The Time Course of the Conflict Effect in Bilinguals and Monolinguals

Manjunath Narra

B.Sc., (Speech & Hearing), M.Sc., (Speech & Hearing)

Department of Cognitive Science

ARC Centre of Excellence in Cognition and its Disorders

Perception in Action Research centre

Faculty of Human Sciences

Macquarie University, Sydney, Australia

This dissertation is presented for the degree of Doctor of Philosophy (PhD)

June, 2016

Table of Contents

Abstract

In cognitive control tasks, studies have reported a faster reaction time and a smaller conflict effect in bilinguals as compared to monolinguals. However, these findings are inconsistent across studies and sometimes absent. In the present thesis, the magnitude of the conflict effect was investigated using the response-signal and the stimulation of the motor cortex procedures by eliminating the reaction time distribution differences between the groups. In Chapter 2 (Experiment 1a), a mathematical model was used to investigate the decision processing mechanism in bilinguals and monolinguals by fitting reaction time and accuracy data to the linear ballistic model. The findings indicated no difference between groups and trial types in any of the model parameter estimates. In Chapter 2 (Experiment 1b), a reach-to-touch paradigm combined with the response-signal procedure was used to investigate the magnitude and the time course of the conflict effect in the Simon task. The findings demonstrated similar time points of onset and decay of the conflict effect between the language groups. In Chapter 3, a transcranial magnetic stimulation was used to investigate the time course of the conflict effect in the Simon task by recording motor evoked potentials at the level of the motor cortex. The findings suggested no evidence for the group differences in the magnitude and the time course of the conflict effect. In Chapter 4, a reach-to-touch paradigm was used to investigate the time course of the conflict effect in the Stroop task. The findings showed an early emergence of the conflict effect in bilinguals relative to monolinguals. Together, the results obtained from Chapters (2, 3, 4) provide no evidence for a bilingual advantage in the conflict effect across cognitive control tasks over a broad range of stimulus processing time. The findings are discussed with reference to the current theories of bilingual cognitive advantage.

Declaration

I, Manjunath Narra, certify that the work in this thesis entitled “The time course of the conflict effect in bilinguals and monolinguals” has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged.

In addition, I certify that all information sources and literature used are indicated in the thesis.

The research presented in this thesis was approved by Macquarie University Ethics Review Committee, reference number: **5201300060** on 30th April, 2013 and **HEMAY2009 RO660** on 23rd July, 2013.

Signature

Manjunath Narra (Student ID: 42945615)

June, 2016

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Matthew Finkbeiner. This would not have been made possible, without his constant guidance, encouragement and technical assistance during the entire course of my project. I will be forever thankful for his valuable time teaching R and Presentation programming.

I owe my deepest gratitude to, Andrew Heathcote and Paul Sowman, for extending their expertise, which gave this project an interdisciplinary structure. I extend my sincere gratitude to Anina Rich, Mark Williams, and Cognition in Action group lab members for their numerous suggestions and discussions throughout my research. I am immensely grateful to, Shahd Al-Janabi for her constant guidance in carrying out TMS experiment.

I am thankful to the Department of Cognitive Science, Macquarie University for providing an ideal work space and funds to attend conferences. I would also like to thank, Lesley McKnight, Marcus Ockenden, and Teri Roberts for all the administrative and technical support during my candidature. I wish to acknowledge the financial support from the Macquarie University (International Macquarie University Research Excellence Scholarship No.2012242) to carry out this research project.

I am thankful to all my friends, Sneha, Ganesh, Avinash, Vishnu who have been a source of moral support.

This journey would not have been possible without the support of my family, especially my parents, Rajeshwari and Kota Reddy, and brothers, Subi and Kittu, who always stood beside me and supported me selflessly in all my endeavors.

My heartfelt thanks to my wife, Sailaja for unconditional love and encouraging me to pursue my dreams. Thank you for believing in me.

List of Tables

List of Figures

Chapter 1

General Introduction

General Introduction

1.1 Bilingualism and Cognitive Control

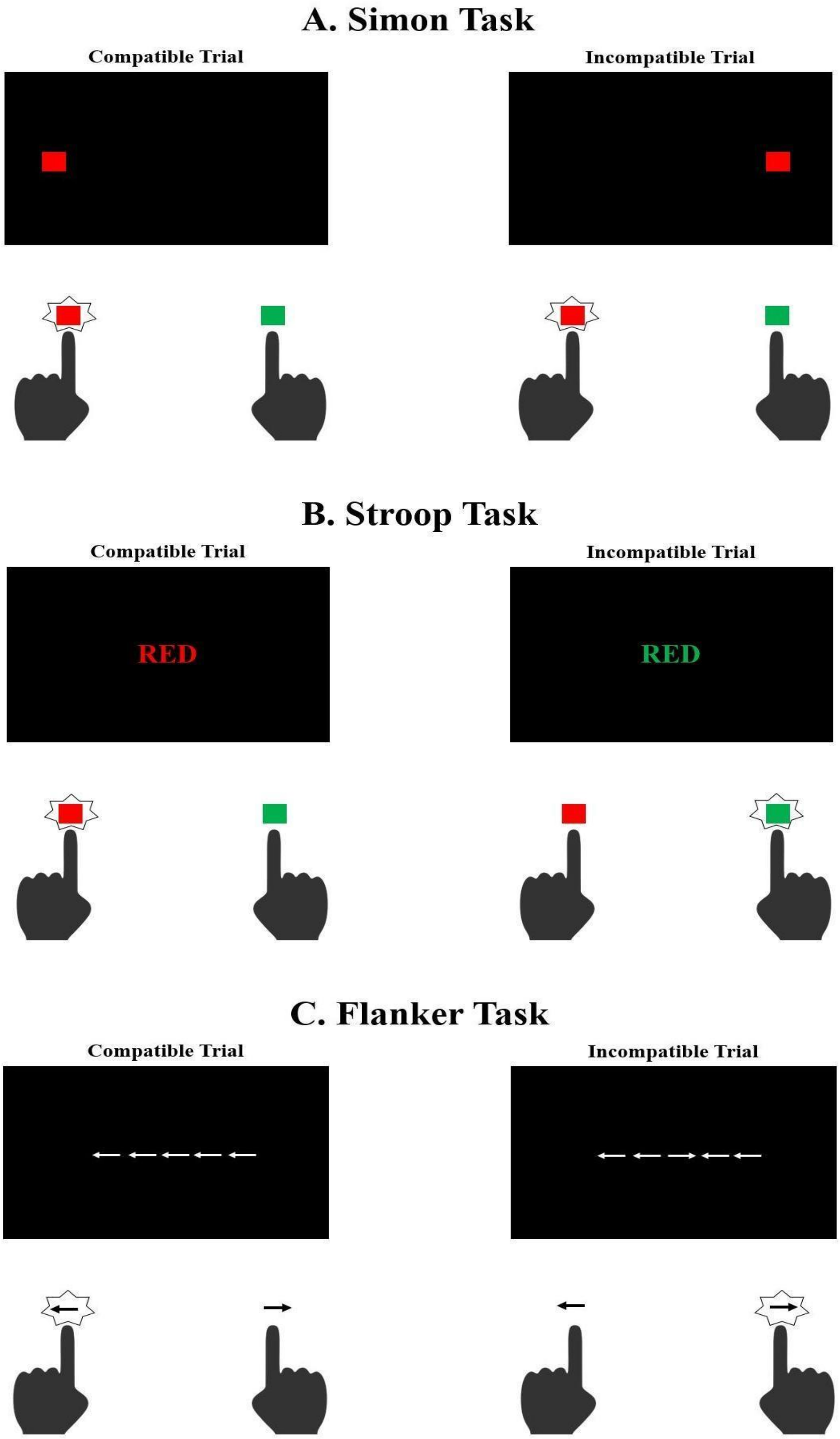
Language is an integral part of the communication process through which one can expresses their ideas, thoughts and experiences. Due to globalization, almost fifty per cent of the world's population speak another language in addition to their mother tongue. According to the Australian census reports, 20.4 % of the population speaks a language other than English (Australian Bureau of Statistics, 2011). Thus, the concepts of bilingualism and multilingualism have increasingly become prevalent, and in turn have increased the need to understand their underlying mechanisms and the consequences of their presence in the brain.

Researchers have investigated the enigma of the bilingual language control mechanism of lexical selection (e.g., Costa & Caramazza, 1999; Costa, Santesteben, & Ivanova, 2006; Finkbeiner, Almeida, Janssen, & Caramazza, 2006; Green, 1998; La Heij, 2005). The bilingual lexical selection processes referred to as the "hard problem" (Finkbeiner, Gollan, & Caramazza, 2006, p.153) have been accounted for by language-specific lexical selection mechanism (e.g., Costa, Miozza, & Caramazza, 1999) and by language non-specific lexical selection mechanism (e.g., Green, 1998). According to language-specific selection mechanism, the hard problem is solved by selectively activating only the lexical items in the target language (e.g., Costa, Miozza, & Caramazza, 1999; Costa, Santesteban, & Ivanova, 2006). On the other hand, language non-specific lexical selection accounts propose that both languages compete for selection, and competition is resolved by suppressing activation in the non-target language (e.g., Green, 1998; Meuter & Allport, 1999). Although, there is no general consensus on the specific mechanism of lexical selection in bilinguals, there is some agreement in regard to the involvement of a language control mechanism that resolves the conflict between two languages. An example would be a Spanish-English bilingual speaker being asked to name a picture of a 'dog' using Spanish. The lexical items related to the target word would also be activated for a response selection (e.g., perro, gato, dog, cat). The language control mechanism is thought to resolve this conflict and to select the appropriate target word (‘perro’ - ‘dog’ in Spanish).

Recently, it has been suggested that the bilinguals’ extensive experience of processing two (or more) languages may translated into a ‘bilingual advantage’ in various domains (e.g., Bialystok, Craik, Green, & Gollan, 2009; Costa & Sebastián-Gallés, 2014). For instance, evidence indicates that the bilinguals outperform monolinguals on tasks that measures cognitive control (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa, Hernández, & Sebastián-Gallés, 2008). Similarly, it has also been shown that the language learning mechanism has been positively affected by bilingualism (e.g., Kaushanskaya & Marian, 2009), and bilingualism may prevent cognitive decline in the elderly population (e.g., Bialystok et al., 2004; Bialystok, Craik, & Luk, 2008), as well as delays the onset of Alzheimer’s disease (e.g., Alladi et al., 2013; Craik, Bialystok, & Freedman, 2010). The present thesis focuses mainly on the impact of bilingualism on the cognitive control mechanism.

Cognitive control is a complex system that refers to, but is not limited to, updating and shifting between mental sets as well as filtering out the irrelevant information (Friedman, Miyake, Corley, Young, DeFries, & Hewitt, 2006; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Cognitive control abilities are measured using various tasks such as the Stroop task (Stroop, 1935), the Simon task (Simon, 1969), and the flanker task (Eriksen & Eriksen, 1974). The cognitive control tasks (Figure 1.1) make use of stimuli that have both a task-relevant dimension to which participants respond to as well as a task-irrelevant dimension that participants are instructed to ignore. The participants responses are faster when both the task-relevant and task-irrelevant dimensions of the stimulus activate the same response code (i.e., on compatible trials) than when the two dimensions activate opposite responses (i.e., on incompatible trials). The mean response time difference between the compatible and incompatible trials is referred to as the conflict effect. The magnitude of the conflict effect is used to index the ability of a person to manage the interference from the task-irrelevant dimension and to respond accurately to the task-relevant dimension. That is, the smaller the magnitude of the conflict effect the stronger the ability to control the interference. The relative activation levels of task-irrelevant and task-relevant information modulates the magnitude of the conflict effect.

Figure 1.1. Cognitive control tasks (on the right page). In the “classic” version of the **Simon task** (A), a target colour square (red or green) is presented on the left or right-side of the central fixation. Participants are instructed to respond by pressing the appropriate button corresponding to the target stimulus colour, i.e., task-relevant dimension, by ignoring the stimulus’ location, i.e., task-irrelevant dimension. On compatible trials (e.g., trials in which a red colour was presented on the left-side of fixation and which required a left button press), the responses were faster and more accurate than the incompatible trials (e.g., trials in which a green colour was presented on the left-side of fixation and required a right button press). The response time difference between the compatible and incompatible trials is referred to as the Simon effect. In the standard **Stroop colour word task** (B), participants were asked to respond to the ink colour of a word, i.e., task-relevant dimension and simultaneously ignore the meaning of the word, i.e., task-irrelevant dimension. Participants respond faster and more accurately when the word meaning and its ink colour were same (compatible trials) than when they were different (incompatible trials). The response time difference between compatible and incompatible trials is referred to as the Stroop effect. In the **flanker task** (C), an array of arrows was presented at the central fixation. Participants are asked to respond to the pointing direction of the central arrow, i.e., task-relevant dimension, by pressing the button appropriate to its direction whilst simultaneously ignoring the stimuli around the target, i.e., task-irrelevant dimension. The responses were faster and more accurate in the compatible trials in which the pointing direction of the target and the distractors were the same as compared to the incompatible trials in which the pointing direction of the target and distractors were opposite. The difference in response time between compatible and incompatible trials is termed as the flanker effect.


A. Simon Task
Compatible Trial
Incompatible Trial
B. Stroop Task
Compatible Trial
Incompatible Trial
RED
RED
C. Flanker Task
Compatible Trial
Incompatible Trial

Interestingly, it has been reported that the magnitude of the conflict effect is modulated by the reaction time (RT) speed as a function of stimulus processing time (Pratte, Rouder, Morey, & Feng, 2010; Speckman, Rouder, Morey, & Pratte, 2008). The dynamic interaction of the conflict effect over response time has been captured in delta plots (De Jong et al., 1994). A delta plot (see Figure 1.2A) is a graphical representation of the conflict effect measured from the reaction time distributions of compatible and incompatible trials across reaction time percentiles as a function of response speed (Burle, van den Wildenberg, & Ridderinkhof, 2005; De Jong et al., 1994; Ridderinkhof, 2002; Roelofs, Piai, & Garrido Rodriguez, 2011). For example (see Figure 1.2A), in the Stroop task, the conflict effect size is minimal at the fastest reaction time due to a relatively small variance between compatible and incompatible trials (see Figure 1.2B). The conflict effect is maximum at the slowest responses, due to a large variance between trials in the tail of the RT distribution. In contrast, in the Simon task, the conflict effect size is higher at the fastest reaction times due to the high variance between trials. The conflict effect size is smaller at the slowest responses due to there being less variance (see Figure 1.2C). The delta plot results suggest that the conflict effect size varies as a function of response speed which is mainly attributed to the reaction time distribution properties (mean and variance) of compatible and incompatible trials (Speckman et al., 2008; Zhang & Kornblum, 1997).

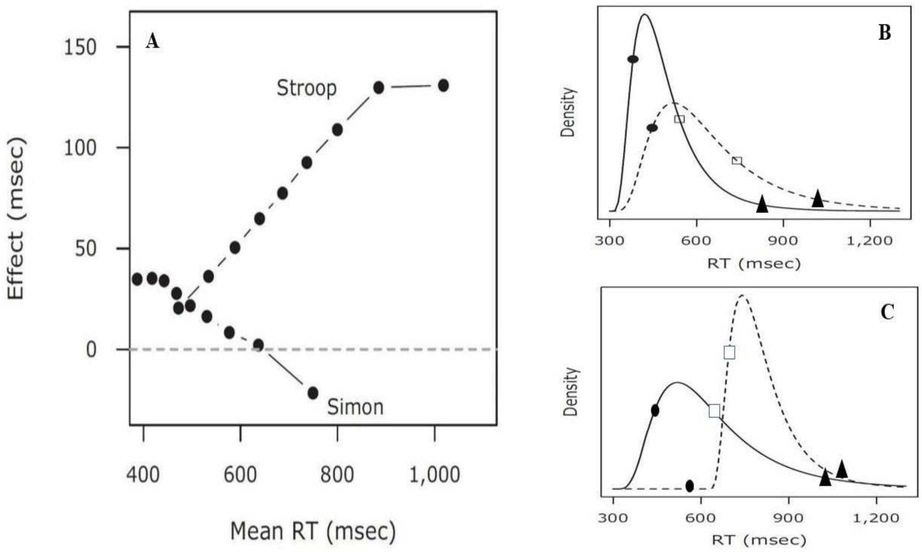


Figure 1.2. Delta plot. (A) Delta plot from Pratte, Rouder, Morey, and Feng (2010; Exp 1). The y-axis represents the conflict effect size, i.e., the reaction time difference between compatible and incompatible trials. The x-axis represents the mean reaction time, i.e., the average of reaction time obtained from the compatible and incompatible trials. The dark dots represents the conflict effect size at desired number of percentiles i.e., at each decile of the two distributions. (B) Hypothetical reaction time distribution for the Stroop task, in which the variance between compatible trials (solid line) and incompatible trials (dotted line) is lesser at the fastest response times and higher at the slowest responses. (C) Hypothetical reaction time distribution for the Simon task, in which the variance between compatible trials (solid line) and incompatible trials (dotted line) is higher at the fastest response times and lesser at the slowest responses. The y-axis in figure B and C is the probability density function, which is the area under curve represents the probability of getting an x-value between a range of x-values.

In literature regarding bilingual cognitive advantages, the magnitude of the conflict effect is used as a proxy to indicate the positive benefits of bilingualism in cognitive control tasks (see Hilchey & Klein, 2011; Zhou & Krott, 2015 for review). Studies have reported that the bilinguals exhibit a smaller magnitude of the conflict effect and an overall faster reaction time relative to monolinguals in tasks measuring cognitive control (see Blumenfeld & Marian, 2014; Costa et al., 2009; Hilchey & Klein, 2011; Paap & Sawi, 2014; Tao et al., 2011 for review). However, these findings are inconsistent across studies and sometimes absent (e.g., Paap & Greenberg, 2013; von Bastian, Souza, & Gade, 2016). Even if it is assumed that there are positive effects of bilingualism on cognitive control, the reaction time advantage is more robust than the conflict effect advantage in bilinguals (e.g., Costa et al., 2009; Hilchey & Klein, 2011). Previous studies have measured the magnitude of the conflict effect at two different response times between language groups, i.e., at fast responses for bilinguals and at slow responses for monolinguals. In the present thesis, the magnitude of the conflict effect will be explored across same response time bins across groups. The response-signal procedure combined with the reach-to-touch paradigm (Chapters 2 and 4) and stimulation of the motor cortex combined with the motor evoked potentials (Chapter 3) will be employed to minimize the reaction time distribution differences across groups (I will discuss this in detail in section 1.4).

In the following section, I will present a review of studies reporting the reaction time and the conflict effect differences between bilinguals and monolinguals on various cognitive control tasks. Further, the current theories of bilingual cognitive advantage will also be addressed.

1.2 Consequences of Bilingualism on Cognitive Control Tasks

The seminal work by Peal and Lambert (1962) reporting the superior ability of bilinguals on both verbal and nonverbal intelligence tests has opened up a new avenue of research in cognitive science. Since then, researchers have been exploring the interaction between bilingualism and cognitive control abilities (e.g., Bialystok et al., 2004; Costa et al., 2009). The studies investigating possible cognitive advantages due to bilingualism by using behavioural measures in cognitive control tasks have four different findings: first, behavioural evidence supporting a bilingual cognitive advantage in both global reaction time and magnitude of the conflict effect (e.g., Bialystok et al., 2004; Costa, Hernández, & Sebastián-Gallés, 2008; Hernández et al., 2010); second, evidence of bilingual advantage only in the reaction time (e.g., Bialystok, Craik, Grady et al., 2005; Bialystok, Martin, & Viswanathan, 2005); third, evidence of bilingual advantage only in the magnitude of the conflict effect (e.g., Prior & Gollan, 2011; Prior & MacWhinney, 2010; Schroeder & Marian, 2012). Fourth, and in contrast to the previous three, several recent studies have challenged the findings of a bilingual advantage in both reaction time and conflict effect (e.g., Duñabeitia et al., 2014; Kirk et al., 2014; Morton & Harper, 2007; Paap & Greenberg, 2013; von Bastian, Souza, & Gade, 2016).

1.2.1 Reaction Time Advantage and Conflict Effect Advantage

In a seminal paper, Bialystok et al. (2004) investigated reaction time and the conflict effect magnitude across different experimental paradigms in the aging population. The middle-aged (mean age = 43 years) and old-aged (mean age = 71.9 years) bilingual and monolingual adults' behavioural performance was compared in the standard Simon task. The results demonstrated faster reaction time and smaller magnitude of the Simon effect for the bilinguals relative to the monolinguals. Further, the researchers increased the complexity of the Simon task by including four target colours. Even for this more complex Simon task, the bilinguals showed faster reaction times across trials and a smaller Simon effect relative to the monolinguals. In the final experiment, Bialystok et al. (2004) investigated language group differences across ten blocks in neutral trials (four target colours) and standard Simon task by increasing the number of trials (n = 240). On the neutral trials, the results revealed reaction time advantage for bilinguals in the initial seven blocks. Further, in bilinguals, the Simon effect was smaller in the earliest blocks (Blocks 1 to 4) relative to the monolinguals. Bialystok et al. (2004) argued that this evidence for both a controlled processing advantage and an inhibitory control advantage in bilinguals as compared with monolinguals.

In the bilingual cognitive advantage literature, the attentional network task (ANT) (developed by Fan, McCandliss, Sommer, Raz, & Posner, 2002) is also one of the most commonly used tasks to investigate cognitive control in bilinguals and monolinguals (e.g., Antón et al., 2014; Costa et al., 2008; Costa et al., 2009). The ANT is a combination of the flanker task (Eriksen & Eriksen, 1974) and the cued reaction time task (Posner, 1980). Costa et al. (2008) explored the cognitive advantage in bilingual and monolingual young adults using the ANT. They compared the performance of bilinguals and monolinguals on three attentional networks (alerting, orienting and conflict effect). Costa et al. (2008) showed that bilinguals outperformed monolinguals in both reaction time and in the magnitude of the conflict effect (first two blocks). The faster reaction time and smaller magnitude of the conflict effect in bilinguals was attributed to their superior control of monitoring processes and conflict resolution.

To further explore whether the faster reaction time in bilinguals was due to better conflict monitoring abilities, Costa et al. (2009) investigated bilingual and monolingual young adult performance by varying the percentage of compatible and incompatible trials in an adapted version of the ANT task. The trials were presented in two different versions. In the low monitoring version, the proportion of compatible trials was either 8 % or 92 %, and the remaining trials were incompatible trials. The results revealed no group differences in overall reaction time and conflict effect. In the high monitoring version, the proportion of compatible trials was either 75 % or 50 %, and the remaining trials were incompatible trials. It was found that the bilinguals were faster than the monolinguals only in the high monitoring versions. Additionally, the bilinguals showed smaller conflict effect size relative to monolinguals only in the first block of the 75 % version (112 ms in bilinguals vs. 139 ms in monolinguals). These results suggested that the bilingual advantage is observed in conditions when the cognitive demands are high in the task. The results were taken as evidence of the superior ability of the monitoring system in bilinguals.

