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in this language?

	Never this language 0	5	Always this language 10
Speaking			
Listening			
Reading			
Writing			

18.1 **Other Language:** ______________________________

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

18.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in this language?

	Never this language 0	5	Always this language 10
Speaking			
Listening			
Reading			
Writing			

19.1 **Other Language:** ______________________________

	No Proficiency 0	5	High Proficiency 10
Speaking			
Understanding			
Reading			
Writing			

19.2 Of the time you spend engaged in each of the following activities, how much of that time is carried out in this language?

	Never this language 0	5	Always this language 10
Speaking			
Listening			
Reading			
Writing			

20. Please indicate how often you use a non-English language in daily life.
If you do not know any language(s) other than English, fill in all the questions with 0, as appropriate.

		Always English 0	5	Always non-English 10
20.1	Language spoken to family members			
20.2	Language spoken to friends			
20.3	Language for watching TV and movies			
20.4	Language for reading books, magazines etc.			
20.5	Language used for writing (e.g. shopping lists, notes, etc.)			
20.6	Language used in the community (e.g. social activities, shopping, health care etc.)			
20.7	Language used for religious activities			

21. **Global Self-Assessment**

Overall, how would you describe your level of bilingualism or multilingualism? Please indicate

Monolingual — Bilingual/Multilingual

Thank you for participating!

Appendix C: Shipley-2 Vocabulary Scale

Instructions:

Circle the word that has the same meaning as the one written in capital letters. If you want to change an answer, draw an X through your first answer and then circle your new choice. Please press hard when marking your responses.

Sample Slide:

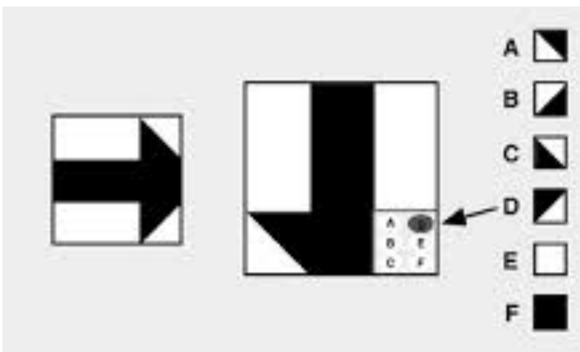
LARGE	red	big	silent	wet

Appendix D: Shipley-2 Blocks Pattern Scale

Instructions:

You will see a template pattern *(point to template)* and next to it you will see the same pattern with a missing piece *(point to middle pattern)*. Use the template to decide which of the four options on the right *(point to the options on the right)* would complete the pattern. Fill in only one bubble in the missing piece. As you move forward in the task it will become more difficult by having more than one missing piece, rotations in the image, or parts that are shaded off. Please do not make any other marks on the page such as drawing on the patterns.

Sample Slide:



Appendix E: Informed Consent Form

INFORMED CONSENT
Language Experience and Attentional Control

Researcher: Dr. Ellen Bialystok

Sponsor: York University
This research has been approved by the Human Participants Review Subcommittee (HPRC) of York University for compliance with York University Senate Ethics policy.

Purpose of the Study
The purpose of the study is to better understand the effect of language experience on resolving conflicting information. We will study adults form the York University URPP. Participants are selected based on their history of only using English or actively using another language in addition to English.

What You will be Asked to Do in the Study
You will be asked to complete some paper-based and computer-based cognitive tasks, for example:

- Answer some questions about your experience learning and speaking English and a second language.
- Select the corresponding picture upon hearing a word.
- Look at a pattern and fill in the missing piece.
- Make left or right decisions based on a stimulus on the screen.

We will provide you with clear instructions and examples at the beginning of each task so that you will know what to do. When using the computer, you will give your answers by either clicking a mouse, pressing a key on the keyboard, or by entering your solution using the keyboard. If you do not know how to use a mouse, we will show you how to use it. Your eye movements will be recorded under invisible infrared light. This technique is non-invasive and has been used on infants. We will provide you with breaks throughout the testing time if you wish to take them, and we will answer any questions that you may have. The study will take approximately 1 hour to complete. You will receive course credit for the time you spent with the researcher.