Recently, to represent the entire distribution of reaction time, a few sets of studies employed ex-Gaussian distribution analyses (Heathcote, Popiel, & Mewhort, 1991) in order to investigate language group differences across two parameter estimates: a Gaussian parameter (μ-mu) and an exponential parameter (τ-tau) (Abutalebi et al., 2015; Calabria, Branzi, Marne, Hernández, & Costa, 2015; Calabria, Hernández, Martin, & Costa, 2011; Tse & Altarriba, 2012). The Gaussian parameter refers to the normal mean component of the reaction time distribution. The exponential parameter is referred to as the tail of the reaction time distribution. By fitting an ex-Gaussian function, Calabria et al. (2011) reanalysed the Costa et al. (2008, 2009) reaction time data obtained from the ANT task. They specifically explored whether the bilingual advantage (reaction time, conflict effect) is observed in the mean (μ) portion of the RT distribution or in the tail (τ) of the RT distribution. Calabria et al. (2011) reported overall smaller μ and τ values in bilinguals relative to monolinguals, suggesting a reaction time advantage in bilinguals at both mean RT distribution and at the tail of the RT distribution. Conversely, in the tail of the reaction time distribution, monolinguals showed higher τ values for incompatible trials relative to compatible trials, indicating a higher magnitude of conflict effect for monolinguals.

In young adults using the numerical version of the Stroop task, Hernández et al. (2010) investigated the effect of managing two languages on the cognitive control system. In their task, participants were instructed to indicate the number of items presented on the screen. The number of items varied from 1 to 3 and participants were asked to press appropriate response keys. The target stimulus was presented in three conditions: on compatible trials, the number of items matched the digit (e.g., 333), on incompatible trials the number of items and digits mismatched (e.g., 3), and on neutral trials, instead of numbers, letters were presented (e.g., A). The results demonstrated overall faster reaction time in bilinguals (543 ms) as compared to monolinguals (574 ms). Additionally, the bilinguals demonstrated a smaller Stroop interference effect (26 ms vs. 40 ms) and a larger Stroop facilitation effect (39 ms vs. 27 ms) than the monolinguals. The researchers argued in favour of a conflict monitoring advantage in bilinguals because the bilinguals performed better in regard to both the interference and facilitation effects.

Tao et al. (2011) investigated cognitive control in bilinguals (early and late) and monolinguals using a modified version of the flanker task called the lateralized attentional network test (LANT) (Greene et al., 2008). The early bilinguals acquired L2 before the age of six and late bilinguals acquired L2 after 12 years of age. A faster reaction time was reported in early bilinguals across all trials relative to monolinguals. However, late bilinguals and monolinguals performed the task similarly. The evidence of faster reaction time in early bilinguals was argued for enhanced monitoring abilities due to early exposure to two languages. The results also demonstrated a smaller magnitude of the conflict effect in both early and late bilinguals relative to monolinguals, which gives the former better suppression abilities and was argued to be due to their experience in handling two languages (Tao et al., 2011).

In all the above-mentioned literature, the bilinguals were overall faster across trial types and also displayed a smaller magnitude of conflict effect relative to monolinguals. If we consider the delta plot function, the bilinguals' mean reaction time will be faster with a smaller magnitude of conflict effect size as compared with the monolinguals. The difference in both reaction time and conflict effect suggests that both the mean and variance parameters of reaction time distribution were different across the two groups. I will now review studies reporting a bilingual cognitive advantage only in regard to reaction time.

1.2.2 Reaction Time Advantage Only

Bialystok, Martin, and Viswanathan (2005) explored cognitive control abilities in bilingual and monolingual children (mean age = 5 years), young adults (age range: 20 to 30 years), middle-aged adults (mean age = 40.6 years) and old-aged adults (mean age = 70.3 years). The bilingual children, middle-aged and old-aged adults performed the task faster than their monolingual counterparts on both compatible and incompatible trials. Further, no evidence for Simon effect differences was observed across the language groups. The faster responses on compatible and incompatible trials in bilinguals was attributed to their better control of attentional processes. However, the bilingual and monolingual young adults performed the task similarly across trial types (compatible, incompatible and neutral), which was attributed to peak age of cognitive functioning.

In a series of studies, Martin-Rhee and Bialystok (2008) investigated which particular aspect of the attentional control system was modulated by bilingualism in cognitive control tasks. Martin-Rhee and Bialystok (2008) compared the performance of bilingual and monolingual children in regard to interference suppression (i.e., suppression of activation from the task-irrelevant dimension in order to accurately respond to the task-relevant dimension, e.g., the Simon task) and response inhibition (i.e., the ability to control their response to the highly salient stimulus dimension, and instead responding to the less salient stimulus dimension, e.g., the Stroop picture naming task). In the Stroop picture naming task, participants were asked to say "day" for a dark moonlit sky, and "night" for a bright sun picture. The results revealed that on the Simon task, the bilingual children demonstrated faster response time than the monolinguals. However, on the Stroop picture naming task, the groups performed similarly. To negate the possibility of a language processing influence in the Stroop task, Martin-Rhee and Bialystok (2008) used an arrow task (similar to the spatial Stroop task). Participants were asked to respond to the arrow direction presented at the centre of the screen (measuring response inhibition) and on either side of the central fixation point (measuring interference suppression). The groups performed similarly when the arrows were presented at the centre fixation point. Interestingly, the bilingual group performed faster than the monolinguals when the arrows were presented on either side of the central fixation point.

Martin-Rhee and Bialystok (2008) argue that the faster responses in bilinguals show that they have an advantage in the interference suppression aspect of the attentional control system.

Kapa and Colombo (2013) investigated the attentional control mechanism in children from three different language exposures: monolinguals, early bilinguals (L1 and L2 before 3 years of age) and late bilinguals (L2 after 3 years of age). An adapted version of the ANT was used to measure the performance difference between the groups on three attentional network systems (alerting, orienting and conflict effect). The bilingual and monolingual groups performed similarly across alerting, orienting and executive attentional network systems. However, the early bilinguals performed the overall ANT faster than the monolinguals and late bilinguals. The faster reaction time in early bilinguals was attributed to their enhanced monitoring abilities due to exposure to two languages from an early age.

In the above-mentioned studies, the bilinguals were overall faster in the tasks as compared to the monolinguals but they still did not show any advantage in the magnitude of the conflict effect. So, if we consider the delta plot function, the bilinguals mean reaction time will be at the faster end relative to the monolinguals mean reaction time. This might be due to large difference in the mean parameter of reaction time distribution across groups. I will now review studies reporting a bilingual cognitive advantage only in the magnitude of the conflict effect.

1.2.3 Conflict Effect Advantage Only

The conflict effect advantage has been most controversial and a highly inconsistent measure reported across studies investigating a bilingual cognitive advantage. Bialystok et al. (2004; Exp 1) reported an unusually large Simon effect difference between old-aged bilinguals and monolinguals (748 ms in bilinguals vs. 1713 ms in monolinguals), which no studies were able to replicate. The large magnitude of Simon effect was attributed to a small number of experimental trials (only n = 28). However, in their follow-up experiment, Bialystok et al. (2004) increased the number of trials (n = 192) and the complexity of the Simon task. These results reported a similar bilingual advantage in the magnitude of the Simon effect. Based on this evidence, Bialystok et al. (2004, p.301) noted that “bilingualism boosts inhibitory control and that bilingualism would therefore be associated with a smaller Simon effect.”

Furthermore, in their series of experiments Bialystok, Craik, and Luk (2008) recruited bilinguals and monolinguals from two age groups (younger group: mean age = 20 years; older group: mean age = 68 years) to investigate lexical access and cognitive control. The two cognitive control tasks that were used were the Simon arrow task and the Stroop colour word naming task. In an adapted version of the Simon arrow task, Bialystok, Craik, and Luk (2008) presented directional arrows in three different conditions. In the neutral condition, the directional arrow was presented at the central fixation; participants were instructed to respond to the arrow direction by pressing the left key for a left directed arrow and the right key for the right directed arrow. On the reverse condition, participants were instructed to press the response key opposite to the direction of the arrow. The third condition included the presentation of an arrow on the left or right-side of the central fixation point in two different trial types (compatible and incompatible trials). For the neutral and reverse conditions, both the groups performed similarly. However, the magnitude of the Simon effect in the third condition was smaller in bilinguals relative to the monolinguals in the older group.

Additionally, in Bialystok, Craik, and Luk (2008) study participants also completed the Stroop colour word naming task. The target stimulus was presented in four different trial types (neutral-colour, neutral-word, compatible, incompatible). The groups performed similarly on the neutral-colour (e.g., a series of Xs presented in red ink) and on the neutral-word trials (e.g., “RED” word presented in black ink). The results showed that the magnitude of the Stroop effect in bilinguals is smaller relative to monolinguals. Additionally, the bilinguals showed a smaller interference effect (i.e., the response time difference between incompatible and neutral-colour trials) and a larger facilitation effect (i.e., the response time difference between compatible and neutral-colour trials) than their monolingual counterparts. Bialystok et al. (2008, p.870) attribute the superior ability of bilinguals in cognitive control to "some aspect of the bilingual experience, and in our view the necessity to suppress interference from the nonused language is a strong candidate to account for both the advantage in control and the disadvantage in lexical access."

In old-aged adults (mean age = 80.7 years), Schroeder and Marian (2012) reported only the Simon effect advantage in bilinguals as compared to monolinguals (23 ms in bilinguals vs. 51 ms in monolinguals). Pelham and Abrams (2014) showed that both early and late bilingual young adults performed the ANT better with a smaller magnitude of conflict effect than their monolingual counterparts (early bilinguals: 86 ms; late bilinguals: 92 ms; monolinguals: 123 ms). Furthermore, Prior and MacWhinney (2010) investigated language group performance in task switching (colour and shape) paradigm consisting of single task blocks and mixed task blocks. The results showed smaller switching cost in bilinguals compared to monolinguals and no evidence for differences in the mixing cost. All the above studies that showed a bilingual advantage in the conflict effect attributed this advantage to better inhibitory function due to the bilingual experience.

In the above-presented literature, the bilinguals demonstrated a smaller magnitude of conflict effect relative to monolinguals, but the evidence for reaction time difference was absent. If we consider the delta plot function, the bilinguals' and monolinguals' mean reaction time will be similar; however, differ only in the magnitude of the conflict effect. This might be due to the differences in the variance of reaction time distribution across the two groups. In my thesis, I will use two approaches to minimize the reaction time distributions across the two groups. Moreover, I will measure how each group perform in linguistic and nonlinguistic cognitive control tasks (discussed in later section 1.4).

Overall, the findings discussed above suggest that the bilingual advantage is observed in either the speed of reaction time or in the magnitude of the conflict effect, or in both. In the following section, I present two hypotheses proposed by Hilchey and Klein (2011) based on the above findings to account for a bilingual cognitive advantage.

1.3 Theories of Bilingual Cognitive Advantage

In a highly influential review article, Hilchey and Klein (2011) proposed two hypotheses (the bilingual inhibitory control advantage and the bilingual executive processing advantage) to account for the bilingual cognitive advantage. This was based on the behavioural evidence from 31 studies conducted from 2004 to 2010 that investigated the bilingual cognitive advantage in various nonlinguistic cognitive control tasks.

1.3.1 Bilingual Inhibitory Control Advantage

First, the bilingual inhibitory control advantage (BICA) hypothesis was proposed to account for the reduced magnitude of the conflict effect in bilinguals, based on the inhibitory control model of language processing (Green, 1998). According to the inhibitory control model of language selection (i.e., language non-specific lexical selection mechanism), the cross-language competition was thought to be resolved by suppressing words in the non-target language (Abutalebi & Green, 2007; Green, 1998). Hilchey and Klein (2011, p.628) refer to the bilingual inhibitory control advantage hypothesis as follows:

> "Frequent use of the inhibitory processes involved in language selection in bilinguals will result in more efficient inhibitory processes, which will confer general advantages

> on nonlinguistic interference tasks - that is, those requiring conflict resolution. These advantages will be reflected in reduced interference effects in bilinguals as compared to monolinguals. In other words, bilinguals should show an advantage over monolinguals on trials with response conflict." (Hilchey & Klein, 2011, p.628)

The basic assumption is that the recruitment of suppression to resolve language conflict on an everyday basis is thought to enhance the domain-general cognitive control mechanism in bilinguals, thus leading to a smaller magnitude of conflict effect. As presented by Hilchey and Klein (2011), the BICA hypothesis strongly suggests that the bilinguals respond faster only on the response conflict trials (i.e., incompatible trials) which require the suppression of irrelevant dimension in the task. This, in turn, reduces the magnitude of conflict effect, which is one of the patterns observed in bilinguals on cognitive control tasks. Further, the BICA hypothesis predicts a similar behavioural performance between language groups on trials without conflict (i.e., in the compatible and neutral trials).

1.3.2 Bilingual Executive Processing Advantage

Second, the bilingual executive processing advantage (BEPA) hypothesis was proposed to account for an overall faster reaction time in bilinguals. This is based on the conflict monitoring and goal maintenance abilities of bilinguals in language processing (Costa et al., 2009; Hilchey & Klein, 2011). Hilchey and Klein (2011) refer to BEPA as follows:

> "Assuming that the conflict monitoring system is adapted to detect any instance in which a conflict materialized, one could reasonably follow the same logical road map as D. W. Green (1998) to explain why bilinguals might possess a more advanced monitoring system. Thus, when two monitoring system will recognize the presence of two simultaneously active competing responses, adjust the level of cognitive control to

aid in the resolution of competing representations, and signal relevant pathways to allow for task-appropriate response selection." (Hilchey & Klein, 2011, p. 629)

It is speculated that the constant need to maintain and monitor the target language relative to the context and listener has contributed to enhanced executive processing abilities more generally in bilinguals. The BEPA hypothesis is also based on the findings of Costa et al. (2009), who observed a bilingual advantage in high inter-trial switches between compatible and incompatible trials, suggesting a superior ability of bilinguals in the monitoring system.

1.3.3 Interim Summary

The initial studies which reported a bilingual advantage on cognitive control tasks based their claims on the BICA hypothesis (e.g., Bialystok et al., 2004; Bialystok et al., 2005; Bialystok, Craik, & Luk, 2008; Bialystok & Craik, 2010; Costa et al., 2008; Luk et al., 2010). However, the studies reporting a conflict effect advantage were inconsistent in children and young adults in regard to the support for the BICA hypothesis (Hilchey & Klein, 2011). Furthermore, studies reported reaction time advantage in trials other than the incompatible trials. These findings forced researchers to propose an alternative hypothesis based on the monitoring mechanism in order to account for the overall reaction time advantage in bilinguals (e.g., Costa et al., 2009). The review of studies reporting a bilingual advantage in reaction time strongly supports the BEPA hypothesis in which the bilinguals perform nonlinguistic cognitive control tasks faster across compatible, incompatible and neutral trials (e.g., Bialystok et al., 2006; Colzato et al., 2008; Costa et al., 2009; Martin-Rhee & Bialystok, 2008).

The findings suggest that the conflict effect advantage is not as robust as the reaction time advantage in the bilingual cognitive advantage literature. I suspect that this might be due to the differences in the way in which the comparison of the groups with different reaction time speed is made. In the following section, I will show how the magnitude of the conflict effect is modulated as a function of reaction time, and how this relation could mask some of the effects of bilingualism on cognitive control tasks.

1.4 Dynamic Interaction Between the Reaction Time and the Conflict Effect

It has been reported that the magnitude of the conflict effect modulates over response time speed depending on the mean and variance properties of the reaction time distributions. Speckman, Rouder, Morey, and Pratte (2008, p.262) indicated that if two groups have different mean reaction times, then this leads to different RT distributions. The differences are mainly attributed to the inconsistencies in the mean and variance properties of the RT distributions across groups which “imply complex relations such as the presence of multiple processes or mixtures” (Speckman, Rouder, Morey, & Pratte, 2008, p.265). In the bilingual cognitive advantage literature, studies have reported overall faster reaction time in bilinguals as compared with monolinguals (e.g., Bialystok et al., 2005; Costa et al., 2009; see Hilchey & Klein, 2011 for a review). Furthermore, the studies using distributional analyses demonstrated that the language groups differ in the mean of the reaction time distribution and in the tail of the reaction time distribution (e.g., Abutalebi et al., 2015; Calabria et al., 2011; Calabria, Branzi, Marne, Hernández, & Costa, 2015; Tse & Altarriba, 2012). Hence, I suppose that there are high possibilities of RT distribution differences between language groups to measure the magnitude of conflict effect.

For example, in the hypothetical case shown in Figure 1.3 for the Simon task, if a bilingual group shows a faster mean response time and a smaller variance (between compatible and incompatible trials), then the corresponding conflict effect will be smaller. On the other hand, if monolinguals are slower relative to bilinguals, then the conflict effect size will be higher across all the percentiles. In the latter case, the bilinguals show an advantage both in terms of reaction time speed and in terms of the conflict effect size. I suppose that the bilingual advantage depends on the degree of differences between groups in the mean and variance properties of reaction time distributions. If the differences are higher in the mean of the reaction time distribution across groups, then it might show a global reaction time advantage in bilinguals as is indeed reported in the majority of studies. If the differences are higher in the variance of the reaction time distribution across groups, then it might show only a conflict effect advantage. The degree of differences in the reaction time distribution properties might be one of the sources for inconsistent and mixed findings across groups and tasks designs.

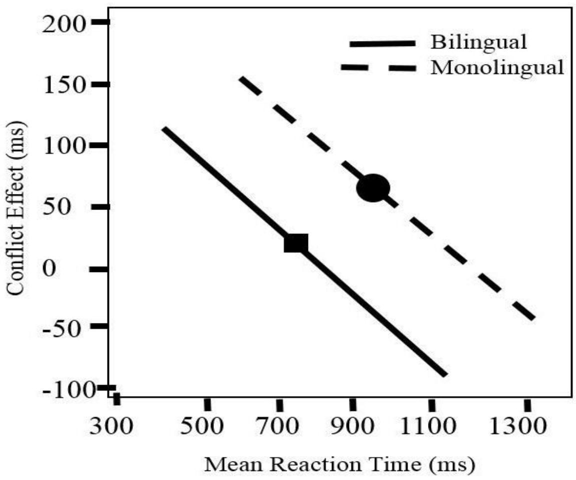


Figure 1.3. Delta plot for a hypothetical case in bilinguals and monolinguals for modulation in both mean and variance of RT distribution in the Simon task.

Theoretically, to get a pure measure of any possible conflict effect differences, the groups should be compared across the same reaction time percentiles (or response bins). The magnitude of the conflict effect at the same response bins across groups would allow one to predict the cognitive control abilities engaged to resolve interference from the task-irrelevant dimension at a specific time frame. Furthermore, as shown in the delta plots (Figure 1.2A), the magnitude of the conflict effect is dynamic and varies across response time percentiles across tasks. Complex interpretations result when one compares group differences across response bins obtained from two different response times. The variation in the response bins across groups might be due to the differences in the RT distribution properties (mean and variance). If this is so then, one needs to minimize the differences to compare between groups at the same response time bins. But how can we minimize the reaction time distribution differences across groups? One way of attempting this could be by eliminating the reaction time advantage across groups, which in turn reduces the RT distribution differences. Such a removal allows one to compare bilinguals and monolinguals in regard to the magnitude of the conflict effect at similar response bins.

If the reaction time advantage is eliminated, will the conflict effect modulates across the language groups for cognitive control tasks? Will the bilingual advantage still be observed after minimizing the RT distribution differences? I will pursue these questions in my thesis using two independent approaches that will eliminate reaction time advantage. In the first approach, I use a response-signal procedure combined with a reach-to-touch paradigm (Chapters 2 and 4) and in the second approach, I use a stimulation of the motor cortex with transcranial magnetic stimulation procedure at predefined response time points (Chapter 3). In the following section, I will briefly introduce the two procedures that I applied in order to minimize the reaction time distribution differences across bilinguals and monolinguals.

1.4.1 Response-Signal Procedure Coupled with the Reach-to-Touch Paradigm

In the traditional button press paradigm, participants respond to the target stimulus as soon as possible after target onset. This can cause inconsistency in response speed across groups. To eliminate the reaction time advantage across groups, one needs to control response speed relative to the target stimulus. To reduce this variability, I employed a response-signal procedure (e.g., Finkbeiner et al., 2014). In the response-signal procedure, participants are instructed to respond to an imperative go signal, which is the final beep in a sequence of three beeps. So the participants are trained to initiate their responses on the final beep instead of on the target stimulus. The imperative go signal has a response time window of 300 ms, in which it opens 100 ms before the go signal and closes 200 ms after the go signal. The responses before and after the response time window are considered as an error. Through this design, one can monitor the participants to make sure that they initiate their responses at the same time window relative to the imperative go signal. This, in turn, made it possible to eliminate the RT distribution differences across groups for stimulus information.

The button press paradigm combined with the response-signal procedure is limited to capture the early effects of stimulus information processing (Hilchey, Ivanoff, Taylor, & Klein, 2011 as cited in Finkbeiner & Heathcote, 2016). This being the case, I used the reach-to-touch paradigm (Chapters 2 and 4) coupled with the response-signal procedure to uncover the magnitude of the conflict effect between the language groups (Finkbeiner et al., 2014; Finkbeiner & Heathcote, 2016; Quek, & Finkbeiner, 2013; 2014). In the reach-to-touch paradigm, instead of button pressing the participants reach out and touch the appropriate response panel in compliance with the task instructions. For example, in the reach-to-touch version of the Simon task, for the green colour stimuli participants are asked to reach out and touch the right response panel, whereas for the red colour stimuli they are asked to reach and touch the left response panel. In reach-to-touch paradigm, the *x-velocity* (cm/sec) is the dependent variable measured from reaching responses. The x-velocity is the speed of the reaching movements along the left-right dimension (x-axis) towards the response panel.

Furthermore, the imperative go signal is presented at three different stimulus-onset-asynchronies (SOAs) relative to the target onset: at 0 ms SOA (target and go signal are presented simultaneously), at 150 ms (the target was presented 150 ms before the go signal), and at 250 ms (the target was presented 250 ms before the go signal). The SOA modulation between target onset and imperative go signal allows one to capture the reaching responses over a wide range of stimulus viewing time. The time in milliseconds between the stimulus onset and the response initiation is referred to as ‘movement initiation time’ (MIT), which is the proxy for the stimulus viewing time. Figure 1.4 shows the distribution of movement initiation time relative to the target onset across trial types (A) and groups (B). Further, the wide range of MITs obtained from the three SOAs were distributed to group the x-velocities into 20 quantiles of equal proportion. The responses obtained in these MIT quantiles are from the same response time bins across groups. Measuring the magnitude of conflict effect across these MIT quantiles provides a temporal aspect of conflict resolution over stimulus viewing time across groups. With this fine-grained design, I was able to minimize the reaction time distribution differences across groups.

Using the reach-to-touch paradigm, I will investigate how the magnitude of the conflict effect is modulated in bilinguals and monolinguals across the same response time bins in the Simon task (Chapter 2, Experiment 1b) and in the Stroop task (Chapter 4). If bilinguals are better at conflict resolution, as predicted by the BICA hypothesis (Hilchey & Klein, 2011), then I expect a smaller and later onset of the conflict effect in bilinguals relative to monolinguals. The late onset of the conflict effect indicates a better ability to suppress task-irrelevant information in order to respond accurately to the task-relevant information. To anticipate the results, there was no evidence for a bilingual advantage in the time course of the Simon effect (Chapter 2, Experiment 1b), suggesting similar conflict resolution abilities across groups. Furthermore, in contrast to my prediction, in the Stroop task (Chapter 4) the bilinguals exhibited an early onset of the Stroop effect, indicating poor control of the resolution of the conflict between a task-irrelevant word and a task-relevant colour dimension.

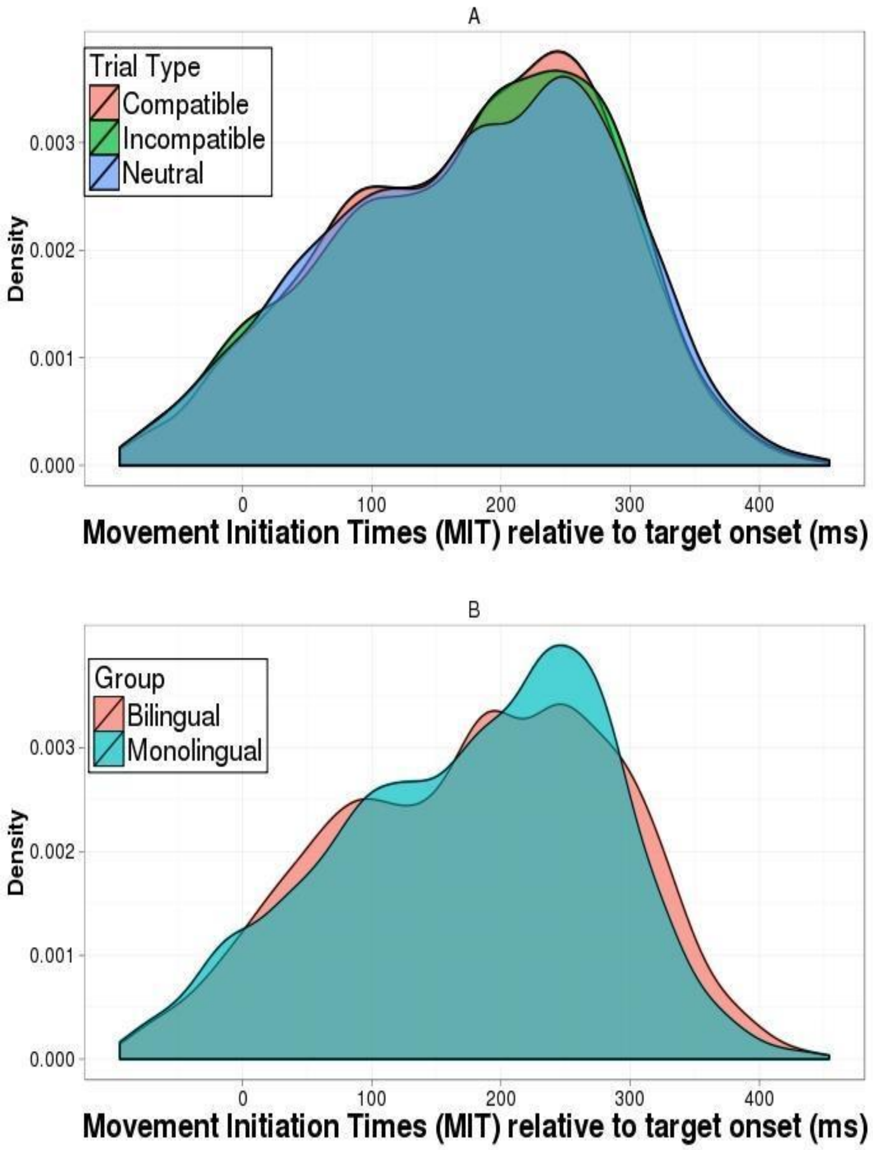


Figure 1.4. Distribution of movement initiation times relative to the target onset across trial types (A) and groups (B) in the reach-to-touch version of the Simon task. The y-axis in figure A and B is the probability density function, which is the area under curve represents the probability of getting an x-value between a range of x-values.

1.4.2 Transcranial Magnetic Stimulation Combined with Motor Evoked Potential

In my second approach (Chapter 3), I used the transcranial magnetic stimulation (TMS) paradigm to eliminate the reaction time advantage over the magnitude of the conflict effect between groups. In the reach-to-touch paradigm, the responses were time locked to the imperative go signal in order to minimize response speed differences across groups. However, in the TMS paradigm, I presented single-pulse TMS at a predefined response time points over the left hemisphere motor cortex. The TMS pulse was delivered at four different stimulus-to-stimulation asynchronies (SSAs: at 50 ms, 100 ms, 150 ms, 200 ms) after the target onset. These specific time points allowed me to capture the responses generated at the level of the motor cortex by eliminating processing the speed differences across groups.

The motor evoked potentials (MEPs) were recorded from the target muscles following a single-pulse TMS to measure the motor cortex excitability. The amplitude of MEPs represents the amount of motor preparation for stimulus information in the motor system (Terao & Ugawa, 2002). The MEPs elicited at four SSA time points represents the response time bins, which will be the same across bilinguals and monolinguals. The MEP response amplitudes allowed me to uncover the time course of the conflict effect in the early motor preparation stage of stimulus processing time. Through this fine-grained procedure, the differences in the reaction time distributions (mean and variance) were minimized across the language groups.

Using the TMS paradigm (Chapter 3), I will investigate how the magnitude of the Simon effect is modulated over the stimulus processing time in bilinguals and monolinguals. If bilinguals are better at conflict resolution, as predicted by the BICA hypothesis (Hilchey & Klein, 2011), then I expect a later onset of the Simon effect in bilinguals relative to monolinguals. The late onset of the Simon effect indicates a better ability to resolve the conflict between task-irrelevant spatial information and task-relevant colour information. To anticipate the results once again, there was no evidence for a bilingual advantage in the time course of the Simon effect, when the reaction time advantage is eliminated using the stimulation procedure.

In the following section, I will present the summary of confounding variables that are discussed in the bilingual cognitive advantage literature. Apart from the studies mentioned above that report a bilingual advantage, there are other researchers who failed to report any advantage on cognitive control tasks in bilinguals (e.g., Antón et al., 2014; Duñabeitia et al., 2014; Gathercole et al., 2014; Kirk et al., 2014; Paap & Greenberg, 2013; Paap & Liu, 2014; Paap & Sawi, 2014; Paap, Sawi, Dalibar, Darrow, & Johnson, 2015; von Bastian, Souza, & Gade, 2016). For example, Gathercole et al. (2014) demonstrated a similar behavioural performance between bilinguals (simultaneous and sequential) and monolinguals on the Simon task, Card Sorting task, and a judgement task. Work conducted by Paap and colleagues (e.g., Paap & Greenberg, 2013; Paap & Sawi, 2014) also reported no difference between bilinguals and monolinguals on cognitive control tasks for both reaction time and the conflict effect. The inconsistency across studies has also been discussed with reference to confounding variables considered to match bilingual and monolingual participants (see Dong & Li, 2015; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Paap, Sawi, Dalibar, Darrow, & Johnson, 2015; Valian, 2015 for review).

1.5 Confounding Variables for Inconclusive Findings

In what follows I have classified the confounding variables into three different categories: language experience variables, task variables, and background variables.

First, the language experience variables are related to the diversity of the linguistic profiles of participants included in the studies. These include, but are not limited to, age of L1/L2 acquisition (e.g., Luk, De Sa, & Bialystok, 2011; Tao et al., 2011), frequency of language usage (e.g., Prior & Gollan, 2011), language proficiency in L1/L2 (e.g., Singh & Mishra, 2012; 2013; 2014; Singh & Mishra, 2015), and monolinguals' exposure to a second language (e.g., Coderre & van Heuven, 2014; Paap & Greenberg, 2013; von Bastian, Souza, & Gade, 2016). For example, Paap and Greenberg (2013) compared performance differences between bilinguals, who had exposure to two languages from childhood, and monolinguals, who also had minimal exposure to a second language. Their results suggested a similar behavioural performance across various cognitive control tasks (such as the Simon task, the flanker task). However, the studies reporting a bilingual advantage strictly compared bilinguals with monolinguals who had no exposure to a second language at all (e.g., Tao et al., 2011). The language experience of participants is an important factor, however, there appears to be no consistency across studies in general, due to the wide spectrum of language profiles across bilingual and monolingual participants (e.g., Kaushanskaya & Prior, 2015; Valian, 2015).

Second, the task variables refer to the nature of the task employed in the particular study. These include, but are not limited to, task type (interference suppression vs. response inhibition; Luk et al., 2010; Martin-Rhee & Bialystok, 2008), task load (low monitoring vs. high monitoring; Bialystok, 2006; Costa et al., 2009; Salvatierra & Rosselli, 2011), task design (blocked design: Bialystok et al., 2008; mixed design: Bialystok, Martin, & Viswanathan, 2005; Bialystok et al., 2005; Bialystok, Craik, & Ryan, 2006; Kousaie & Phillips, 2012a; Martin-Rhee & Bialystok, 2008;), task stimuli (linguistic: Bialystok et al., 2008; nonlinguistic: Bialystok et al., 2004) and task mode (visual: Bialystok et al., 2004; auditory: Krizman, Skoe, Marian, & Kraus, 2014). In young adults, studies have reported a bilingual advantage only in the high monitoring versions (e.g., Bialystok, 2006; Costa et al., 2008). The bilinguals performed the task faster only on incompatible trials when the task design was a blocked presentation (e.g., Bialystok et al., 2006; Bialystok et al., 2008; Kousaie & Phillips, 2012b). On the other hand, when the trials were mixed, the bilinguals performed faster on all the trials (e.g., Bialystok, Martin, & Viswanathan, 2005; Martin-Rhee, & Bialystok, 2008).

Finally, the background variables have been the most debated in the bilingual cognitive advantage literature (e.g., Morton & Harper, 2007; Valian, 2015). These variables include, but are not limited to, sample size (e.g., Antón et al., 2014; Duñabeitia et al., 2014; Paap & Sawi, 2014), age group (e.g., Bialystok, Martin, & Viswanathan, 2005; Craik &

Bialystok, 2006; Salvatierra & Rosselli, 2011), socioeconomic status (e.g., Morton & Harper, 2007), nonverbal intelligence (e.g., Duñabeitia. et al., 2014), immigration status (e.g., Kousaie & Phillips, 2012b), videogame playing and computer usage (e.g., Bialystok, 2006). Paap et al. (2014) reported that the evidence for a bilingual advantage is not observed when the sample size is high. On the other hand, studies recruiting large samples have reported a bilingual advantage in both reaction time and conflict effect (e.g., Costa et al., 2009; Hernández et al., 2010). Salvatierra and Rosselli (2011) examined cognitive control in late bilinguals (younger and older) and monolinguals in the Simon task. Their results revealed a bilingual advantage in the Simon effect only in older bilingual adults, and there was no evidence for an advantage in younger bilingual adults. Morton and Harper (2007) reported that when the socioeconomic status and intelligence scores were matched in bilingual and monolingual children, there was no evidence in the language group difference in the Simon task. Rosselli, Ardila, Lalwani, and Vélez-Uribe (2016) showed that bilingual and monolingual young adults performed similarly in the Stroop task when the language groups were matched for nonverbal intelligence and language proficiency. Additionally, on matching early bilingual and monolingual children for age, literacy skills, verbal and nonverbal intelligence skills, Duñabeitia et al. (2014) demonstrated similar performance between groups for the colour naming Stroop task and the numerical Stroop task.

Additionally, the mixed evidence across studies have also been pointed towards the removal of reaction time outliers in the data analysis investigating a bilingual cognitive advantage. Recently, Zhou and Krott (2015) reported that the effect of bilingualism on cognitive control tasks is modulated by the removal of longer response times in the reaction time data analyses. They reviewed 33 studies investigating cognitive control in nonlinguistic conflict tasks across bilinguals and monolinguals (the Simon task, the flanker task, and the spatial Stroop task). A total of 67 experiments involving children (n = 16), young adults (n = 33), middle-aged adults (n = 5) and old-aged adults (n = 12) were considered. Depending on the range of RT outliers removal, Zhou and Krott (2015) distributed 67 studies under three different categories: shorter responses (which included studies with RTs below 1000 ms), medium responses (which included studies with RTs from 1000 to 3000 ms) and longer responses (which included studies with RTs > 3000 ms). The analysis revealed that the effect of bilingualism on cognitive control tasks was significant in studies which included outliers > 1000 ms. Zhou and Krott (2015) suggested caution in interpreting reaction time data for a bilingual advantage.

To sum up, the evidence for a bilingual cognitive advantage is mixed across linguistic profiles, task designs and background variables. If at all present, the bilingual advantage is more robust in the speed of reaction time compared to the magnitude of the conflict effect. I predict that this difference might be due to the differences in the reaction time distributions (mean and variance) across language groups. In the present thesis, I matched the reaction time distributions of bilinguals and monolinguals to investigate the magnitude of the conflict effect at similar response bins across groups. I used two approaches (the response-signal procedure and the stimulation procedure) to eliminate the reaction time advantage across groups. In contrast to comparing group at two different response times, this design provides a deeper insight into the magnitude of the conflict effect size at similar time points. Apart from the main research question as summarized below, I will investigate additional research questions in nonlinguistic and linguistic cognitive control tasks between bilinguals and monolinguals. The bilinguals and monolinguals will be matched on most of the variables which are discussed in the literature.

1.6 Summary and Overview

In Chapter 2 (Experiment 1a), I incorporate an evidence accumulation model of two-choice reaction time tasks, in particular a linear ballistic accumulator model (LBA) (Brown & Heathcote, 2008), in order to investigate the decision processing mechanism between bilingual and monolingual participants in the Simon task. To my knowledge, this is the first study fitting reaction time and accuracy data to the LBA model in the bilingual cognitive advantage literature. This was done in order to provide further insight into how (if at all) the two groups differ in terms of evidence accumulation for overt responses using a modelling approach. The LBA model is the simplest evidence accumulation model applied to two-choice reaction time experiments that estimates parameters (drift rate and response threshold) from the accuracy and reaction time data obtained from the button press paradigm (Brown & Heathcote, 2008; Donkin, Averell, Brown, & Heathcote, 2009). In this experiment, I predicted the following outcomes: (i) if bilinguals are better at conflict resolution as proposed by the BICA hypothesis in cognitive control tasks (Hilchey & Klein, 2011), I predicted a faster drift rate and a smaller response threshold values in bilinguals relative to monolinguals only on incompatible trials; (ii) if bilinguals are faster as proposed by the BEPA hypothesis in cognitive control tasks (Hilchey & Klein, 2011), and so I predicted an overall faster drift rate and smaller response threshold values in bilinguals relative to monolinguals across all the trial types.

To pursue the possibility of a bilingual advantage further, in Chapter 2 (Experiment 1b) and Chapter 3 I investigate the time course of the Simon effect in bilingual and monolingual young adults. This will be achieved by using the response-signal procedure coupled with the reach-to-touch paradigm (Chapter 2, Experiment 1b), and the stimulation procedure in the TMS paradigm (Chapter 3). Additionally, in these experiments I explored the time course of task-relevant (colour) and task-irrelevant (location) information. To my knowledge, this is the first study investigating the time course of task-relevant and task-irrelevant response activation differences between bilinguals and monolinguals in the Simon task which uses the reach-to-touch paradigm and the TMS paradigm. Based on the temporal information, I predicted the following outcomes: (i) if bilinguals are faster at responding on incompatible trials relative to monolinguals as predicted by the BICA hypothesis (Hilchey &

Klein, 2011), then I expected a faster response activation for task-relevant colour information only in incompatible trials for bilinguals relative to monolinguals; (ii) if bilinguals are overall faster in cognitive control tasks as predicted by the BEPA hypothesis (Hilchey & Klein, 2011), then I expected a faster response activation for task-relevant information across all the trial types in bilinguals relative to monolinguals.

As mentioned above, in Chapter 4 I employed a reach-to-touch version of the Stroop task in order to investigate the time course of the Stroop effect in bilinguals and monolinguals. If bilinguals are better at conflict resolution, as predicted by the bilingual inhibitory control advantage hypothesis showing a smaller magnitude of the conflict effect (Hilchey & Klein, 2011): if this is the case then there should be a later onset of the Stroop effect in bilinguals relative to monolinguals.

In Chapter 5, I discuss the general findings from all the three experiments and discuss the results with reference to the current theories of bilingual cognitive advantage and conclude with limitations and suggestions for future directions.

References

Australian Bureau of Statistics. (2011). 2011 Census quickstats. http://www.censusdata.abs.gov.au/census_services/getproduct/census/2011/quickstat/0

Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*(3), 242-275. doi:10.1016/j.jneuroling.2006.10.003

Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P. A., Parris, B. A., & Weekes, B. S. (2015). Bilingualism provides a neural reserve for aging populations. *Neuropsychologia*, *69*, 201-210. doi:10.1016/j.neuropsychologia.2015.01.040

Alladi, S., Bak, T. H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A. K., ... & Kaul, S. (2013). Bilingualism delays age at onset of dementia, independent of education and immigration status. *Neurology*, *81*(22), 1938-1944. doi: 10.1212/01.wnl.0000436620. 33155.a4.

Antón, E., Duñabeitia, J. A., Estévez, A., Hernández, J. A., Castillo, A., Fuentes, L. J., & Carreiras, M. (2014). Is there a bilingual advantage in the ANT task? Evidence from children. *Frontiers in Psychology*, *5*(398), 1-12. doi: 10.3389/fpsyg.2014.00398

Bialystok, E. (2006). Effect of Bilingualism and Computer Video Game Experience on the Simon Task. *Canadian Journal of Experimental Psychology*, *60*(1), 68-79. doi: 10.1037/cjep2006008

Bialystok, E. (2009). Bilingualism: The good, the bad, and the indifferent. *Bilingualism: Language and Cognition*, *12*(01), 3-11. doi: 10.1017/S1366728908003477

Bialystok, E., & Craik, F. I. (2010). Cognitive and linguistic processing in the bilingual mind. *Current directions in Psychological Science*, *19*(1), 19-23. doi: 10.1177/0963721409358571

Bialystok, E., Craik, F. I., & Ryan, J. (2006). Executive control in a modified antisaccade task: Effects of aging and bilingualism. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(6), 1341-1354. doi: 10.1037/0278-7393.32.6.1341

Bialystok, E., Craik, F. I., Grady, C., Chau, W., Ishii, R., Gunji, A., & Pantev, C. (2005). Effect of bilingualism on cognitive control in the Simon task: Evidence from MEG. *NeuroImage*, *24*(1), 40-49. doi:10.1016/j.neuroimage.2004.09.044

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and Aging*, *19*(2), 290-303. doi: 10.1037/0882-7974.19.2.290

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859-873. doi: 10.1037/0278-7393.34.4.859

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism*, *9*(1), 103-119. doi: 10.1177/13670069050090010701

Bialystok, E., Craik, F. I., Green, D. W., & Gollan, T. H. (2009). Bilingual minds. *Psychological Science in the Public Interest*, *10*(3), 89-129. doi:10.1177/1529100610387084

Blumenfeld, H. K., & Marian, V. (2014). Cognitive control in bilinguals: Advantages in Stimulus–Stimulus inhibition. *Bilingualism: Language and Cognition*, *17*(03), 610-629. doi: 10.1017/S1366728913000564

Brown, S. D., & Heathcote, A. (2008). The simplest complete model of choice response time: linear ballistic accumulation. *Cognitive Psychology*, *57*(3), 153-178. doi: 10.1016/j.cogpsych.2007.12.002

Burle, B., van den Wildenberg, W., & Ridderinkhof, K. R. (2005). Dynamics of facilitation and interference in cue-priming and Simon tasks. *European Journal of Cognitive Psychology*, *17*(5), 619-641. doi: 10.1080/09541440540000121.

Calabria, M., Branzi, F. M., Marne, P., Hernández, M., & Costa, A. (2015). Age-related effects over bilingual language control and executive control. *Bilingualism: Language and Cognition*, *18*(01), 65-78. doi: 10.1017/S1366728913000138

Calabria, M., Hernández, M., Martin, C. D., & Costa, A. (2011). When the tail counts: the advantage of bilingualism through the ex-Gaussian distribution analysis. *Frontiers in Psychology*, *2*, 250. doi: 10.3389/fpsyg.2011.00250

Coderre, E. L., & van Heuven, W. J. B. (2014). Electrophysiological explorations of the bilingual advantage: evidence from a Stroop task. *PLoS one*, 9(7). doi: 10.1371/journal.pone.0103424.

Colzato, L. S., Bajo, M. T., van den Wildenberg, W., Paolieri, D., Nieuwenhuis, S., La Heij, W., & Hommel, B. (2008). How does bilingualism improve executive control? A comparison of active and reactive inhibition mechanisms. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(2), 302-312. doi: 10.1037/0278-7393.34.2.302

Costa, A., & Caramazza, A. (1999). Is lexical selection in bilingual speech production language-specific? Further evidence from Spanish–English and English–Spanish bilinguals. *Bilingualism: Language and Cognition*, *2*(03), 231-244.

Costa, A., & Sebastián-Gallés, N. (2014). How does the bilingual experience sculpt the brain?. *Nature Reviews Neuroscience*, *15*(5), 336-345. doi: 10.1038/nrn3709

Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition*, *106*(1), 59-86. doi:10.1016/j.cognition.2006.12.013

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don't. *Cognition, 113*(2), 135–149. doi:10.1016/j.cognition.2009.08.001

Costa, A., Miozzo, M., & Caramazza, A. (1999). Lexical selection in bilinguals: Do words in the bilingual's two lexicons compete for selection?. *Journal of Memory and Language, 41*(3), 365-397. doi: 10.1006/jmla.1999.2651

Costa, A., Santesteban, M., & Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(5), 1057-1074. doi: 10.1037/0278-7393.32.5.1057

Craik, F. I., Bialystok, E., & Freedman, M. (2010). Delaying the onset of Alzheimer disease Bilingualism as a form of cognitive reserve. *Neurology*, *75*(19), 1726-1729. doi: 10. 1212/WNL.0b013e3181fc2a1c

Craik, F. I., & Bialystok, E. (2006). Cognition through the lifespan: mechanisms of change. *Trends in Cognitive Sciences*, *10*(3), 131-138. doi:10.1016/j.tics.2006.01.007

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: a dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, 20(4), 731-750. doi:10.1037/0096-1523.20.4.731

Dong, Y., & Li, P. (2015). The cognitive science of bilingualism. *Language and Linguistics Compass*, *9*(1), 1-13. doi: 10.1111/lnc3.12099

Donkin, C., Averell, L., Brown, S., & Heathcote, A. (2009). Getting more from accuracy and response time data: Methods for fitting the linear ballistic accumulator. *Behavior Research Methods*, *41*(4), 1095-1110. doi:10.3758/BRM.41.4.1095

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited. *Experimental Psychology, 61*, 234-251. doi:10.1027/1618-3169/a000243

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143-149. doi: 10.3758/BF03203267

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*(3), 340-347. doi: 10.1162/089892902317361886.

Finkbeiner, M. & Heathcote, A. (2016). Distinguishing the time- and magnitude-difference accounts of the Simon effect. *Attention, Perception and Psychophysics, 78,* 848-867. doi: 10.3758/s13414-015-1044-9

Finkbeiner, M., Almeida, J., Janssen, N., & Caramazza, A. (2006). Lexical selection in bilingual speech production does not involve language suppression. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(5), 1075-1089. doi: 10.1037/0278-7393.32.5.1075

Finkbeiner, M., Coltheart, M., & Coltheart, V. (2014). Pointing the Way to New Constraints on the Dynamical Claims of Computational Models. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 172-185. doi:10.1037/a0033169

Finkbeiner, M., Gollan, T. H., & Caramazza, A. (2006). Lexical access in bilingual speakers: What's the (hard) problem?. *Bilingualism: Language and Cognition*, *9*(02), 153-166. doi: 10.1017/S1366728906002501

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science*, *17*(2), 172-179. doi: 10.1111/j.1467-9280.2006.01681.x

Gathercole, V. C. M., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Guasch, N. V., ... & Jones, L. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Frontiers in Psychology*, *5*, 11. doi: 10.3389/fpsyg.2014.00011

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, *1*(02), 67-81. doi: 10.1017/S1366728998000133

Greene, D. J., Barnea, A., Herzberg, K., Rassis, A., Neta, M., Raz, A., & Zaidel, E. (2008). Measuring attention in the hemispheres: The lateralized attention network test (LANT). *Brain and Cognition*, *66*(1), 21-31. doi:10.1016/j.bandc.2007.05.003

Heathcote, A., Popiel, S. J., & Mewhort, D. J. (1991). Analysis of response time distributions: An example using the Stroop task. *Psychological Bulletin*, *109*(2), 340-347. doi: 10.1037/0033-2909.109.2.340

Hernández, M., Costa, A., Fuentes, L. J., Vivas, A. B., & Sebastián-Gallés, N. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Bilingualism: Language and Cognition*, *13*(03), 315-325. doi: 10.1017/S1366728909990010

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625-658. doi: 10.3758/s13423-011-0116-7

Hilchey, M. D., Ivanoff, J., Taylor, T. L., & Klein, R. M. (2011). Visualizing the temporal dynamics of spatial information processing responsible for the Simon effect and its amplification by inhibition of return. *Acta Psychologica*, *136*(2), 235-244. doi:10.1016/j.actpsy.2010.09.003

Kapa, L. L., & Colombo, J. (2013). Attentional control in early and later bilingual children. *Cognitive Development*, *28*(3), 233-246. doi:10.1016/j.cogdev.2013.01.011

Kaushanskaya, M., & Marian, V. (2009). The bilingual advantage in novel word learning. *Psychonomic Bulletin & Review*, *16*(4), 705-710. doi: 10.3758/PBR.16.4.705.