Voluntary Participation
Participation in this study is completely voluntary. The decision to participate is entirely up to you.

Risks and Discomforts
We do not expect the study to cause any risks or discomforts for you. However, if you feel uncomfortable or become tired, you can take a break whenever you want.

Withdrawal from Study: You can stop participating in the study any time you want, for any reason you want. If you decide to withdraw, you do not need to give a reason, and it will not prejudice your future relations with me, with this university, or any part of this university. If you decide to stop participating for any reason, you will still be eligible to receive the promised pay (URPP credits) for agreeing to take part in the study. Should you withdraw from the study all of your data generated will be destroyed.

Confidentiality
The information (data) we get from you during the study will be kept confidential. Your name will never be used in connection with any of the data we collect. Your signature below indicates that you are willing for the *information* we got from you to be used in an article or lecture as long as your name is not revealed. Your data will be safely stored in a locked file cabinet and only my supervisor and I will have access to this information. The data will be stored for seven years, after which it will be destroyed (e.g. paper copies will be shredded, electronic files will be deleted). Your confidentiality will be maintained to the extent allowed by law.

Benefits
You will not benefit directly from being in the study. However, your participation will facilitate our understanding the role of language on the development of various cognitive processes, including attention.

Questions
If you have any questions about the research in general or about your role in the study, please feel free to contact the principal investigator, Dr. Ellen Bialystok, either by phone at [redacted] or by e-mail ([redacted]). This research has been reviewed by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, [redacted], York University (telephone [redacted] or e-mail [redacted]).

Ellen Bialystok, Ph.D.
Principal Investigator

Legal Rights and Signatures
You will receive a copy of this informed consent. You are not waiving any of your legal rights by signing this form. Your signature below indicates that you agree to participate in this study.

Name of Participant (Print): ____________________________ Birthdate: ___________________

Signature of Participant: ____________________________ Today's Date: ___________________

Signature of Experimenter: __________________________________ Date: ___________________

Appendix F: Debriefing Form

DEBRIEFING FORM

<u>Study title:</u> Language Experience and Cognitive Control

<u>Research's name:</u> Ashley Chung-Fat-Yim

<u>Supervisor's name:</u> Dr. Ellen Bialystok

<u>Purpose of the Research:</u>

The purpose of this study is to examine the impact of bilingualism on executive control using a relatively new methodology known as MouseTracker (Freeman & Ambady, 2010). With MouseTracker, we are able to gain information about the timing and intensity of certain cognitive processes by looking at the trajectory of the mouse. This study is important because there are advantages and disadvantages to being bilingual and this research will try to explain these effects by finding out how monolinguals and bilinguals differ quantitatively (reaction times and accuracy) as well as qualitatively (patterns and strategies) in the way they process conflicting information.

The global-local task and oculomotor Stroop task you performed requires some degree of cognitive control necessary by asking you to focus on a particular dimension or feature. A study by Incera and McLennan (2016) demonstrated that bilinguals behave like experts when presented with conflicting information by delaying the initiation of their response.

First you filled out a questionnaire that assessed whether you were monolingual or bilingual, to make sure that you were eligible for the study. You were asked to perform some computerized tasks so that we could assess all of our participants on measures of executive control capabilities. You were also asked to solve some visual puzzles and complete a vocabulary test. This information will give us insight into the relation between certain cognitive and verbal capacities.

If you have any questions, please do not hesitate to contact me at [redacted]. You can also contact my supervisor at [redacted]. If you have any concerns about this study, please contact the departmental ethics committee at [redacted] or [redacted].

Thank you for participating in this study!
Ashley

References

Freeman, J.B. & Ambady, N. (2010). MouseTracker: Software for studying real-time mental processing using a computer mouse-tracking method. *Behavior Research Methods, 42,* 226-241.

Incera, S. & McLennan, C. T. (2016). Mouse tracking reveals that bilinguals behave like experts. *Bilingualism: Language and Cognition, 19*(3), 610-620.