Kaushanskaya, M., & Prior, A. (2015). Variability in the effects of bilingualism on cognition: It is not just about cognition, it is also about bilingualism. *Bilingualism: Language and Cognition*, *18*(01), 27-28. doi: 10.1017/S1366728914000510

Kirk, N. W., Fiala, L., Scott-Brown, K. C., & Kempe, V. (2014). No evidence for reduced Simon cost in elderly bilinguals and bidialectals. *Journal of Cognitive Psychology*, *26*(6), 640-648. doi: 10.1080/20445911.2014.929580.

Kousaie, S., & Phillips, N. A. (2012a). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research*, *1446*, 71-90. doi: 10.1016/j.brainres.2012.01.052

Kousaie, S., & Phillips, N. A. (2012b). Ageing and bilingualism: Absence of a "bilingual advantage" in Stroop interference in a nonimmigrant sample. *The Quarterly Journal of Experimental Psychology*, *65*(2), 356-369. doi:10.1080/17470218.2011.604788

Krizman, J., Skoe, E., Marian, V., & Kraus, N. (2014). Bilingualism increases neural response consistency and attentional control: Evidence for sensory and cognitive coupling. *Brain and Language*, *128*(1), 34-40. doi: 10.1016/j.bandl.2013.11.006

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology*, *25*(5), 497-514. doi: 10.1080/20445911.2013.799170.

La Heij, W. (2005). Selection processes in monolingual and bilingual lexical access. In J. F. Kroll & A. M. B. de Groot (eds), *Handbook of bilingualism: Psycholinguistic approaches*, 289-307. New York: Oxford University Press.

Luk, G., Anderson, J. A., Craik, F. I., Grady, C., & Bialystok, E. (2010). Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. *Brain and Cognition*, *74*(3), 347-357. doi: 10.1016/j.bandc.2010.09.004

Luk, G., De Sa, E., & Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control?. *Bilingualism: Language and Cognition*, *14*(04), 588-595. doi: 10.1017/S1366728911000010

Martin-Rhee, M. M., & Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism Language and Cognition*, *11*(1), 81-93. doi: 10.1017/S1366728907003227

Meuter, R. F., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language*, *40*(1), 25-40. doi: 10.1006/jmla.1998.2602

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49-100. doi: 10.1006/cogp.1999.0734.

Morton, J. B., & Harper, S. N. (2007). What did Simon say? Revisiting the bilingual advantage. *Developmental Science*, *10*(6), 719-726. doi:10.1111/j.1467-7687.2007.00623.x

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232-258. doi:10.1016/j.cogpsych.2012.12.002

Paap, K. R., & Liu, Y. (2014). Conflict resolution in sentence processing is the same for bilinguals and monolinguals: The role of confirmation bias in testing for bilingual advantages. *Journal of Neurolinguistics*, *27*(1), 50-74. doi: 10.1016/j.jneuroling.2013.09.002

Paap, K. R., & Sawi, O. (2014). Bilingual advantages in executive functioning: problems in convergent validity, discriminant validity, and the identification of the theoretical constructs. *Frontiers in Psychology*, *5*(962), 2. doi: 10.3389/fpsyg.2014.00962

Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex*, *69*, 265-278. doi: 10.1016/j.cortex.2015.04.014

Paap, K. R., Sawi, O. M., Dalibar, C., Darrow, J., & Johnson, H. A. (2015). Beyond panglossian optimism: larger N2 amplitudes probably signal a bilingual disadvantage in conflict monitoring. *AIMS Neuroscience*, *2*(1), 12-17. doi: 10.3934/Neuroscience.2015.1.1.

Peal, E., & Lambert, W. E. (1962). The relation of bilingualism to intelligence. *Psychological Monographs: general and applied*, *76*(27), 1-23. doi: 10.1037/h0093840

Pelham, S. D., & Abrams, L. (2014). Cognitive advantages and disadvantages in early and late bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(2), 313-325. doi:10.1037/a0035224

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3-25. doi: 10.1080/00335558008248231

Pratte, M. S., Rouder, J. N., Morey, R. D., & Feng, C. (2010). Exploring the differences in distributional properties between Stroop and Simon effects using delta plots. *Attention, Perception, & Psychophysics*, *72*(7), 2013-2025. doi: 10.3758/APP.72.7.2013.

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, 17(04), 682-691. doi: 10.1017/S1355617711000580

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognition*, *13*(02), 253-262. doi: 10.1017/S1366728909990526

Quek, G. L., & Finkbeiner, M. (2013). Spatial and temporal attention modulate the early stages of face processing: behavioural evidence from a reaching paradigm. *PLos one*, 8(2). doi: 10.1371/journal.pone.0057365

Quek, G. L., & Finkbeiner, M. (2014). Face-sex categorization is better above fixation than below: Evidence from the reach-to-touch paradigm. *Cognitive, Affective, & Behavioral Neuroscience,* 1-13. doi:10.3758/s13415-014-0282-y

Ridderinkhof, R. K. (2002). Micro-and macro-adjustments of task set: Activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312-323. doi:10.1007/s00426-002-0104-7

Roelofs, A., Piai, V., & Rodriguez, G. G. (2010). Attentional inhibition in bilingual naming performance: evidence from delta-plot analyses. *Frontiers in Psychology*, *2,* 184-184. doi: 10.3389/fpsyg.2011.00184

Rosselli, M., Ardila, A., Lalwani, L. N., & Vélez-Uribe, I. (2016). The effect of language proficiency on executive functions in balanced and unbalanced Spanish–English bilinguals. *Bilingualism: Language and Cognition*, *19*(3). doi: 10.1017/S1366728915000309

Salvatierra, J. L., & Rosselli, M. (2011). The effect of bilingualism and age on inhibitory control. *International Journal of Bilingualism*, *15*(1), 26-37. doi: 10.1177/1367006910371021

Schroeder, S. R., & Marian, V. (2012). A bilingual advantage for episodic memory in older adults. *Journal of Cognitive Psychology*, *24*(5), 591-601. doi:10.1080/20445911.2012.669367

Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology, 81*(1), 174-176. doi: 10.1037/h0027448

Singh, J. P., & Mishra, R. K. (2015). Effect of bilingualism on anticipatory oculomotor control. *International Journal of Bilingualism*. doi: 10.1177/1367006915572398

Singh, N., & Mishra, R. K. (2012). Does language proficiency modulate oculomotor control? Evidence from Hindi–English bilinguals. *Bilingualism: Language and Cognition*, *15*(04), 771-781. doi: 10.1017/S1366728912000065

Singh, N., & Mishra, R. K. (2013). Second language proficiency modulates conflict-monitoring in an oculomotor Stroop task: Evidence from Hindi-English bilinguals. *Frontiers in Psychology, 4*, 322. doi: 10.3389/fpsyg.2013.00322

Singh, N., & Mishra, R. K. (2014). The modulatory role of second language proficiency on performance monitoring: Evidence from a saccadic countermanding task in high and low proficient bilinguals. *Frontiers in Psychology*, *5*. doi: 10.3389/fpsyg.2014.01481

Speckman, P. L., Rouder, J. N., Morey, R. D., & Pratte, M. S. (2008). Delta plots and coherent distribution ordering. *The American Statistician*, *62*(3), 262-266. doi: 10.1198/000313008X333493

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643-662. doi: 10.1037/h0054651

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology*, 2, 123, 83-101. doi: 10.3389/fpsyg.2011.00123

Terao, Y., & Ugawa, Y. (2002). Basic mechanisms of TMS. *Journal of Clinical Neurophysiology*, *19*(4), 322-343.

Tse, C. S., & Altarriba, J. (2012). The effects of first-and second-language proficiency on conflict resolution and goal maintenance in bilinguals: Evidence from reaction time distributional analyses in a Stroop task. *Bilingualism: Language and Cognition*, *15*(03), 663-676. doi: 10.1017/S1366728912000077

Valian, V. (2015). Bilingualism and cognition. *Bilingualism: Language and Cognition*, *18*(01), 3-24. doi: 10.1017/S1366728914000522

von Bastian, C. C., Souza, A. S., & Gade, M. (2016). No evidence for bilingual cognitive advantage: A test of four hypotheses. *Journal of Experimental Psychology: General*, *145*(2), 246-258. doi: 10.1037/xge0000120

Zhang, J., & Kornblum, S. (1997). Distributional analysis and De Jong, Liang, and Lauber's (1994) dual-process model of the Simon effect. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(5), 1543-1551. doi: 10.1037/0096-1523.23.5.1543

Zhou, B., & Krott, A. (2015). Data trimming procedure can eliminate bilingual cognitive advantage. *Psychonomic Bulletin & Review*, 1-10. doi:10.3758/s13423-015-0981-6

Chapter 2

Time Course of the Simon Effect in Bilinguals and Monolinguals*

Manjunath Narra[1,2,3], Andrew Heathcote[4] & Matthew Finkbeiner[1,2,3]

[1] Perception in Action Research Centre, Macquarie University, Australia

[2]Department of Cognitive Science, Macquarie University, Australia

[3]ARC Centre of Excellence in Cognition and its Disorders, Macquarie University, Australia

[4]School of Psychology, The University of Newcastle, Australia

*This chapter is an extended version of a book chapter:

Narra, M., Heathcote, A., & Finkbeiner, M. (in press). Time course differences between bilinguals and monolinguals in the Simon task. In J. Schwieter (Ed.), *Cognitive Control and Consequences of Multilingualism*, 399-428. Amsterdam: John Benjamins.

Abstract

In the Simon task, individuals need to indicate the colour of the target stimulus while ignoring its spatial location. The Simon effect refers to the finding that participants respond more quickly when the target stimulus and response effector are spatially compatible compared to when they are not. Thus, to optimize performance in the Simon task, individuals need to ignore the task-irrelevant (spatial) dimension and attend to the task-relevant (colour) dimension. Interestingly, it has been reported that bilinguals are faster than monolinguals in the Simon task and that they exhibit a smaller Simon effect. The present study investigates whether this so-called bilingual advantage is due to bilinguals being better at ignoring task-irrelevant information, or better at activating task-relevant information, or both. In a button press version of the task, we do not observe a bilingual advantage, but in a reach-to-touch paradigm, we find that bilinguals suppress task-irrelevant information for longer and activate task-relevant information sooner. However, there was no evidence for the group difference in the time course of the Simon effect. The study furthers our understanding of how bilinguals and monolinguals perform in conflict-inducing tasks.

Time Course of the Simon Effect in Bilinguals and Monolinguals

2.1 Introduction

The Simon task has been commonly used to study cognitive control processes involved in resolving the conflict between stimulus and response code (Lu & Proctor, 1995; Simon & Rudell, 1967). The response time difference between the compatible and incompatible trials is referred to as the Simon effect (Hedge & Marsh, 1975) and it is well accounted by dual-route models (De Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990; Lu & Proctor, 1995; Ridderinkhof, 2002; Wascher, Schatz, Kuder, & Verleger, 2001). According to dual-route models, it is assumed that the Simon effect is driven by the response activation from the two independent routes of processing: the direct route (automatic processing) and the indirect route (controlled processing) (see Figure 2.1). Along the direct route processes, it is thought that the stimulus location information automatically activates its corresponding response code. For example, on trials in which the coloured square is presented on the left, the left response is thought to be automatically activated via the direct route. An important feature of these models is that the response activation from the direct route for task-irrelevant spatial information is thought to dissipate rapidly over stimulus processing time (Hommel, 1994; Ridderinkhof, 2002). The direct route is also referred to as automatic processing and unconditional route (Lu & Proctor, 1995; Stürmer et al., 2002).

On the other hand, along the indirect route, it is proposed that the response (i.e., stimulus colour information) is activated according to the task instructions. For example, the red colour square presented on the left visual field requires left response button press (see Figure 2.1). The response activation produced along this route is thought to proceed more slowly than the direct route. The indirect route is also referred to as controlled processing and conditional/cognitive route (Lu & Proctor, 1995; Stürmer et al., 2002). The fast and more accurate responses on compatible trials is attributed to same response code activation through the direct and indirect routes, thus facilitating the response. In contrast, the slower and less accurate responses on incompatible trials are argued to be due to the conflict between the direct and the indirect route response activation, thus requiring suppression of the irrelevant information which in turn, delays the response.

The aim of the present study was to use the dual-route accounts of the Simon effect to guide a systematic investigation of where, if at all, differences between monolinguals and bilinguals exist in the Simon task. Are group differences present in the dynamics of activating task-relevant information or are group differences present in the dynamics of ignoring task-irrelevant information? We investigated this question across two experiments. In the first experiment, we used a mathematical modelling approach of reaction time data and in the second experiment, we used a *reach-to-touch* paradigm.

The Simon task is the most commonly used nonlinguistic response conflict task in bilingual cognitive advantage studies (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Martin, & Viswanathan, 2005; Bialystok, 2009; for a review see Hilchey & Klein, 2011). In this literature, there is ample evidence of a bilingual cognitive advantage in children, middle-aged and old-aged adults for the Simon task (e.g., Bialystok et al., 2004; Bialystok, Craik, & Luk, 2012; Bialystok, Martin, & Viswanathan, 2005; Martin-Rhee & Bialystok, 2008; Poarch & van Hell, 2012; Salvatierra & Rosselli, 2011; Schroeder & Marian, 2012). However, in young adults a bilingual cognitive advantage is quite elusive in the Simon task (e.g., Bialystok, 2006; Bialystok, Craik, Grady, Chau, Ishii, Gunji, & Pantev, 2005; Bialystok, Martin, & Viswanathan, 2005; Gathercole et al., 2014; Kousaie & Phillips, 2012; Paap, Johnson, & Sawi, 2014; Salvatierra & Rosselli, 2011).

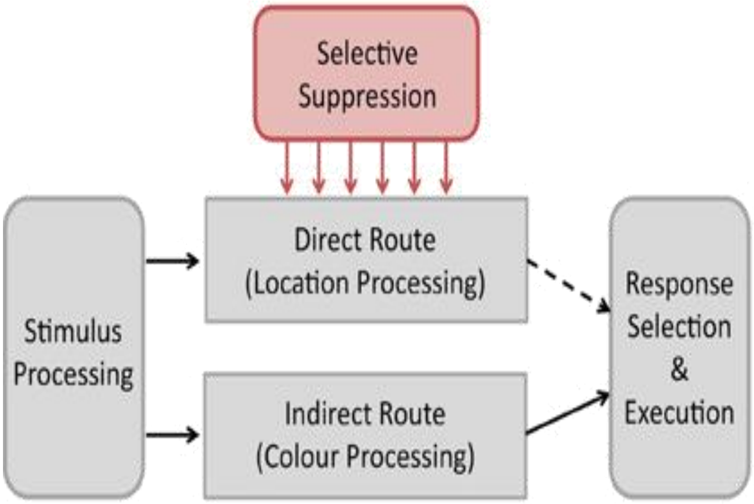


Figure 2.1. Dual-route model reprinted from McBride, Boy, Husain, & Sumner (2012).

For example, Bialystok and colleagues investigated cognitive control differences between monolinguals and bilinguals across children, young adults and elderly adults using the Simon task (Bialystok, Martin, & Viswanathan, 2005). Their results suggested faster reaction time and smaller magnitude of Simon effect only in bilingual children and elderly adults. Similar behavioural performance between bilingual and monolingual young adults was attributed to peak age of cognitive functioning (e.g., Bialystok, Craik, & Luk, 2012; Bialystok, Martin, & Viswanathan, 2005; Hilchey & Klien, 2011; Salvatierra & Rosselli, 2011). These results were consistent even on varying different participant and experimental factors such as the type of bilingualism (early bilinguals: Bialystok, Martin, & Viswanathan, 2005; late bilinguals: Salvatierra & Rosselli, 2011), bilingual language sample (e.g., Bialystok, Martin, & Viswanathan, 2005; Gathercole et al., 2014; Kousaie & Phillips, 2012; Paap, Johnson, & Sawi, 2014; Salvatierra & Rosselli, 2011), experimental task load (e.g., Bialystok, 2006; Salvatierra & Rosselli, 2011), and block design (only compatible and incompatible trials: Bialystok, 2006; Bialystok, Martin, & Viswanathan, 2005; Bialystok et al., 2005; Paap, Johnson, & Sawi, 2014; Salvatierra & Rosselli, 2011; all compatible, incompatible and neutral trials: Kousaie & Phillips, 2012). However, this was not the case in other nonlinguistic conflict tasks, in which bilingual young adults outperformed monolinguals in the attentional network task (e.g., Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa, Hernández, & Sebastián-Gallés, 2008; Pelham & Abrams, 2014), the spatial Stroop task (e.g., Bialystok, 2006; Bialystok & DePape, 2009; Blumenfeld & Marian, 2014), the Stroop task (e.g., Bialystok, Craik, & Luk, 2008; Coderre & van Heuven, 2014; Hernández, Costa, Fuentes, Vivas, & Sebastián- Gallés, 2010; Yow & Li, 2015), the lateralised attentional network task (e.g., Marzecová, Asanowicz, Krivá, & Wodniecka, 2013; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011;), and task switching (e.g., Prior & Gollan, 2011; Prior & MacWhinney, 2010; Wiseheart, Viswanathan, & Bialystok, 2014).

Interestingly, there have been a handful of studies that have failed to detect a bilingual advantage in their behavioural measure, i.e., reaction time, even while detecting a group difference in physiological measures such as magneto-encephalography (MEG), and event-related potentials (ERPs) (cf. Bialystok et al. 2005; Heidlmayr, Hemforth, Moutier, & Isel, 2015; Kousaie & Phillips, 2012). For example, Bialystok et al. (2005) used MEG to investigate the neural correlates of the cognitive control mechanism in the Simon task in young adults. They correlated behavioural performance (response latencies) with brain activity and found in bilingual young adults that faster response latencies correlated with increased brain activation in the right superior and middle temporal, left superior and inferior frontal and cingulate regions. This same correlation in monolinguals was noted only in the left middle frontal regions. The authors speculated that the brain areas activated during the Simon task in bilinguals were similar to the brain areas that subserve language selection in bilingual speech production (e.g., Abutalebi & Green, 2007; Bialystok et al., 2005; Luk, Anderson, Craik, Grady, & Bialystok, 2010).

Recently, Kousaie and Phillips (2012) examined the possibility of a bilingual cognitive advantage using ERPs in the Stroop, Simon, and flanker tasks. The amplitude and latencies of N2 (said to be related to conflict detection and monitoring), P3 (said to be related to stimulus categorization time and resource allocation) and error-related negativity (ERN) components were compared between groups. They did not observe any group differences in the behavioural measures but did in the ERP data. Specifically, the ERP data revealed processing differences between bilinguals and monolinguals in conflict monitoring (N2) and error detection (ERN) for the Stroop task, in resource allocation (P3 amplitude) for the Simon task and; in stimulus categorization (P3 latency) and error detection (ERN) for the flanker task. The ERP data demonstrated that bilinguals and monolinguals use different processes as a function of conflict tasks. To summarize, these studies present a puzzle insofar as bilinguals and monolinguals appear to recruit different brain areas to resolve conflict in the Simon and Stroop tasks even while achieving similar levels of performance.

To date, behavioural studies have largely used accuracy and reaction time data (from button press measures) separately to investigate the possibility of a bilingual advantage in the Simon task. However, the complex association between the accuracy and reaction time data in bilinguals and monolinguals decision processing remains unexplored. In the present study, we incorporate an evidence accumulation model of two-choice reaction time tasks, in specific, the linear ballistic accumulator model (LBA) (Brown & Heathcote, 2008), to investigate decision processing mechanism between bilingual and monolingual participants. The evidence accumulation model uses both response preference (accuracy) and response time taken to complete a response choice, to reveal the dynamics of decision processing (e.g., Brown & Heathcote, 2005; 2008; Donkin, Brown, Heathcote, & Wagenmakers, 2011; Ratcliff & Rouder, 1998). The decision for a choice response was made when the accumulation of information (evidence) reaches its response threshold over time. There is a long history of simultaneously fitting both response latency and accuracy data to evidence accumulation models in cognitive psychology to reveal the decision processing mechanism (e.g., Brown & Heathcote, 2005; 2008; Donkin, Brown, Heathcote, & Wagenmakers, 2011; Ratcliff & Rouder, 1998). Previous researchers have employed modelling approach to capture the underlying decision making differences between elderly and young adults (Ratcliff, Thapar, & McKoon, 2001; 2003), children with and without attention deficit hyperactive disorder (Kralunas & Huang-Pollock, 2013), high working-memory and fluid intelligence young adults (Schmiedek, Oberauer, Wilhelm, Süβ, & Wittmann, 2007), when the mean reaction time and accuracy data alone failed to capture subtle group differences (Donkin, Averell, Brown, & Heathcote, 2009).

In our first experiment, we compared bilingual and monolingual young adults' accuracy and reaction time data by fitting them to the LBA model (Brown & Heathcote, 2008). The modelling approach was carried out to provide further insight into how (if at all) the two groups differed in terms of speed of information processing for overt responses using a modelling approach. The LBA model is the simplest mathematical model of cognitive processing applied to two-choice reaction time experiments that estimates parameters (drift rate and response threshold) from the accuracy and reaction time data simultaneously (Brown & Heathcote, 2008; Donkin, Averell, Brown, & Heathcote, 2009). The drift rate (v) is the rate at which evidence for a particular response is accumulated. The drift rate varies relative to the accumulator (True vs. False), and it indicates the quality of the stimulus. For example, in Figure 2.2 the drift rate on true accumulator (vT) indicates faster accumulation of evidence (information) and overt response choice than the drift on false accumulator (vF). On the other hand, the response threshold (b) is the amount of evidence required before making a response. For example, a lower response threshold value produces a less cautious response, and an increased response threshold value indicates more cautious response (see Figure 2.2).

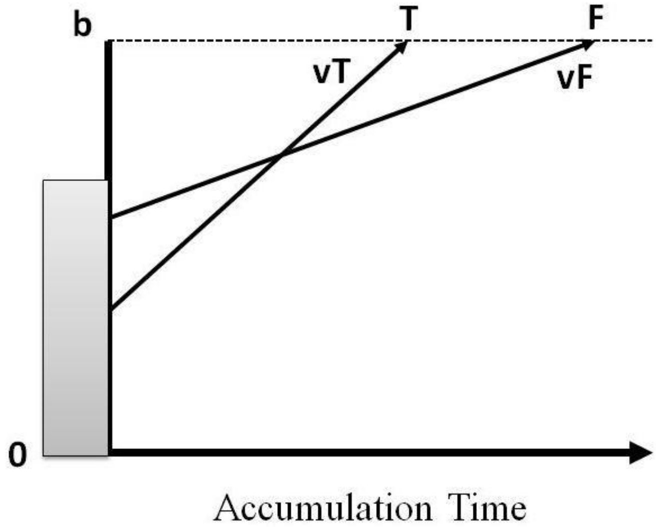


Figure 2.2. Linear Ballistic Accumulator model (b = response threshold; vT = drift rate for true accumulator; vF = drift rate for false accumulator). The shaded rectangle represents the start point variation from trial to trial.

2.2 Experiment 1a: Modelling Button Press Latencies

In our first experiment, participants indicated the colour of a peripherally presented square by pressing an appropriate button as quickly and as accurately as they could. The purpose of this initial experiment was to fit the response latency and accuracy data to the LBA model to see if the modelling approach might reveal any differences between bilinguals and monolinguals that straight reaction times have failed to reveal with young adults. To anticipate our results, we find a very strong Simon effect but do not find any differences between the two groups.

2.2.1 Method

2.2.1.1 Participants

A total of 40 participants were recruited from the Macquarie University participant pool. All participants completed a Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian, Blumenfeld, & Kaushankaya, 2007) (see Appendix A), and Edinburgh Handedness Inventory (Oldfield, 1971) (see Appendix B) before participating in the experiment. From this preliminary interview, the participants were assigned to either the bilingual group (n = 20, mean age = 20.65 years, SD = 3.5; 15 females) or the monolingual group (n = 20, mean age = 21.20 years, SD = 4.78; 14 females). For each of the languages they mentioned in the questionnaire, participants specified their age of acquisition, amount of language usage on a daily basis, and proficiency rating in speaking, listening, and reading (on a 10-point rating scale from *0 = None* to *10 = Perfect*).

The demographic information of bilinguals and monolinguals are reported in Table 2.1. The two groups were matched across age, years of formal education, handedness, nonverbal intelligence, video game playing, and parental education level. The handedness of participants was established using an Edinburgh Handedness Inventory (Oldfield, 1971) questionnaire. The average cumulative scores were calculated for each participant and only participants scoring above 40 were included in the study (right-handed). In order to match for nonverbal intelligence across the groups, participants completed a shortened version of Raven's Advanced Progressive Matrices-Set I (Raven, Raven, & Court, 1998) (see Appendix C). One point was given for each correct answer, with a maximum total of 12. Parental education level, determined as the average of the two parent's highest education level on a five-point scale (1 = *did not graduate from high school*; 5 = *earned a graduate or professional degree*) provided further information about the socioeconomic background. Participants completed the general background questionnaire (see Appendix D), in which they filled out their education history, parental education, history of computer usage, personal and family language history.

The bilingual speakers were heterogeneous language sample with a variety of other languages including Chinese (n = 9), Hindi (n = 3), Bengali (n = 2), Arabic (n = 2), and one speaker each of Serbian, Armenian, Sinhalese and Tagalog. Bilingual participants had been exposed to both English and their other language before the age of six, started actively using second language from the mean age of 4.84 years. None of the participants were left-handed, had a history of speech, language, hearing deficits or any other neurological deficits. Ethical approval was obtained from the Macquarie University Human Research Ethics Committee (see Appendix E). Informed consent was obtained from participants at the beginning of the testing session, and they were compensated financially or with course credit at the end of the each session (see Appendix F).

Table 2.1.

Demographic information for participant groups.

Variables	**Monolinguals Mean (SD)**	**Bilinguals Mean (SD)**	**Sig.**
Age (in years)	21.20 (4.78)	20.65 (3.58)	$p > 0.05$
Formal Education (in years)	13.85 (2.10)	15.30 (3.18)	$p > 0.05$
Edinburgh’s Handedness Scores	83.69 (15.29)	88.69 (17.31)	$p > 0.05$
Ravens Score’s	10.55 (1.23)	10.60 (0.88)	$p > 0.05$
Video Game Playing (Playing hrs/week)	1.45 (2.32)	1.05 (1.93)	$p > 0.05$
Average Parental Education (5 point rating scale)	3.45 (1.39)	3.60 (1.53)	$p > 0.05$
Computer Usage (hrs/day)	4.85 (2.32)	6.60 (2.90)	$p < 0.05$
	English	**English**	**Non-English**
Age of Acquisition (in years)	0.45 (0.68)	3.00 (2.02)	1.57 (1.46)
Language Usage (in %)	100	64.25 (9.49)	29.9 (12.06)
Proficiency Rating (10 point scale)			
Speaking	9.85 (0.48)	9.10 (1.07)	8.40 (0.94)
Understanding	9.80 (0.41)	9.15 (1.08)	8.95 (0.88)
Reading	9.75 (0.55)	9.10 (1.16)	7.55 (1.87)

2.2.1.2 Test Materials

Participants completed the button press and reach-to-touch versions of the Simon task in two different sessions. The order was counterbalanced across participants in each group. In each session, they were seated in front of a 23″ LED monitor (with 1920 x 1080 x 32 pixels at 120 Hz) at a viewing distance of about 90 cm. Presentation® software from Neurobehavioral Systems (version 16.1) was used to deliver the stimulus. The stimuli consisted of red and green colour squares of 50 mm sq. presented at 3° from the central fixation point in one of four locations on the monitor (left, right, up, or down). Participants were instructed to respond to the colour of the target stimulus, irrespective of its location.

There were three different trial types (compatible trial, incompatible trial, and neutral trial). The combination of target location and the corresponding response decided the type of trial. On compatible trials (25 % of the trials) the target was presented on the same side of the screen as its associated response key (e.g., red colour square, presented on the left-side of the fixation, requiring left button press response/reaching towards left response panel). On incompatible trials (25 % of the trials) the stimulus location and its associated response key were on the opposite sides (e.g., red colour square presented on right-side of the fixation, requiring left button press response/reaching towards left response panel). On neutral trials (50 % of the trials), the stimulus location did not correspond to any response key (e.g., red colour square, presented on either top/bottom side of the fixation, requiring left button press response/reaching towards left response panel).

2.2.1.3 Procedure

In the button press version of the Simon task, half of the participants within each group were instructed to press the left button with the left index finger when they saw a red square and the right button with the right index finger when they saw a green square. The opposite response mapping was given to the remaining participants. Each trial began with a fixation cross for 500 ms followed by three beeps at 500 ms, 900 ms, and 1200 ms and the participants were asked to respond as quickly as they could following the third beep. The target stimulus appeared for 300 ms in one of the four locations. The experiment began with a block of practice trials (n = 40) followed by ten blocks of experimental trials (n = 400). The entire task lasted approximately for 45 min.

2.2.2 Results

The dependent measures were mean accuracy rate (%) and mean reaction time (ms). To test our hypothesis, we performed 3 x 2 ANOVA on accuracy (Table 2.2) and reaction time (Table 2.3) separately, with trial type (compatible, incompatible and neutral) as a within-participant factor and group (bilingual and monolingual) as a between-participant factor.

2.2.2.1 Accuracy Rate (%)

The ANOVA analysis revealed a significant main effect of trial type, F (2, 76) = 43.91, $p < .001$, $\eta_p^2 = .32$. Further, we carried out pairwise t-tests with Bonferroni correction in order to investigate the main effect of trial type. The results revealed that participants were more accurate on compatible trials (M = 96.63, SD = 2.97) than neutral trials (M = 95.10, SD = 3.38; t = 2.68, $p < .05$) and incompatible trials (M = 88.30, SD = 8.02; t = 6.81, $p < .001$). And also participants' responses were more accurate on neutral trials than incompatible trials (t = 7.16, $p < .001$). There was no significant main effect of group, F (1, 38) = 1.12, $p = .29$, $\eta_p^2 = .01$; nor interaction between group and trial type, F (2, 76) = 1.51, $p = .22$, $\eta_p^2 = .01$, indicating no difference between bilinguals and monolinguals.

Table 2.2.

Mean accuracy rate and standard deviation (SD) across trial type in bilingual and monolingual participants for button press version of the Simon task.

Trial Type	**Mean Accuracy Rate (SD)**	
	Bilinguals	**Monolinguals**
Compatible Trial	96.29 (18.89)	96.98 (17.09)
Incompatible Trial	86.71 (33.95)	89.90 (30.12)
Neutral Trial	95.04 (21.71)	95.16 (21.71)

2.2.2.2 Reaction Time (ms)

Trials in which responses were too fast (less than 100 ms) or too slow (greater than 1000 ms) were excluded from analyses (resulting in 7.03 % of the trials removed) (Proctor, Yamaguchi, & Vu, 2007). The ANOVA results revealed a significant main effect of trial type, F (2, 76) = 169.8, $p < .001$, $\eta_p^2 = .06$. Pairwise comparisons with Bonferroni corrected p values demonstrated that the participants were significantly faster on compatible trials (M = 503.23 ms, SD = 112.53) than neutral trials (M = 523.54 ms, SD = 106.12; t = 9.17, $p < .001$) and incompatible trials (M = 550.71 ms, SD = 110.04; t = 16.59, $p < .001$). Further, the reaction time was also faster on neutral trials than incompatible trials (t = 10.33, $p < .001$). There was no significant main effect of group, F (1, 38) = 0.006, $p = .93$, $\eta_p^2 = .00$ and no interaction between group and trial type, F (2, 76) = 0.991, $p = .37$, $\eta_p^2 = .00$, suggesting similar performance in bilinguals and monolinguals.

Further to test the above null hypothesis in accuracy and reaction time data, Bayes factor (BF) analysis was administered using the BayesFactor package in R (Morey, Rouder, & Jamil, 2014). BF is a comparison of how well the two hypotheses (null vs. alternative) predict the data with the relative evidence. For accuracy rate, we obtained a BF value of 8.1 for no group and trial type interaction, suggesting positive evidence in favour of the null hypothesis (0.123). For mean correct RT and standard deviation correct RT, we obtained a BF value of 36.5 and 58.9 respectively for no group and trial type interaction, providing strong evidence in favour of the null hypothesis (0.027 & 0.016 respectively).

Table 2.3.

Mean Reaction time (RT) and standard deviation (SD) across trial types in bilingual and monolingual participants for button press version of the Simon task.

	Mean RT (SD)	
Trial Type	**Bilinguals**	**Monolinguals**
Compatible Trial	500.73 (103.43)	505.72 (120.93)
Incompatible Trial	549.84 (100.54)	551.54 (118.57)
Neutral Trial	524.51 (97.86)	522.56 (113.82)

2.2.2.3 Linear Ballistic Accumulator Model

The dependent measures obtained from LBA model (Brown & Heathcote, 2008) are drift rate and response threshold. For drift rate, we performed 3 x 2 x 2 ANOVA with trial type (compatible, incompatible, neutral) and accumulator (true, false) as within-participant factors and group (bilingual, monolingual) as a between-participant factor. The results indicated a main effect of trial type, F (2, 76) = 5.88, $p < .005$, suggesting larger drift rate on compatible trials relative to neutral trials and incompatible trials. The main effect of accumulator, F (1, 38) = 99.57, $p < .001$ was significant suggesting larger drift rate for true accumulator than the false accumulator. There was also a significant interaction between trial type and accumulator, F (2, 76) = 3.79, $p < .05$, indicating larger drift rate for true accumulator relative to false accumulator across all trial types. Interestingly, the significant main effect of group, F (1, 38) = 5.33, $p < .05$ indicated that the bilinguals had overall larger drift rate than the monolinguals. This evidence suggests that bilinguals had a faster evidence accumulation for a corresponding response choice than the monolinguals. There was also a marginal interaction between group and accumulator, F (1, 38) = 3.95, p = .053. The interaction between group and accumulator revealed a lower drift rate for monolinguals than bilinguals, particularly for the false accumulator (monolinguals = - 2.018; bilinguals = - 0.403) and also slightly less for the true accumulator (monolinguals = 1.66; bilinguals = 2.46). The results suggested that the monolinguals received relatively less evidence for decision processing in both false and true accumulator than bilinguals. No other interactions were significant for drift rate (Fs < 0.36).

On the other hand, for response threshold, we performed 3 x 2 x 2 ANOVA, with response location (left, right) and stimulus location (left, right, up, down) as a within-participant factors and group (bilingual, monolingual) as a between-participant factor. The results revealed no significant main effect for response location, F (1, 38) = 0.064, p = .80, stimulus location, F (2, 76) = 0.621, p = .53, and group, F (1, 38) = 0.172, p = .68. However, there was a significant interaction between stimulus location and response location, F (2, 76) = 16.51, p < .001. No other interactions were significant (Fs < 1.75). On further analysis, the results revealed a lower response threshold for left response location compared to that of right response location for left visual field stimulus and; in contrast, the response threshold was lower for right response location relative to left response location for right visual field stimulus. The results suggests that participants were less cautious to select the response when the stimulus location and response location were on the same side, than when they are on the opposite sides. No other comparisons were significant (p's > .05).

In the button press paradigm, the results do not provide evidence for a bilingual advantage in terms of accuracy, and reaction time data. The results are consistent with the previous studies investigating the effect of bilingualism in young adults in behavioural measures, in which they reported no evidence for a bilingual advantage in the Simon task (e.g., Bialystok, 2006; Bialystok, et al., 2005; Bialystok, Martin, & Viswanathan, 2005;

Gathercole et al., 2014; Kousaie & Phillips, 2012; Paap, Johnson, & Sawi, 2014; Salvatierra & Rosselli, 2011). In contrast, for LBA model parameter estimates, in specific for drift rate, the results revealed larger drift rate for bilinguals suggesting faster decision processing relative to monolinguals. However, there was no significant results showing a group by trial type interaction, indicating no evidence for a bilingual cognitive advantage in the Simon task.

Thus, to pursue the possibility of a bilingual advantage further, we turned in Experiment 1b to the *reach-to-touch* paradigm (e.g., Finkbeiner, Coltheart, & Coltheart, 2014; Finkbeiner & Heathcote, 2016; Ocampo & Finkbeiner, 2013; Quek & Finkbeiner, 2013; 2014). The goal of this next experiment was to investigate the time course of response activation along the direct and indirect stimulus-to-response routes in bilingual and monolingual young adults with the aim of better understanding how task-relevant and task-irrelevant information becomes activated and/or suppressed in bilingual and monolingual young adults in the Simon task. Furthermore, by combining the response-signal procedure with the reach-to-touch paradigm, the magnitude and the time course of the Simon effect was investigated across similar response bins between the two groups.

2.3 Experiment 1b: Reach-to-Touch Paradigm

While a great deal of work has been done to establish the presence (or absence) of the so-called bilingual advantage in conflict-inducing tasks, and especially in the Simon task, the reason for the bilingual advantage in this particular task has not yet been established. Are bilinguals better at suppressing the task-irrelevant information? If so, this would suggest that bilinguals are better at controlling the response activation from the direct route which arises “automatically” or “involuntarily” from the spatial location information. Or is it that the bilinguals are better (faster?) at processing task-relevant information. This latter possibility would suggest that bilinguals are faster at activating the response activation from the cognitive route which is thought to be under the participants’ control. In our second experiment we investigated the time course of response activation along these two independent routes in bilingual and monolingual young adults. Since it is difficult to distinguish whether response activation is produced along direct and indirect routes from button press measures (mean RT and accuracy data), a continuous behavioural measure was employed as it is better able to reveal when task-relevant and task-irrelevant information gains control of the overt response (Finkbeiner & Heathcote, 2016). One such continuous behavioural measure which meets these requirements is the reach-to-touch paradigm (e.g., Finkbeiner, Coltheart, & Coltheart, 2014; Quek & Finkbeiner, 2013; 2014; Song & Nakayama, 2009; Spivey, Grosjean, & Knoblich, 2005).

In our version of the reach-to-touch paradigm, participants classified the colour of the stimulus by reaching out and touching the appropriate response panel, fixed on either side of the computer monitor (Finkbeiner & Heathcote, 2016). An electromagnetic motion capture device was used to track the reaching responses, which allowed us to establish whether their initial movement was in the correct or incorrect direction. This was achieved by calculating x-velocity on each trial (Finkbeiner, Coltheart, & Coltheart, 2014; Quek & Finkbeiner, 2013), which is a signed value where positive values indicate reaching movements in the correct direction and negative values indicate reaching movements in the incorrect direction.

Further, we combined the reach-to-touch paradigm with the response-signal procedure, in which participants were instructed to start their reaching movements in synchrony with an imperative go signal (cf. Finkbeiner, Coltheart, & Coltheart, 2014). This procedure is crucial in order to eliminate the reaction time distribution differences between the language groups and compare the magnitude of Simon effect at similar response bins.

The target stimulus and go signal were presented in three different stimulus-onset-asynchronies (SOA's): at 0 ms, 150 ms, and 250 ms. In the latter two SOA's, the target stimulus was presented before the go signal. Across the 3 SOAs, we were able to elicit reaching movements across a wide range of stimulus viewing times. We refer to the time between stimulus onset and movement onset as the 'movement initiation time' (MIT). Finally, we analyse the initial x-velocity of each reaching response as a function of MIT. This allows us to determine how much the participant knew about the target stimulus (i.e., colour) at the time of movement initiation, which allows us to map out the onset, growth and decay of the Simon effect in stimulus processing time.

Using the reach-to-touch paradigm in the Simon task, Finkbeiner and Heathcote (2016) demonstrated how to disentangle response activation of the fast direct route from that of the slow cognitive route on incompatible and neutral trials respectively (see Figure 2.3). On incompatible trials, the stimulus location and the response panel were on spatially opposite sides (Figure 2.3A) and their findings showed that the stimulus location automatically elicited reaching movements in the incorrect direction (but only in movements with the earliest MITs). More specifically, for incompatible trials they found that the initial direction of movements initiated 100 ms following target onset were reliably incorrect (initial x-velocity was reliably negative). On neutral trials, the influence of stimulus location information was eliminated by presenting stimuli on the vertical axis (above and below central fixation) (Figure 2.3B). In this condition, they demonstrated that the stimulus colour information elicited reaching movements in the correct direction (but only in movements with the later MITs). In particular, for neutral trials they reported that the initial direction of movements initiated 240 ms following target onset were reliably correct (initial x-velocity was reliably positive). Thus, supporting dual-route claims, Finkbeiner and Heathcote (2016) were able to differentiate the early emergence of response activation along the direct route for task-irrelevant stimulus information (i.e., location processing) from the later emergence of response activation on cognitive route for task-relevant stimulus information (i.e., colour processing). In our second experiment we employed the same version of the reach-to-touch paradigm to investigate possible differences between monolinguals and bilinguals in the time course of response activation from direct and indirect routes.

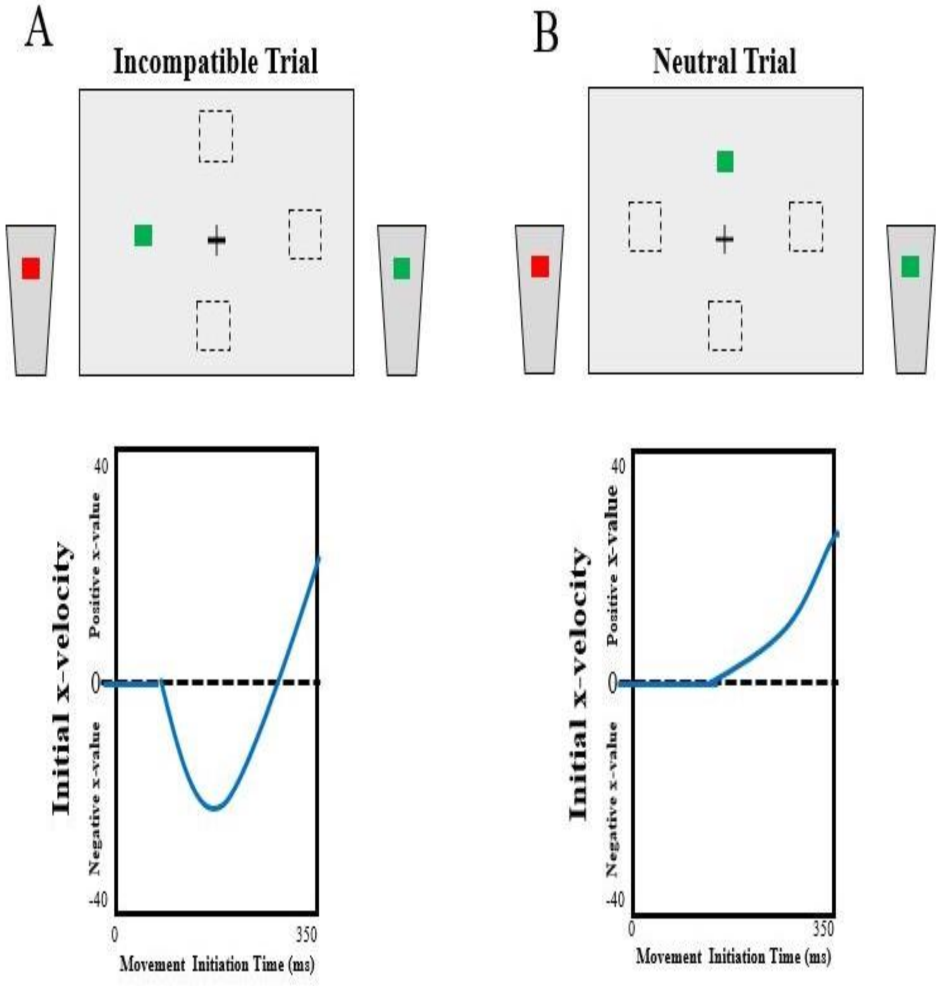


Figure 2.3. Representation of initial x-velocity as a function of movement initiation time for (A) incompatible trials and (B) neutral trials in Finkbeiner and Heathcote (2016) study. The initial x-velocity is the average over the first 150 ms of the reaching responses. The *zero* on y-axis corresponds to initial x-velocity of zero. The reaching responses above *zero* indicate positive x-values in the correct direction and reaching responses below *zero* indicates negative x-values in the incorrect direction. On incompatible trial (A), at early movement initiation time points the initial x-velocity was negative in the incorrect direction. On neutral trials (B), at later movement initiation time points the initial x-velocity was positive in the correct direction. The dotted square inside the screen represents the other three locations of stimuli presentation. The panels on either side of the screen are the response target locations for the corresponding target colour.

2.3.1 Method

Participants and test materials section were identical to those used in Experiment 1a.

2.3.1.1 Procedure

In this version of the Simon task, participants were asked to reach out and touch the left response panel for red targets and the right response panel for green targets (or vice versa depending on the counterbalanced lists). The reaching movements for each trial were recorded using an electromagnetic motion capture system Polhemus Liberty (at 240 Hz) from the sensor (weight: 3.69 grams) taped to the right index finger. Participants commenced each trial sequence by moving their right index finger to the "start position" located at the middle edge of the desk of width 140 cm. The experiment began with two blocks of practice trials (n = 80), and followed by eight blocks of experimental trials (n = 320). A central fixation cross was presented on screen for 500 ms, followed by three beeps presented through headphones (Sennheiser, HD 280 Pro). The target colour square was presented for 300 ms in any one of the four locations (see Figure 2.3). The final third beep served as imperative go signal, for which the participants were instructed to initiate their reaching movement. The auditory go signal and target stimulus were presented at three different SOAs: at 0 ms SOA comprising 40 % of the trials (target and go signal appeared simultaneously); at 150 ms SOA comprising 40 % of the trials (target appeared 150 ms before the go signal) and at 250 ms SOA (target appeared 250 ms before the go signal). The purpose of using 3 different target-to-go signal SOAs was simply to elicit a wide range of MITs, which is central to the analyses that we describe below.

On each trial, participants were required to initiate their responses within a 300 ms response time window that opened 100 ms before the go signal and closed 200 ms after the go signal. However, if participants failed to initiate their movement within this response window (~ 450 ms) the trial was terminated with a buzz and visual feedback was presented on screen (e.g. “Too Early!” or “Too Late!”). The reaching responses that were initiated before the target onset were used to establish baseline information processing. This is further supported in the data suggesting that the responses were on an average down the centre in the first MIT quantile, indicating that they were neither in the correct direction nor in the incorrect direction. Thus, the reach-to-touch paradigm coupled with response-signal procedure allowed us to track the reaching responses across a range of target viewing times, from ~ 100 ms before target onset (at 0 ms SOA) to ~ 450 ms after target onset (at 250 ms SOA). Further, participants were required to maintain a continuous forward reaching movement over the first ~ 250 ms of response initiation and, if failed to maintain this criterion the trials were terminated with a buzz and visual feedback.

2.3.1.2 Data Analysis

Practice trials in the initial two blocks were discarded from the analysis and also trials in which participants failed to initiate their reaching movement within the response window. To track the time course of reaching responses as a function of stimulus viewing time in the Simon task, we followed similar protocol as described by Finkbeiner and colleagues to analyse reaching trajectories (see Finkbeiner et al., 2014; Finkbeiner & Heathcote, 2016). On each trial, first the x-velocity was calculated by filtering the position data with a two-way low pass Butterworth filter at 7 Hz, and we calculated the derivatives (i.e., velocity and acceleration) through numerical differentiation. Then the movement onset and movement offset were measured by the tangential velocity profile, such that movement onset was defined as the first of 20 consecutive samples that exceeded 10 cm/s, and movement offset was defined as the first of 20 consecutive samples that occurred after peak tangential velocity and that fell below 10 cm/s. Further, to examine the effect of MITs on x-velocity, we ran a modified version of orthogonal polynomial trend analysis (OPTA) (Karayanidis, Provost, Brown, Paton, & Heathcote, 2011; Woestenburg, Verbaten, Van Hees, & Slangen, 1983) on x-velocity profiles. In this analysis, each trial was ranked according to the MIT latency and then the MIT ranks were included as a covariate in a polynomial regression model of participants' x-velocity profiles (for a detailed description, see Finkbeiner et al., 2014; Quek & Finkbeiner, 2013; 2014).

The regression coefficients were then used to generate predicted x-velocity values for each trial, allowing for a very fine-grained analysis of changes in the reaching response as a function of target viewing time. Only the initial portion of the reaching trajectory, i.e., 150 ms was analysed to note the time course of experimental effects across trials. This, in turn, helps to capture the amount of information accumulated about the target stimulus at the time of movement initiation. We refer to this dependent measure as initial x-velocity. For statistical analysis, we computed the initial x-velocity by averaging across the first 150 ms of the predicted x-velocity profiles and then entered these mean values into a linear mixed-effect model (LMM) (Bates, 2005), with subject as a random factor and MIT percentile as a fixed factor.

As mentioned earlier, the movement initiation times obtained across the three different SOA's were rank ordered and then grouped into 20 quantiles of equal proportion such that the 1^{st} quantile consisted of the trials with the fastest MITs and the 2^{nd} quantile consisted of second fastest MITs and so on. The distribution of MITs for bilinguals and monolinguals are depicted in Figure 2.4 and 2.5 respectively. This broad distribution of MITs is important as it allows us to examine the evolution of correct (and incorrect) responses across the first few hundred milliseconds of stimulus processing time. Figure 2.4 and 2.5 illustrates the mean predicted x-velocity profiles across 20 MIT quantiles compatible for trial types for bilinguals and monolinguals. As figures makes clear, the longer the participants waited to begin their reaching movements, the better they knew how to respond as indicated by their reaching peak x-velocity in the correct direction more quickly (see Figure 2.4 & 2.5).

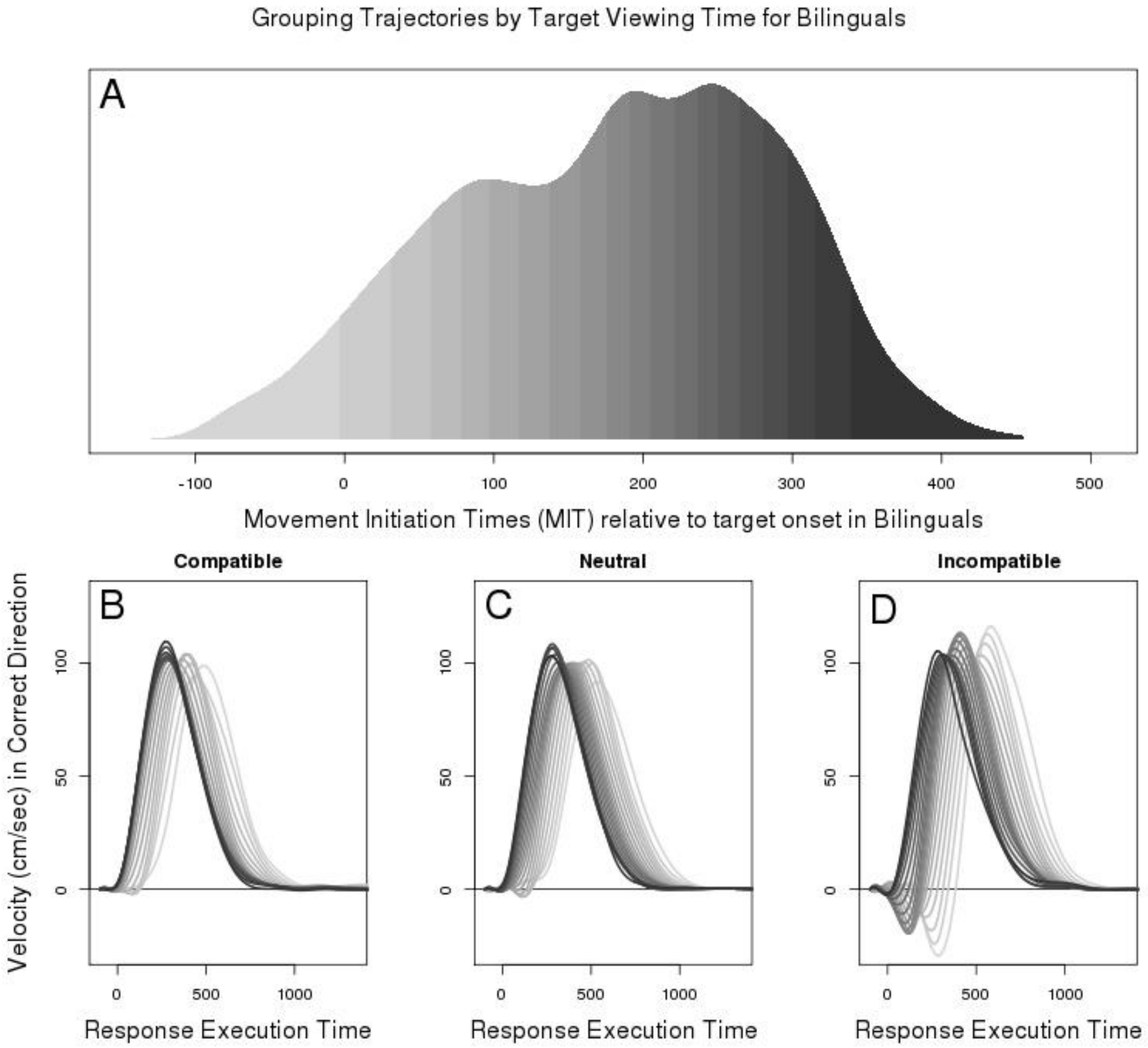


Figure 2.4. Movement initiation time relative to target onset in bilinguals. (A). Distribution of MIT's from -100 ms (before target onset at 0 ms SOA) to 450 ms (after target onset at 250 ms SOA) for bilinguals. Reaching movements across 20 quantiles on compatible (B), neutral (C), and incompatible trials (D). Each quantile consisted of 5 % of total trials arranged in ranking order in which, the 1st quantile consisted of first fastest MITs, and 2nd quantile consisted of next fastest MITs and so on. The greyest lines correspond to reaching responses initiated in the earlier MITs and darkest lines correspond to reaching responses in the longer MITs. The longer that participants view the target stimulus before response initiation, faster the emergence of peak x-velocity in the correct direction.

2.3.1.3 Statistical Analyses

The data was analysed with a linear mixed-effect model (Baayen, Davidson, & Bates, 2008; Bates, 2005) implemented in R with the lmer4 package (Bates, Maechler, & Bolker, 2012). This analysis allowed us to consider both fixed and random factors simultaneously. We further evaluated the contribution of each term to the model by comparing that model with one that excluded the effect. The test values (AIC, BIC, log likelihood) were considered to select the best model. We included subject as a random factor, together with fixed factors trial type (compatible, incompatible, neutral), and group (monolingual, bilingual) for accuracy data and included MIT quantiles (1 to 20) for reaching data. We further report coefficients (b), standard errors (SE), and t-values for the resulting model selected. As is typical in LMM analyses, we have taken a coefficient value twice the size of the standard error (i.e. $|t|>2$) was taken as significant (Baayen, Davidson, & Bates, 2008). The coefficients for the trial type and group factor used the compatible trial and bilingual group as a baseline respectively so that the negative values indicate smaller x-velocities relative to the compatible trial and bilingual group in reaching data.

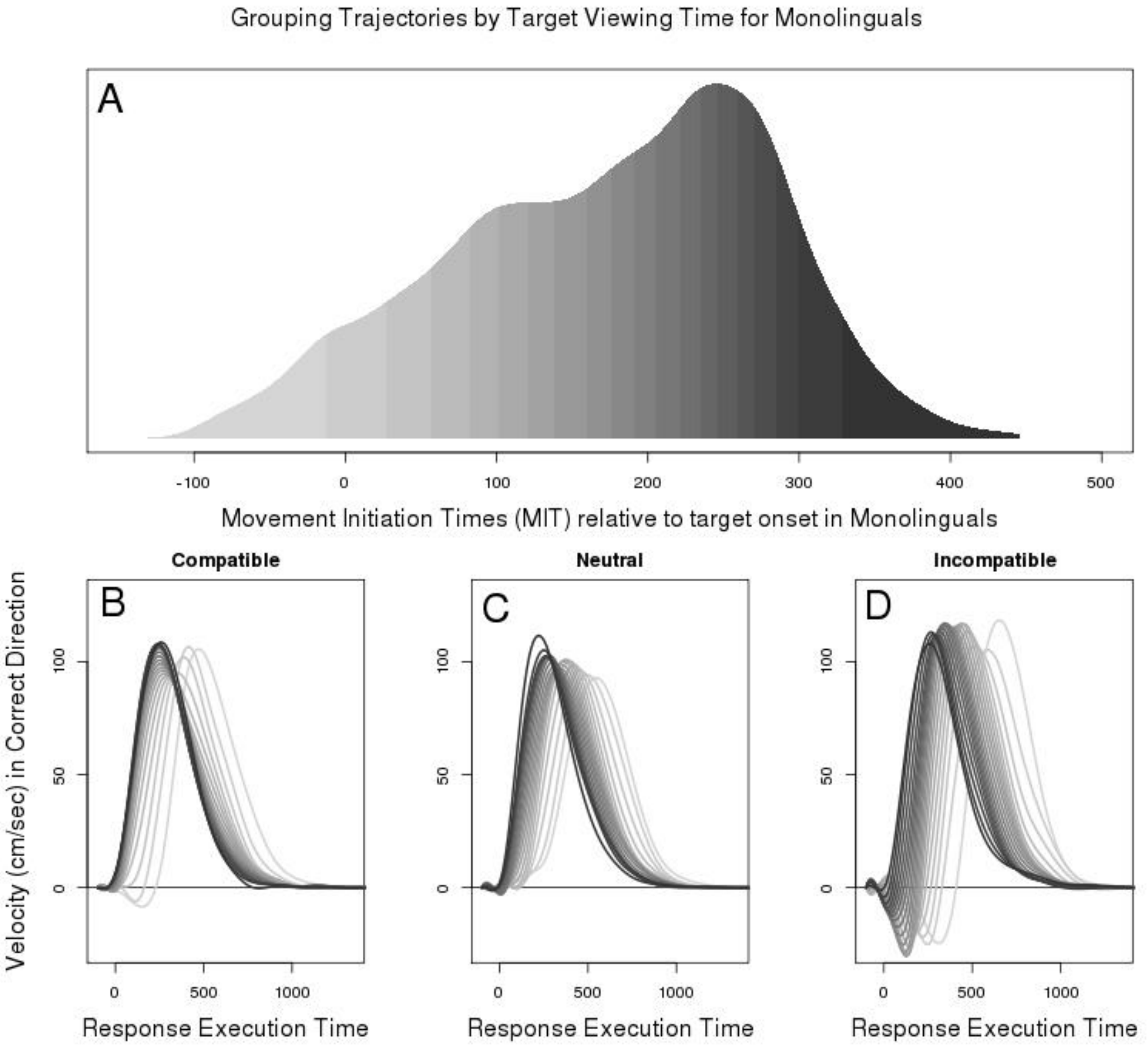


Figure 2.5. Movement initiation time relative to target onset in monolinguals. (A). Distribution of MIT's from -100 ms (before target onset at 0 ms SOA) to 450 ms (after target onset at 250 ms SOA) for monolinguals. Reaching movements across 20 quantiles on compatible (B), neutral (C), and incompatible trials (D). Each quantile consisted of 5 % of total trials arranged in ranking order in which, the first quantile consisted of first fastest MITs, and the second quantile consisted of next fastest MITs and so on. The greyest lines correspond to reaching responses initiated in the earlier MITs and darkest lines correspond to reaching responses in the longer MITs. The longer that participants view the target stimulus before response initiation, faster the emergence of peak x-velocity in the correct direction.

2.3.2 Results

The dependent measures in this paradigm were accuracy rate (%), movement initiation time and initial x-velocity by movement initiation time (ms).

2.3.2.1 Accuracy Rate (%)

The accuracy rates were very high in all the three trial types, consistent with the reach-to-touch paradigm studies, which is presumed to be due to the relatively long duration of the reaching response (e.g., Finkbeiner et al., 2014). This in turn provides participants an opportunity to recognize and correct mistakes in the mid-flight of motor response. The LMM analysis revealed a significant main effect of trial type, indicating higher accuracy rates on compatible trials (M = 99.84, SD = 0.58) relative to incompatible trials (M = 99.27, SD = 1.48), b = - 1.7, SE = 0.54, z = - 3.15. There was no significant difference between compatible and neutral trials (M = 99.85, SD = 0.31), b = - 0.11, SE = 0.60, z = - 0.19. In contrast, including group as a factor did not significantly improve the fit of the model, nor did the interaction between trial type and group (*p's* > .05).

2.3.2.2 Movement Initiation Time

Movement initiation time is the time in milliseconds from the target stimulus onset until the participant began their reaching movement. Figure 2.6 illustrates the distribution of movement initiation times relative to the target onset across trial types and groups. We further run LMM analysis with subject as a random factor and trial type (compatible, incompatible, neutral) and group (bilingual, monolingual) as fixed factors. The results revealed that the fixed effect of trial type, $\chi^2(2) = 0.02$, $p = .98$ and group, $\chi^2(1) = 0.11$, $p = .73$ did not contribute to the fit of the model nor the interaction between trial type and group, $\chi^2(2) = 0.27$, $p = .87$. The data confirms that the movement responses were initiated at similar response time window relative to the imperative go signal (final 3rd beep) across trial type and group, which is critical for interpreting the reaching responses. This data suggests that the two groups had similar response distributions across stimulus viewing time.

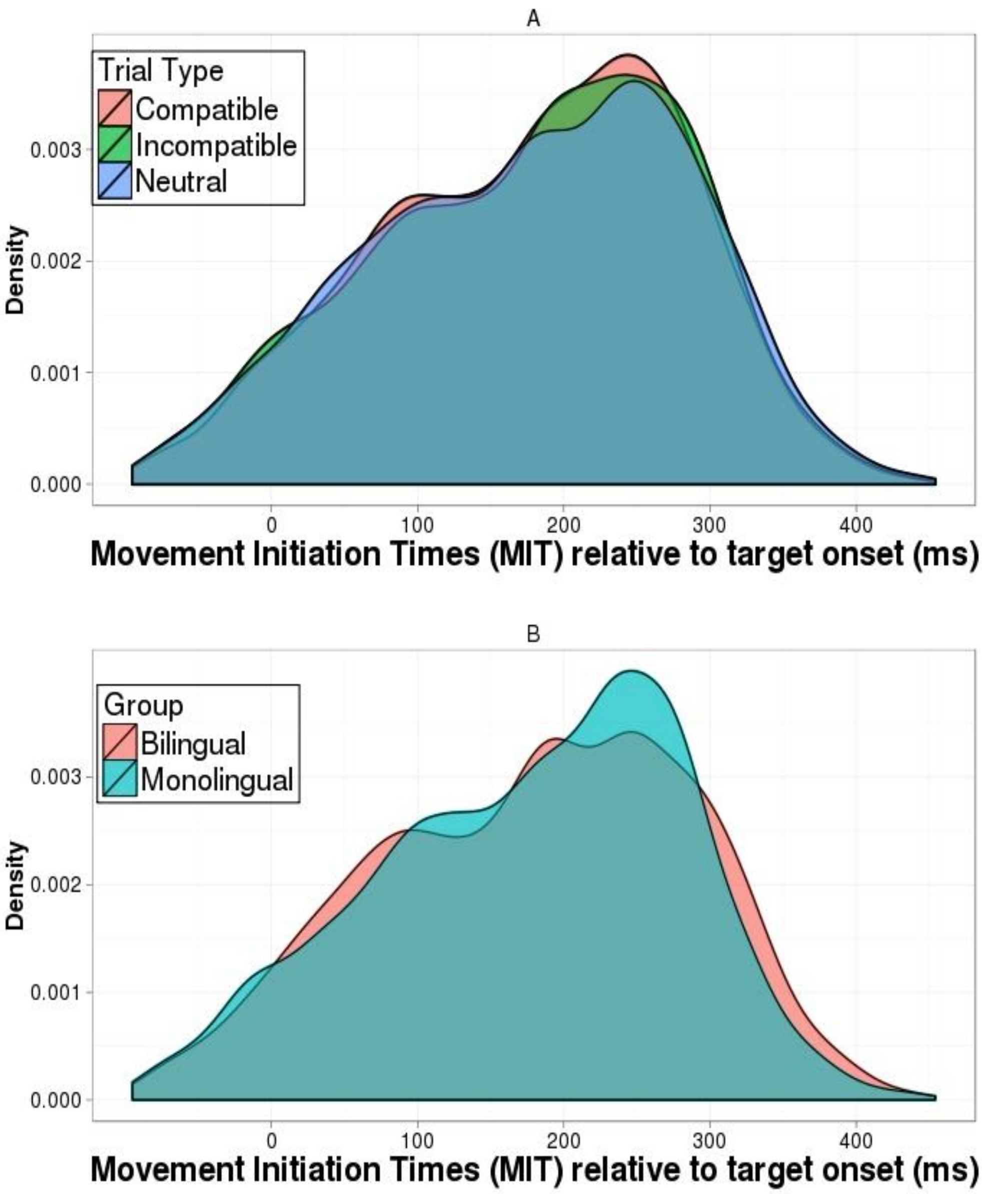


Figure 2.6. Distribution of movement initiation times relative to the target onset across trial types (A) and groups (B). The x-axis indicates the time when the target was presented relative to the imperative go signal. The negative MIT's indicates the response movement samples that were initiated at 0 ms SOA, in which the response time window was opened 100 ms before the target presentation. The negative MIT samples serve as a baseline for reaching responses before the onset of target stimulus. The y-axis in figure A and B is the probability density function, which is the area under curve represents the probability of getting an x-value between a range of x-values.

2.3.2.3 Initial x-velocity Profile

The results revealed a significant main effect of trial type suggesting higher initial x-velocity on compatible trials relative to neutral trials (*b* = - 5.19, *SE* = 0.39, *t* = - 13.25) and incompatible trials (*b* = - 14.67, *SE* = 0.45, *t* = - 32.32). There was no significant main effect of group, χ (1) = 0.85, *p*= *.35*. There was also a significant increase in x-velocity across MIT quantiles (*b* = 928.67, *SE* = 35.24, *t* = 26.35). In addition to these main effects, there was an interaction between MIT quantile and trial type, which suggests higher x-velocity on compatible trials across MIT quantiles relative to neutral trials (*b* = - 125.75, *SE* = 43.31, *t* = - 2.90) and incompatible trials (*b* = - 702.57, *SE* = 50.19, *t* = - 14). Interestingly, there was also an interaction between trial type and group, which suggests lower x-velocity for neutral trials (*b* = - 4.66, *SE* = 0.55, *t* = - 8.37) and incompatible trials (*b* = - 10.17, *SE* = 0.64, *t* = - 15.76) relative to compatible trials for monolinguals than bilinguals. The interaction between group and MIT quantile indicates that the x-velocity was lower for bilinguals relative to monolinguals across MIT quantiles (*b* = 297.66, *SE* = 50.31, *t* = 5.92). There was, however, a significant three-way interaction between MIT quantile, trial type and group on incompatible trials (*b* = - 221.65, *SE* = 71.39, *t* = - 3.10) and neutral trials (*b* = - 134.13, *SE* = 61.69, *t* = - 2.17).

To further examine the nature of the three-way interaction, we analysed each group separately using LMM as described earlier. Table 2.4 presents the coefficients, standard errors (SE's) and t-values for bilingual and monolingual groups presented in the final model. As mentioned earlier, the coefficient value twice the size of the SE was taken as significant (|t|>2). Across both the groups, the initial x-velocity was significantly higher for compatible trials than the incompatible and neutral trials. A significant increase in initial x-velocity as a function of MIT quantiles was observed in both the groups. Further, an interaction between trial type and MIT quantile suggested that the initial x-velocity significantly changed across quantiles between trial types in both the groups. This two-way interaction is illustrated in

Figure 2.6, the zero intercept on the y-axis indicates a net x-velocity of 0 (cm/sec). The initial x-velocity values greater than *zero* correspond to initial reaching movements in the correct direction; values less than *zero* indicate initial reaching movements in the incorrect direction. The mean MIT in the first MIT quantile is negative, indicating that participants' earliest responses were initiated before the target appeared. The reaching movements initiated within the first ~ 100 ms of stimulus viewing time (i.e., the first five MIT quantiles) were on the zero line. This demonstrates that the initial reaching movements were neither in the correct nor incorrect direction. However, the reaching movements that were initiated after ~ 100 ms of stimulus viewing time differ as a function of trial type. On compatible trials, the reaching movements were in the correct direction; in contrast, on incompatible trials, the pattern was bimodal. Initially, the reaching movements were in the incorrect direction at the earliest stimulus processing stage and then with a further increase in the stimulus viewing time the reaching responses were in the correct direction. On neutral trials, the initial x-velocity of movements was not different from zero until after ~ 240 ms of stimulus viewing time. From that time on, the initial x-velocities steadily increased in the correct direction.

Table 2.4.

Fixed effects across groups estimated with LMM.

Group	Fixed effects	b	SE	t-value
Bilingual	Trial type (Incompatible)	-14.73	0.34	-42.70
	Trial type (Neutral)	-5.26	0.29	-17.68
	MIT quantile	671.51	19.01	35.32
	Trial Type* MIT quantile (Incompatible)	-460.10	27.07	-16.99
	Trial Type* MIT quantile (Neutral)	-88.22	23.36	3.78
Monolingual	Trial type (Incompatible)	-24.53	0.53	-45.63
	Trial type (Neutral)	-9.66	0.46	-20.78
	MIT quantile	868.24	29.62	29.31
	Trial Type* MIT quantile (Incompatible)	-599.71	41.89	-14.32
	Trial Type* MIT quantile (Neutral)	-175.45	36.23	4.84

2.3.2.3.1 Time Course of the Simon Effect

In our first pairwise comparison, we investigated when in stimulus processing time the difference emerged between compatible and incompatible trials, i.e., onset of the Simon effect, and when in stimulus processing time the difference resolved, i.e., decay of the Simon effect. To test this we contrasted initial x-velocities across compatible and incompatible trials at each of the 20 MIT quantiles using paired t-test with Bonferroni corrected *p* values separately across groups. The results revealed that for bilinguals the difference emerged from the 6^{th} MIT quantile at 106 ms of stimulus viewing time ($p < .05$) and was resolved by the 18^{th} MIT quantile at 299 ms of stimulus viewing time ($p = .28$). This pattern was identical in the monolinguals, where the difference emerged from the 6^{th} MIT quantile at 110 ms of stimulus viewing time ($p < .01$) and resolved by the 18^{th} MIT quantile at 289 ms of stimulus viewing time ($p = .08$). The data suggested similar time window of onset and decay of the Simon effect across bilingual and monolingual young adults.

2.3.2.3.2 Time Course of the Trial Type (compatible, neutral, incompatible)

In our second set of comparisons, we investigated the point in stimulus viewing time when the initial x-velocity profiles of each trial type (compatible, neutral, and incompatible) differed from the zero horizontal line (see Figure 2.7). To do this, we ran one-sample t-tests with Bonferroni corrected *p* values at each of the 20 MIT quantiles across trial type within each language group.

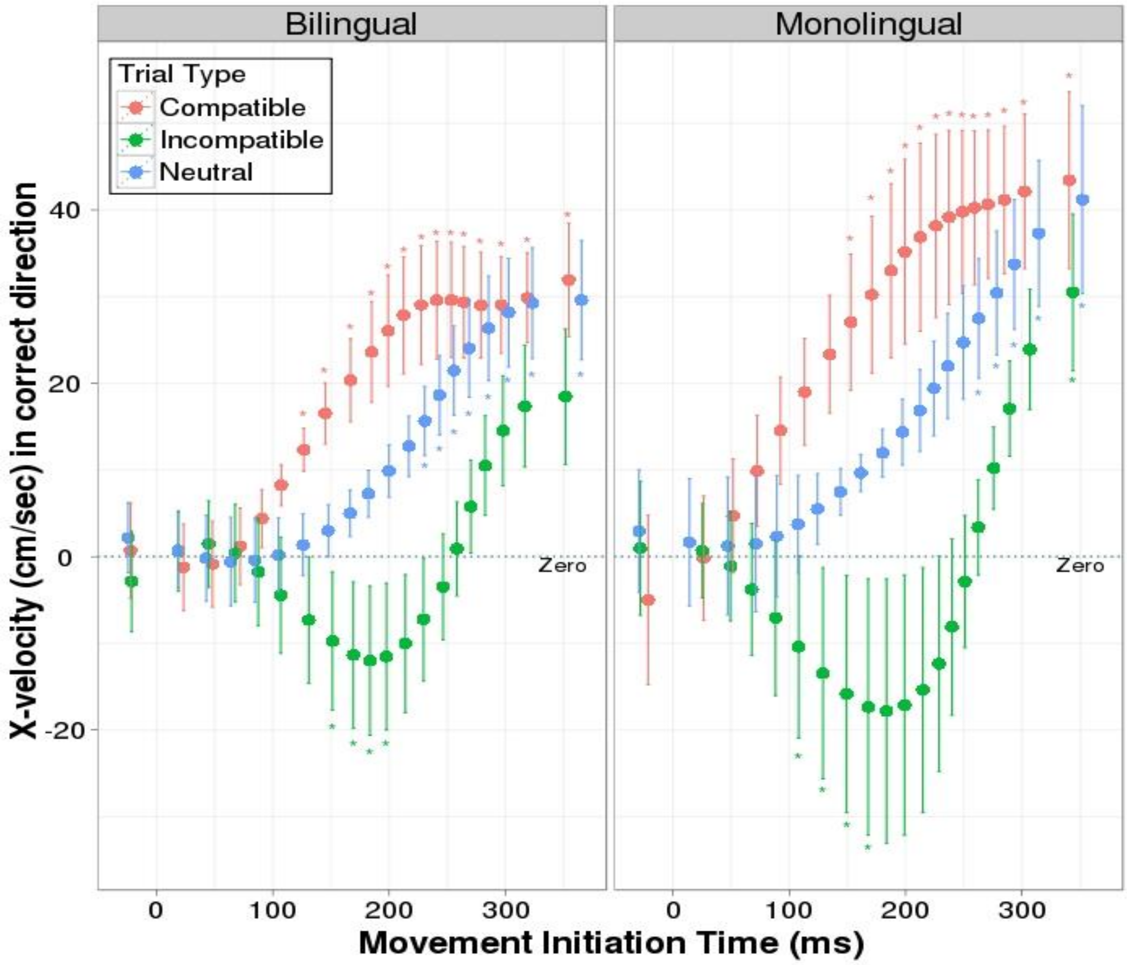


Figure 2.7. Initial x-velocity as a function of movement initiation time for compatible, incompatible and neutral trial types. Error bars represent confidence intervals. The *zero* on y-axis corresponds to x-velocity of zero. The reaching responses above *zero* indicate positive x-values in the correct direction and reaching responses below *zero* indicates negative x-values in the incorrect direction. The reaching profiles vary as a function of trial type after ~ 100 ms of target viewing time. Asterisks indicate Bonferroni corrected ($p < .05$) significant difference between *zero* and x-velocity across trial types.

Compatible Trials. On compatible trials (see Figure 2.7), the initial x-velocities of our bilingual participants were significantly greater than zero for movements that commenced from the 7th MIT quantile at 127 ms (p < .05) until the 20th MIT quantile at 354 ms (p < .01) and in monolinguals it was from the 8th MIT quantile at 153 ms (p < .05) till 20th MIT quantile at 340 ms. The time points across groups indicates that on compatible trials the bilingual participants produced reliably correct initial movements earlier in time than the monolingual participants (by 26 ms).

Neutral Trials. On neutral trials (see Figure 2.7), the initial x-velocities for the bilingual participants were significantly greater than zero for movements commenced from the 13th MIT quantile at 230 ms (p < .05) until the 20th MIT quantile at 365 ms (p < .001*)*, whereas for monolingual group the initial x-velocities were significantly greater than zero for movements that commenced from the 16th MIT quantile at 263 ms (p < .05) until 20th MIT quantile at 352 ms (p < .001). The data points suggest that on neutral trials, the bilinguals produced reliably correct initial movements earlier in time than the monolinguals (by 33 ms).

Incompatible Trials. On incompatible trials, as mentioned earlier the pattern was bimodal, the initial x-velocities were significantly different at two stages along the zero (see Figure 2.7). *First stage*, the initial x-velocities were significantly less than zero, at the earliest stimulus processing time (~ 150 ms), indicates the reaching movements in the incorrect direction i.e., towards the wrong response panel. For bilingual group, the initial x-velocities were significantly less than zero for movements that commenced from the 8th MIT quantile through to the 11th MIT quantile (~ 151 ms through to 198 ms; p < .05), whereas for the monolingual group, it was from the 6th MIT quantile through to the 9th MIT quantile (~ 108 ms through to 168 ms; p < .05). The time course differences between groups at this early stage suggest that the bilingual participants took longer stimulus viewing time to produce initial movements in the incorrect direction relative to monolinguals (by 43 ms). *Second stage*, the initial x-velocities were reliably greater than zero, at the later stimulus processing time (~ 350 ms), illustrates the reaching movements in the correct direction i.e., towards the correct response panel. For the bilingual group, the later stage was not yet observed significantly until the 20^{th} MIT quantile at 351 ms ($p = .22$), whereas for the monolingual group, it was just observed at the 20^{th} MIT quantile at 344 ms ($p < .05$). The data at the later stage indicates that monolinguals' initial x-velocities were reliably above chance in the correct direction relative to bilinguals' initial x-velocities.

The fine-grained analysis reveals when in stimulus viewing time the reaching responses were significantly different from zero and thus helps to distinguish response activation differences from the direct and indirect routes. To summarize, on neutral trials, the time point when the initial x-velocity was significantly greater than zero indicates the response activation from the indirect *cognitive* route for task-relevant information, i.e., colour processing. The group data shows that the bilinguals are faster to activate task-relevant information compared to monolinguals. Further, on incompatible trials, the time point when the initial x-velocity was reliably below zero in the incorrect direction represents the point in time when the activation of task-irrelevant location information gains control of the response formulation process. The group data shows that bilinguals took longer to activate responses along the direct route than monolinguals. Interestingly, when looking at the time course of the Simon effect itself (through pairwise comparisons of compatible and incompatible trials), there were no differences between groups.

2.4 Discussion

The purpose of the present study was two-fold. First, to investigate the decision processing mechanism (Experiment 1a) by fitting accuracy and reaction time data to the LBA model (Brown & Heathcote, 2008). Similar to previous studies, the results of the button press measures (mean accuracy and mean reaction time) suggested similar performance between bilingual and monolingual young adults (e.g., Bialystok, Martin, & Viswanathan, 2005; Kousaie & Phillips, 2012; Paap, Johnson, & Sawi, 2014; Salvatierra & Rosselli, 2011). The modelling data revealed that the bilinguals had larger drift rate suggesting faster evidence accumulation for response execution compared to monolinguals. However, there was no evidence indicating a bilingual cognitive advantage in conflict resolution showing group by trial type interaction. This suggests that the bilinguals and monolinguals resolved the conflict similarly.

The second objective was to investigate the effect of bilingualism on the temporal dynamics of cognitive control (Experiment 1b). In specific, we sought to determine whether the bilinguals are better than monolinguals at controlling the activation of task-irrelevant information along the direct route, or at activating task-relevant information from the indirect route, or both. To investigate this, we combined the reach-to-touch paradigm with the response-signal procedure in the Simon task (Finkbeiner & Heathcote, 2016), in which participants reaching responses were initiated across a wide range of stimulus viewing times. This fine-grained analysis allowed us to reveal the temporal dynamics of response activation from the direct and cognitive routes in the Simon task. The results of the reach-to-touch paradigm illustrated that the bilinguals suppress task-irrelevant information for a longer period of time and that they activate task-relevant information sooner than the monolinguals.

The reaching trajectories across trial types (i.e., compatible, neutral and incompatible) are consistent with the findings reported by Finkbeiner and Heathcote (2016). On compatible trials, the reaching responses were in the correct direction at earliest stimulus viewing time (~ 127 ms for bilinguals; ~ 153 ms for monolinguals). These findings are similar to traditional button press measures (reaction time) in the Simon task, in which the reaction time is faster on compatible trials relative to neutral trials and incompatible trials (Acosta & Simon, 1976;

De Jong et al., 1994; Lu & Proctor, 1995; Simon & Rudell, 1967; Umiltá, Rubichi, & Nicoletti, 1999; Wiegand & Wascher, 2005). However, the reaching responses on compatible trials are ambiguous with respect to isolating whether response activation stems from the direct route or cognitive route.

On incompatible trials the reaching responses were bimodal. First, in the incorrect direction towards the wrong response panel at the earliest stimulus viewing time (at ~ 151 ms for bilinguals; at ~ 108 ms for monolinguals) and second, in the correct direction towards the appropriate response panel at the later stimulus viewing time (no significant difference for bilinguals; at ~ 344 ms for monolinguals). The only information that is driving the reaching responses in the incorrect direction on incompatible trials is the response activation from the task-irrelevant (spatial) information (Buetti & Kerzel, 2009; Finkbeiner & Heathcote, 2016). Moreover, on neutral trials, the reaching responses emerged significantly in the correct direction at longer stimulus viewing time (at ~ 230 ms for bilinguals; at ~ 263 ms for monolinguals). The only source that is driving the reaching responses in the correct direction on neutral trials is the response activation purely from the task-relevant (colour) information.

These observations are consistent with the dual-route accounts of the Simon effect (De Jong, Liang, & Lauber, 1994; Kornblum et al., 1990; Ridderinkhof, 2002; Wiegand & Washer, 2005), which assumes that the stimulus' location automatically activates its corresponding response along a very fast direct route (e.g., right-side stimulus activates right-hand response). In the present study, we captured the direct route activation on incompatible trials, in which the reaching responses were in the incorrect direction towards stimulus location at early stimulus viewing times (Buetti & Kerzel, 2008; 2009; Finkbeiner & Heathcote, 2016). And later as the stimulus viewing time increased, the interference of spatial information was resolved completely. In contrast to the direct route which processes stimulus location, the task-relevant (colour) information is said to be processed along the slower, cognitive route. Using neutral trials, we were able to observe the time course of response activation along this cognitive route. Because the neutral stimuli were presented along the vertical meridian, the spatial location of these stimuli was orthogonal to the response locations, thereby minimizing location-based interference. Consistent with the dual-route accounts, participants needed to view a neutral stimulus for a longer period of time before they were able to produce a reliably correct initial movement. In the next section, we further focus on the reaching trajectories of incompatible and neutral trials between bilingual and monolingual participants, as they explicitly represent the response activation from the direct and cognitive routes respectively.

Are bilinguals faster at activating task-relevant information from the *cognitive route*? As discussed, the reaching responses on neutral trials represented the response activation from the cognitive route (i.e., controlled route). The results between groups revealed that the bilinguals required shorter stimulus viewing time to plan their reaching responses in the correct direction relative to monolinguals. The faster response execution in bilinguals (by 32 ms) suggested earlier response activation from the cognitive route for task-relevant colour information. Are bilinguals better at controlling the activation of task-irrelevant information along the *direct route*? As indicated, reaching responses in the incorrect direction on incompatible trials represent the response activation from the direct route (i.e., automatic route). In this condition, the results showed that the bilinguals required longer stimulus viewing time to initiate movements that travelled in the incorrect direction than monolinguals. Thus, the later emergence of task-irrelevant information in bilinguals (by 43 ms) may suggest that they are better at controlling the response activation from the automatic route for task-irrelevant spatial information. However, while bilinguals took longer to begin producing initial movements in the incorrect direction at earliest stimulus viewing time, it should be noted that the reaching responses that were initiated at the later stimulus viewing time were never in the correct direction for the time window that we used in this study (~ 350 ms). Thus, while bilinguals appear to be better at resisting capture initially by task-irrelevant information, they require more stimulus viewing time to isolate the task-relevant information in incompatible stimuli and to formulate an appropriate response.

To our knowledge, none of the previous studies exclusively investigated the time course of response activation from direct and cognitive routes in bilingual and monolingual participants in the Simon task. In this study, we reported that monolinguals and bilinguals activated task-relevant and task-irrelevant information along the direct and indirect routes differently. Firstly, bilinguals identified the task-relevant colour information at shorter stimulus viewing time relative to monolinguals in the neutral trials which suggested that they are faster at engaging response activation from the cognitive route. Secondly, bilinguals took longer to be captured by the task-irrelevant spatial information in the incompatible condition, which indicated that they adopted a more cautious strategy in our paradigm. One possibility is that bilinguals were better at selectively suppressing activation along the direct route (Ridderinkhof, 2002), which would account for the longer stimulus viewing times relative to monolinguals. However, it is difficult to reconcile this possibility with the finding that bilinguals reaching responses were never in the correct direction at later stimulus viewing time on incompatible condition for the time window selected in the present study (~ 350 ms). In fact, while the overall pattern of initial movements was similar across groups, the bilinguals never did recover in the incompatible condition and produce initial movements that were reliably correct. The results from the reach-to-touch paradigm are further supported by LBA model drift rate data, in which the bilinguals had larger drift rate relative to monolinguals. This data suggests that the bilinguals had accumulated more evidence for the response choice, which in turn might correspond to faster responses for task-relevant information than the monolinguals.

The current study data sheds new light on the temporal dynamics of cognitive control in bilinguals and monolinguals for the Simon task. Using the reach-to-touch paradigm, we were able to track the time course of response selection from the direct and cognitive routes over stimulus processing time. This in turn helped us to reveal when exactly the bilingual and monolingual groups engaged response activation from direct and cognitive routes. While our results indicate that bilinguals were faster to activate task-relevant information and better at controlling task-irrelevant information, this did not translate into a smaller Simon effect. In fact, when quantifying the magnitude of the Simon effect, we found no difference between our monolingual and bilingual groups. If anything, our findings suggest that, once captured by the task-irrelevant spatial information, our bilingual participants found it more difficult than our monolingual participants to recover and activate task-relevant stimulus information.

The same set of language groups matched across age, years of formal education, handedness, nonverbal intelligence, video game playing, and parental education level, completed both the button press and the reach-to-touch version of the Simon task. However, group differences were picked up only in the reaching responses. One possible explanation for this contrast may be due to the differences between the response time window captured in the button press and reach-to-touch paradigm measures. The button press measures such as mean reaction time data represents the end point of cognitive decision making (~ 500 ms), which is an amalgamation of multiple processes (perception, cognitive process, motor preparation, motor execution). Due to this poor temporal resolution with button press measures, it might be insensitive to capture the subtle group differences in the Simon task. Whereas the reach-to-touch paradigm coupled with the response-signal procedure (e.g., Finkbeiner et al., 2014) are designed to capture the interactive nature of the cognitive process and the motor response in the Simon task as it unfolds over time at an early stimulus processing stage (~ 250 ms). Thus, the reaching trajectories are much more sensitive and dynamic than mean reaction times, (which range from ‘fast’ to ‘slow’ in a single positive direction) to record subtle group differences (Finkbeiner et al., 2014). Moreover, in previous studies, when there was no difference between monolingual and bilingual young adults in the button press paradigm, high temporal measures such as ERP's, were capable of detecting processing differences between bilingual and monolingual participants (e.g., Coderre & van Heuven, 2014; Fernandez, Tartar, Padron, & Acosta, 2013; Heidlmayr, Hemforth, Moutier, & Isel, 2015; Kousaie & Phillips, 2012; Sullivan, Janus, Moreno, Astheimer, & Bialystok, 2014). These findings suggest that the high temporal measures are sensitive enough to detect subtle processing differences between groups, which were not captured in the button press measures.

In conclusion, the present study has documented differences in the temporal dynamics of cognitive control between bilinguals and monolinguals in the Simon task using a reach-to-touch paradigm. The data is suggestive of a more efficient and dynamic attentional control system in bilinguals relative to monolinguals, as indicated by faster activation of task-relevant stimulus information in the neutral condition and a delay in the activation of task-irrelevant stimulus information in the incompatible condition. Nevertheless, not even the fine-grained analysis afforded by the reach-to-touch paradigm coupled with the response-signal procedure was able to reveal a bilingual advantage in the form of a smaller Simon effect or in the time course of conflict resolution.

References

Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*(3), 242-275. doi: 10.1016/j.jneuroling.2006.10.003

Acosta Jr, E., & Richard Simon, J. (1976). The effect of irrelevant information on the stages of processing. *Journal of Motor Behavior*, *8*(3), 181-187. doi: 10.1080/00222895.1976.10735070

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modelling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390-412. doi: 10.1016/j.jml.2007.12.005

Bates, D. (2005). Fitting linear mixed models in R. *R news*, *5*(1), 27-30.

Bates, D., Maechler, M., & Bolker, B. (2012). lme4: Linear mixed-effects models using S4 classes (2011). R package version 0.999375-42, http://lme4.r-forge.r-project.org./

Bialystok, E. (2006). Effect of Bilingualism and Computer Video Game Experience on the Simon Task. *Canadian Journal of Experimental Psychology*, *60*(1), 68-79. doi: 10.1037/cjep2006008

Bialystok, E. (2009). Bilingualism: The good, the bad, and the indifferent. *Bilingualism: Language and Cognition*, *12*(01), 3-11. doi: 10.1017/S1366728908003477

Bialystok, E., & DePape, A. M. (2009). Musical expertise, bilingualism, and executive functioning. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(2), 565-574. doi: 10.1037/a0012735

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: consequences for mind and brain. *Trends in Cognitive Sciences*, *16*(4), 240-250. doi: 10.1016/j.tics.2012.03.001

Bialystok, E., Craik, F. I., Grady, C., Chau, W., Ishii, R., Gunji, A., & Pantev, C. (2005). Effect of bilingualism on cognitive control in the Simon task: Evidence from MEG. *NeuroImage*, *24*(1), 40-49. doi: 10.1016/j.neuroimage.2004.09.044

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and Aging*, *19*(2), 290-303. doi: 10.1037/0882-7974.19.2.290

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*(4), 859-873. doi: 10.1037/0278-7393.34.4.859.

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism*, *9*(1), 103-119. doi: 10.1177/13670069050090010701

Blumenfeld, H. K., & Marian, V. (2014). Cognitive control in bilinguals: Advantages in Stimulus–Stimulus inhibition. *Bilingualism: Language and Cognition*, *17*(03), 610-629. doi: 10.1017/S1366728913000564

Brown, S. D., & Heathcote, A. (2008). The simplest complete model of choice response time: linear ballistic accumulation. *Cognitive Psychology*, *57*(3), 153-178. doi: 10.1016/j.cogpsych.2007.12.002

Brown, S., & Heathcote, A. (2005). A ballistic model of choice response time. *Psychological Review*, *112*(1), 117-128. doi: 10.1037/0033-295X.112.1.117

Buetti, S., & Kerzel, D. (2008). Time course of the Simon effect in pointing movements for horizontal, vertical, and acoustic stimuli: Evidence for a common mechanism. *Acta Psychologica, 129*(3), 420-428. doi: 10.1016/j.actpsy.2008.09.007

Buetti, S., & Kerzel, D. (2009). Conflicts during response selection affect response programming: reactions toward the source of stimulation. *Journal of Experimental Psychology: Human Perception and Performance, 35*(3), 816-834. doi: 10.1037/a0011092.

Coderre, E. L., & van Heuven, W. J. B. (2014). Electrophysiological explorations of the bilingual advantage: evidence from a Stroop task. *PLos one*. 9(7). doi: 10.1371/journal.pone.0103424

Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition*, *106*(1), 59-86. doi: 10.1016/j.cognition.2006.12.013

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don't. *Cognition*, *113*(2), 135–149. doi: 10.1016/j.cognition.2009.08.001

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: a dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(4), 731-750. doi: 10.1037/0096-1523.20.4.731

Donkin, C., Averell, L., Brown, S., & Heathcote, A. (2009). Getting more from accuracy and response time data: Methods for fitting the linear ballistic accumulator. *Behavior Research Methods*, *41*(4), 1095-1110. doi: 10.3758/BRM.41.4.1095

Donkin, C., Brown, S., Heathcote, A., & Wagenmakers, E. J. (2011). Diffusion versus linear ballistic accumulation: different models but the same conclusions about psychological processes?. *Psychonomic Bulletin & Review, 18*(1), 61-69. doi: 10.3758/s13423-010-0022-4

Fernandez, M., Tartar, J. L., Padron, D., & Acosta, J. (2013). Neurophysiological marker of inhibition distinguishes language groups on a non-linguistic executive function test. *Brain and cognition*, *83*(3), 330-336. doi: 10.1016/j.bandc.2013.09.010

Finkbeiner, M. & Heathcote, A. (2016). Distinguishing the time- and magnitude-difference accounts of the Simon effect. *Attention, Perception and Psychophysics, 78,* 848-867. doi: 10.3758/s13414-015-1044-9

Finkbeiner, M., Coltheart, M., & Coltheart, V. (2014). Pointing the Way to New Constraints on the Dynamical Claims of Computational Models. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 172-185. doi: 10.1037/a0033169

Gathercole, V. C. M., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Guasch, N. V., ... & Jones, L. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Frontiers in Psychology*, *5*,11. doi: 10.3389/fpsyg.2014.00011

Hedge, A., & Marsh, N. W. A. (1975). The effect of irrelevant spatial correspondences on two-choice response-time. *Acta psychologica*, *39*(6), 427-439. doi: 10.1016/0001-6918(75)90041-4

Heidlmayr, K., Hemforth, B., Moutier, S., & Isel, F. (2015). Neurodynamics of executive control processes in bilinguals: evidence from ERP and source reconstruction analyses. *Frontiers in Psychology*, *6*. doi: 10.3389/fpsyg.2015.00821

Hernández, M., Costa, A., Fuentes, L. J., Vivas, A. B., & Sebastián-Gallés, N. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Bilingualism: Language and Cognition*, *13*(03), 315-325. doi: 10.1017/S1366728909990010

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625-658. doi: 10.3758/s13423-011-0116-7

Hommel, B. (1994). Spontaneous decay of response-code activation. *Psychological research*, *56*(4), 261-268. doi:10.1007/BF00419656

Karalunas, S. L., & Huang-Pollock, C. L. (2013). Integrating impairments in reaction time and executive function using a diffusion model framework. *Journal of Abnormal Child Psychology*, *41*(5), 837-850. doi: 10.1007/s10802-013-9715-2

Karayanidis, F., Provost, A., Brown, S., Paton, B., & Heathcote, A. (2011). Switch-specific and general preparation map onto different ERP components in a task-switching paradigm. *Psychophysiology*, *48*(4), 559-568. doi: 10.1111/j.1469-8986.2010.01115.x

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: cognitive basis for stimulus-response compatibility--a model and taxonomy. *Psychological Review*, *97*(2), 253-270. doi: 10.1037/0033-295X.97.2.253

Kousaie, S., & Phillips, N. A. (2012). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research, 1446,* 71 – 90. doi: 10.1016/j.brainres.2012.01.052

Lu, C. H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*(2), 174-207. doi: 10.3758/BF03210959

Luk, G., Anderson, J. A., Craik, F. I., Grady, C., & Bialystok, E. (2010). Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. *Brain and Cognition*, *74*(3), 347-357. doi: 10.1016/j.bandc.2010.09.004

Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech, Language, and Hearing Research, 50,* 940–967. doi: 10.1044/1092-4388(2007/067)

Martin-Rhee, M. M., & Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism Language and Cognition*, *11*(1), 81-93. doi: 10.1017/S1366728907003227

Marzecová, A., Asanowicz, D., Krivá, L. U., & Wodniecka, Z. (2013). The effects of bilingualism on efficiency and lateralization of attentional networks. *Bilingualism: Language and Cognition*, *16*(03), 608-623. doi: 10.1017/S1366728912000569

McBride, J., Boy, F., Husain, M., & Sumner, P. (2012). Automatic motor activation in the executive control of action. *Frontiers in Human Neuroscience*, *6*. doi: http://dx.doi.org/10.3389/fnhum.2012.00082

Morey, R. D., Rouder, J. N., & Jamil, T. (2014). BayesFactor: Computation of Bayes factors for common designs. *R package version 0.9*, *7*.

Ocampo, B., & Finkbeiner, M. (2013). The negative compatibility effect with relevant masks: a case for automatic motor inhibition. *Frontiers in Psychology*, *4, 822*. doi: 10.3389/fpsyg.2013.00822

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113. doi: 10.1016/0028-3932(71)90067-4

Paap, K. R., Johnson, H. A., & Sawi, O. (2014). Are bilingual advantages dependent upon specific tasks or specific bilingual experiences?. *Journal of Cognitive Psychology*, *26*(6), 615-639. doi: 10.1080/20445911.2014.944914

Pelham, S. D., & Abrams, L. (2014). Cognitive advantages and disadvantages in early and late bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(2), 313-325. doi: 10.1037/a0035224

Poarch, G. J., & van Hell, J. G. (2012). Executive functions and inhibitory control in multilingual children: Evidence from second-language learners, bilinguals, and trilinguals. *Journal of Experimental Child Psychology*, *113*(4), 535-551. doi: 10.1016/j.jecp.2012.06.013

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(04), 682-691. doi: 10.1017/S1355617711000580

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognition*, *13*(02), 253-262. doi: 10.1017/S1366728909990526

Proctor, R. W., Yamaguchi, M., & Vu, K. P. L. (2007). Transfer of non corresponding spatial associations to the auditory Simon task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(1), 245-253. doi: 10.1037/0278-7393.33.1.245

Quek, G. L., & Finkbeiner, M. (2013). Spatial and temporal attention modulate the early stages of face processing: behavioural evidence from a reaching paradigm. *PLos one*, *8*(2). doi: 10.1371/journal.pone.0057365

Quek, G. L., & Finkbeiner, M. (2014). Face-sex categorization is better above fixation than below: Evidence from the reach-to-touch paradigm. *Cognitive, Affective, & Behavioral Neuroscience,* 1-13. doi: 10.3758/s13415-014-0282-y

Ratcliff, R., & Rouder, J. N. (1998). Modeling response times for two-choice decisions. *Psychological Science*, *9*(5), 347-356. doi: 10.1111/1467-9280.00067

Ratcliff, R., Thapar, A., & McKoon, G. (2001). The effects of aging on reaction time in a signal detection task. *Psychology and Aging*, *16*(2), 323-341. doi: 10.1037/0882-7974.16.2.323

Ratcliff, R., Thapar, A., & Mckoon, G. (2003). A diffusion model analysis of the effects of aging on brightness discrimination. *Perception & Psychophysics*, *65*(4), 523-535. doi: 10.3758/BF03194580

Raven, J., Raven, J. C. & Court, J. H (1998). Raven manual: Section 4, Advanced Progressive Matrices, 1998 edition. Oxford, UK: Oxford Psychologists Press Ltd.

Ridderinkhof, R. K. (2002). Micro-and macro-adjustments of task set: Activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312-323. doi: 10.1007/s00426-002-0104-7

Salvatierra, J. L., & Rosselli, M. (2011). The effect of bilingualism and age on inhibitory control. *International Journal of Bilingualism*, *15*(1), 26-37. doi: 10.1177/1367006910371021

Schmiedek, F., Oberauer, K., Wilhelm, O., Süβ, H.-M., & Wittmann, W.W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology: General*, 136, 414-429. doi: 10.1037/0096-3445.136.3.414

Schroeder, S. R., & Marian, V. (2012). A bilingual advantage for episodic memory in older adults. *Journal of Cognitive Psychology*, *24*(5), 591-601. doi: 10.1080/20445911.2012.669367

Simon, J. R., & Rudell, A. P. (1967). Auditory SR compatibility: the effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*(3), 300-304. doi: 10.1037/0096-3445.136.3.414

Song, J. H., & Nakayama, K. (2009). Hidden cognitive states revealed in choice reaching tasks. *Trends in Cognitive Sciences*, *13*(8), 360-366. doi: 10.1016/j.tics.2009.04.009

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(29), 10393-10398. doi: 10.1073/pnas.0503903102

Stürmer, B., Leuthold, H., Soetens, E., Schröter, H., & Sommer, W. (2002). Control over location-based response activation in the Simon task: behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(6), 1345. doi: 10.1037/0096-1523.28.6.1345

Sullivan, M. D., Janus, M., Moreno, S., Astheimer, L., & Bialystok, E. (2014). Early stage second-language learning improves executive control: Evidence from ERP. *Brain and Language*, *139*, 84-98. doi: 10.1016/j.bandl.2014.10.004

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology, 2, 123, 83-101*. doi: 10.3389/fpsyg.2011.00123

Umiltá, C., Rubichi, S., & Nicoletti, R. (1999). Facilitation and interference components in the Simon effect. *Archives Italiennes de Biologie*, *137*(2), 139-149.

Wascher, E., Schatz, U., Kuder, T., & Verleger, R. (2001). Validity and boundary conditions of automatic response activation in the Simon task. *Journal of Experimental Psychology: Human Perception and Performance, 27*(3), 731-751. doi: 10.1037/0096-1523.27.3.731

Wiegand, K., & Wascher, E. (2005). Dynamic aspects of stimulus-response correspondence: evidence for two mechanisms involved in the Simon effect. *Journal of Experimental Psychology: Human Perception and Performance, 31*(3), 453-464. doi: 10.1037/0096-1523.31.3.453

Wiseheart, M., Viswanathan, M., & Bialystok, E. (2016). Flexibility in task switching by monolinguals and bilinguals. *Bilingualism: Language and Cognition*, *19*(1), 141-146. doi: 10.1017/S1366728914000273

Woestenburg, J. C., Verbaten, M. N., Van Hees, H. H., & Slangen, J. L. (1983). Single trial ERP estimation in the frequency domain using orthogonal polynomial trend analysis (OPTA): estimation of individual habituation. *Biological Psychology*, *17*(2), 173-191. doi: 10.1016/0301-0511(83)90018-2

Yow, W. Q., & Li, X. (2015). Balanced bilingualism and early age of second language acquisition as the underlying mechanisms of a bilingual executive control advantage: why variations in bilingual experiences matter. *Frontiers in Psychology*, *6, 164*. doi:10.3389/fpsyg.2015.00164

Chapter 3

Tracking the Evolution of Task-Relevant and Task-Irrelevant Information in the Simon Task

Manjunath Narra[1, 2, 3], Shahd Al-Janabi[4], Paul F. Sowman[1, 2, 3], & Matthew Finkbeiner[1, 2, 3]

[1] Perception in Action Research Centre, Macquarie University, Australia

[2]Department of Cognitive Science, Macquarie University, Australia

[3]ARC Centre of Excellence in Cognition and its Disorders, Macquarie University, Australia

[4]Department of Psychology, University of Wisconsin-Milwaukee, USA

Abstract

In this study, we investigated the response activation of task-relevant and task-irrelevant dimension in the Simon task across language groups at the level of the motor cortex. The reaction time distribution differences between the two groups were minimized by presenting single-pulse transcranial magnetic stimulation at predefined response time points. We delivered single-pulse TMS over the left motor cortex at 4 different stimulus-to-stimulation asynchronies (50 ms, 100 ms, 150 ms, 200 ms) relative to target onset. The motor evoked potentials were recorded at these specific time points whilst participants completed the Simon task. Our results show that task-irrelevant spatial information is activated earlier than task-relevant colour information. We found no difference in the activated time courses between bilingual and monolingual participants, challenging the notion of a bilingual advantage in the early motor preparation stage. To conclude, the benefits of bilingualism on this popular cognitive control task were absent in the early stages of motor preparation.

Tracking the Evolution of Task-Relevant and Task-Irrelevant Information in the Simon Task

3.1 Introduction

The purpose of the present study was: first, to explore the temporal dynamics of motor cortex excitability for task-irrelevant and task-relevant dimension in the Simon task. Second, to follow-up with the Chapter 2 (Experiment 1b) reach-to-touch paradigm results, we sought to investigate the response activation of stimulus information in the Simon task across the language groups at the level of the motor cortex. Furthermore, the magnitude and the time course of the Simon effect was explored between bilinguals and monolinguals at predefined response time points. As the objectives were the same as Chapter 2 (Experiment 1b), the bilingual cognitive advantage literature is not discussed in this draft to reduce the redundancy.

In the following section, I will present the studies investigating the time course of task-irrelevant information by applying single-pulse transcranial magnetic stimulation (TMS) to the motor cortex at different time points (e.g., Stürmer, Siggelkow, Dengler, & Leuthold, 2000; van Campen, Keuken, van den Wildenberg, & Ridderinkhof, 2014). The application of TMS over the motor cortex produces motor evoked potentials (MEPs) in the hand muscles contralateral and ipsilateral to the side of stimulation (Wassermann, Pascual-leone, & Hallett, 1994). Importantly, the magnitude of the MEP is modulated by the preparation of a motor response (e.g., Terao & Ugawa, 2002). Thus, MEPs can be used as a direct measure of response preparation or suppression during the Simon task.

Stürmer et al. (2000), for example, applied single-pulse TMS over the left motor cortex while participants completed a Simon task. In their task, the stimulus location and response buttons were aligned along the vertical axis. Participants were asked to press the upper response button using their right index finger and the lower response button using their left index finger appropriately to the target shape. The target location and the response key were matched on compatible trials (e.g., a diamond shape presented above fixation required an upper response button press) and unmatched on incompatible trials (e.g., a diamond shape presented at below fixation required a lower button press). However, on neutral trials, the target was presented at central fixation on the screen (e.g., for diamond shape presented at central fixation required an upper response button press). The TMS pulse occurred 200 ms following target onset. To determine motor cortex excitability for the task-irrelevant spatial information, the MEP responses from compatible and incompatible trials were compared with levels of motor activation on neutral trials. Stürmer et al. (2000) demonstrated an early motor preparation for task-irrelevant spatial information over the contralateral motor cortex on compatible trials and ipsilateral motor cortex on incompatible trials relative to the responding hand. Although this result serves to establish that the Simon effect is present at the level of the motor cortex at 200 ms following stimulus onset, it does not indicate when the task-relevant and task-irrelevant information is first activated during the course of stimulus processing.

More recently, van Campen et al. (2014) set out to explore the time course of the Simon effect by applying single-pulse TMS at five different stimulus-to-stimulation asynchronies (SSAs) in relation to target onset. The SSAs were determined separately for each participant based on the distribution of their response latencies. Participants were asked to identify blue and green coloured stimuli that appeared along the horizontal axis (left and right-side of fixation) by pressing appropriate horizontally-aligned buttons using their left and right hand. The researchers measured both MEP amplitudes and silent periods (SPs) from the right abductor pollicis brevis muscle at each TMS time point. These dependent variables index motor cortex excitability and suppression, respectively. Importantly, the researchers stimulated only the left hemisphere motor cortex, hence only MEPs from the right-hand were recorded. van Campen et al. (2014) reported higher MEP amplitudes for compatible trials relative to incompatible trials for the responding effector between the second and third SSA intervals (Simon effect: approximately between 150 ms to 213 ms). The researchers also reported a trend of higher MEP amplitudes for incompatible trials relative to compatible trials for the non-responding effector in the first and second SSA intervals (reverse Simon effect: approximately between 71 ms to 142 ms after target onset). Additionally, a longer SP was observed on incompatible trials relative to compatible trials between the first and second SSA intervals over the non-responding hand. van Campen et al. (2014) proposed that the trend of higher MEPs and longer SPs on incompatible trials should be attributed to early response activation, which is followed by suppression of the task-irrelevant spatial information, over the non-responding effector.

At the level of motor cortex, the time course of the Simon effect could be due to response-facilitation of stimulus information or response-suppression of stimulus information, or, alternatively, due to a combination of both processes. This means that van Campen et al. (2014) time course data do not provide sufficient information to differentiate between task-irrelevant and task-relevant response activation in the Simon task. To distinguish the time courses of these two sources of response activation we included neutral trials to differentiate between the response activation for task-relevant and task-irrelevant dimensions. On neutral trials, we presented the target either below or above a central fixation point on the vertical meridian, thus minimizing the interference caused by the spatial location information (Aisenberg & Henik, 2012; Finkbeiner & Heathcote, 2016; Umiltá, Rubuchi, & Nicoletti, 1999). Using this design, the response formulation process on neutral trials should represent a ‘pure’ measure of motor preparation for the task-relevant (colour) dimension. Therefore, the activation levels on neutral trials were taken as a baseline against which we could measure response-facilitation and response-suppression effects (Lu & Proctor, 1995; Umiltá, Rubuchi, & Nicoletti, 1999; Wühr & Ansorge, 2005).

We are not the first ones to include a neutral condition. For example, in the first study reviewed above, Stürmer et al. (2000) included neutral trials in their task as well. However, Stürmer et al. (2000) presented the target shapes at central fixation on neutral trials and this is not ideal as it confounds visual eccentricity (and, hence, spatial attention) with response compatibility. To vary response compatibility, and not simultaneously vary visual eccentricity, we presented our neutral stimuli at the same eccentricity as the compatible and incompatible stimuli, but along the vertical meridian to achieve a neutral relationship between stimulus and response locations.

In the present study, we asked participants to complete a Simon task by moving either their right-hand index-finger or their right-hand little-finger laterally to the appropriate response location. Specifically, in our task, the target (a green square or a red square) was presented in four different locations (i.e., left, right, up, or down) relative to central fixation. Based on the relationship between the stimulus location and response location, the trials were classified as stimulus-response: compatible, incompatible or neutral. As participants were completing the task, we delivered single-pulse TMS over the left hemisphere motor cortex at four different SSAs (50 ms, 100 ms, 150 ms, and 200 ms) relative to the target onset. The MEPs were recorded simultaneously over the right-hand index and right-hand little-finger on each trial. This design allowed us to capture the motor cortex excitability over the responding and non-responding effector at the same time within each trial. We expected higher MEP amplitudes on incompatible trials relative to the neutral trials over the non-responding effector. This finding would be suggestive of task-irrelevant spatial information. The only source that could be driving the higher MEPs on incompatible trials over the non-responding effector would be task-irrelevant spatial information. Further, we expected higher MEP responses of neutral trials relative to compatible trials over the responding effector corresponding to task-relevant information activation. The only source that could be driving the higher MEPs on neutral trials over responding effector would be task-relevant colour information. To preview the findings, we observed that the task-irrelevant (spatial) information was activated earlier than the task-relevant (colour) information. This pattern of results strongly supports the dual-route model assumptions, which suggest faster response activation from the direct route for task-irrelevant information that is followed by slower response activation from the indirect route for task-relevant information (De Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990; Ridderinkhof, 2002).

Further, across language groups, we hypothesised that if bilinguals are better at cognitive control as suggested in the previous studies, there should be a later onset of task-irrelevant information in bilinguals relative to monolinguals. There should also be a faster activation of task-relevant information in bilinguals relative to monolinguals. Furthermore, if bilinguals are better at conflict resolution as indicated by the lower magnitude of the conflict effect, we expected to see a later onset of the Simon effect in bilinguals relative to monolinguals. To anticipate our findings, we did not find any evidence of MEP amplitude differences between bilingual and monolingual participants, challenging the notion of a bilingual cognitive advantage. The effect of bilingualism on cognitive function was absent in the early motor preparation stage.

3.2 Method

3.2.1 Participants

Twenty-four bilinguals (18 females, 6 males) and twenty-three monolinguals (17 females, 6 males) from Macquarie University participated in this study. All participants completed the Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian, Blumenfeld, & Kaushankaya, 2007) (see Appendix A), Edinburgh Handedness Inventory (Oldfield, 1971) (see Appendix B), Raven's Advanced Progressive Matrices-Set I (Raven et al., 1998) (see Appendix C) and a general background questionnaire (see Appendix D). Participants had normal or corrected-to-normal vision, and reported no history of speech, hearing or other neurological disorders as assessed by completion of a TMS safety screening questionnaire prior to the experiment (Keel et al., 2001) (see Appendix G). Ethical permission for this study was obtained from Macquarie University and all protocols were in accord with the Helsinki declaration (see Appendix H). Informed consent was obtained from all participants, and they were compensated financially or with course credit for participating (see Appendix I).

Data from seven participants were excluded from subsequent analyses: two participants were excluded due to technical issues with the TMS machine, four were excluded due to high noise in the electromyogram (EMG) signal and one participant was excluded for having made too many movement errors. Thus, there were a total of 40 participants included in the analyses, 20 monolinguals (15 females, 5 males; 21 ± 4.61 years; range: 18 to 34 years) and 20 bilinguals (16 females, 4 males; 20 ± 4.63 years; range: 18 to 35 years).

Participants' demographic information is presented in Table 3.1. Bilinguals and monolinguals were matched across age, years of education, handedness scores, Raven's scores, parental education, and the amount of hours spent playing video game. Monolingual participants were native English speakers who acquired the language at the average age of 1 year (*SD* = 0.8 years) and reported no exposure to any other language. Bilingual participants were speakers of English, and Chinese (n = 6), Arabic (n = 4), Hindi (n = 2), Telugu (n = 1), French (n = 1), Gujarati (n = 1), Sinhala (n = 1), Korean (n = 1), Vietnamese (n = 1), German (n = 1), or Russian (n = 1). Bilingual participants acquired English and the other language before the age of 6 (English: *M* = 4 years, *SD* = 1.75; other language: *M* = 2 years, *SD* = 1.3), and they reported daily usage of 64 % for English (*SD* = 14) and 34 % for the other (*SD* = 11) language.

Table 3.1.

Demographic information for participant groups.

Variables	**Monolinguals Mean (SD)**	**Bilinguals Mean (SD)**	**Sig.**
Age (in years)	20.95 (4.61)	20.30 (4.63)	$p > .05$
Formal Education (in years)	14.2 (1.93)	13.7 (2.20)	$p > .05$
Edinburgh's Handedness Scores	85.76 (18.12)	82.74 (22.21)	$p > .05$
Ravens Score's	10.4 (1.69)	11.0 (1.12)	$p > .05$
Video Game Playing (Playing hrs/week)	2.22 (1.92)	3.66 (2.08)	$p > .05$
Average Parental Education (5 point rating scale)	3.4 (1.08)	3.22 (1.25)	$p > .05$
Computer Usage (hrs/day)	3.8 (1.15)	5.1 (2.04)	$p < .05$
	English	**English**	**Non-English**
Age of Acquisition (in years)	0.7 (0.57)	3.65 (1.75)	1.7 (1.30)
Language Usage (in %)	100	63.5 (13.58)	34.10 (10.83)
Proficiency Rating (10 point scale)			
Speaking	10	9.05 (1.05)	8.40 (0.94)
Understanding	10	9.15 (1.03)	8.95 (0.88)
Reading	10	9.20 (1.00)	7.55 (1.87)

3.2.2 Simon Task Apparatus

Participants were seated in front of a touchscreen computer monitor (70 x 39 cm). To record participants' response movements during the experiment, we used an Optotrak (200 Hz) motion capture system with two sensors that were placed over the middle phalanges of the right-hand index and little fingers (see Figure 3.1A). Participants' right-hand was placed on a table, and the middle and fourth fingers of that hand were held together by Velcro to aid smooth movement of the response fingers. The Velcro was attached to a small box (3.5 x 5.5 cm), which was placed on the table at an offset of 20.5 cm from the midline. This point on the table served as the 'start position' from which participants commenced each trial by moving their right index finger and little finger. The response locations were calibrated on either side of the two fingers prior to the experiment. For each participant, the most comfortable abducted position of the index and little finger was locked as the response location. Hence, participants responded by moving either finger to the calibrated response location, which was appropriate to the target colour in each trial.

3.2.3 Simon Task Stimuli

The stimuli consisted of red (RGB: 255, 0, 255) and green (RGB: 0, 255, 0) squares that measured 1.7 x 1.7 degrees of visual angle at a viewing distance of 51 cm. These targets were presented 2.87 degrees from the central fixation dot (i.e., left, right, above, or below). Stimulus presentation was controlled using Presentation software (Neurobehavioral Systems).

3.2.4 MEP Recording

The MEPs were recorded from surface EMG leads placed over the first dorsal interrosei (FDI) and abductor digit minimi (ADM) of the right-hand. The EMG signals were amplified (1000 x gain) and bandpass-filtered at 20 Hz to 500 Hz from a bipolar electrode (Medi-Trace 100, Kendall/Tyco Healthcare, USA) montage. EMGs were recorded from 0 ms until 3000 ms in each trial (LabChart, ADInstruments).

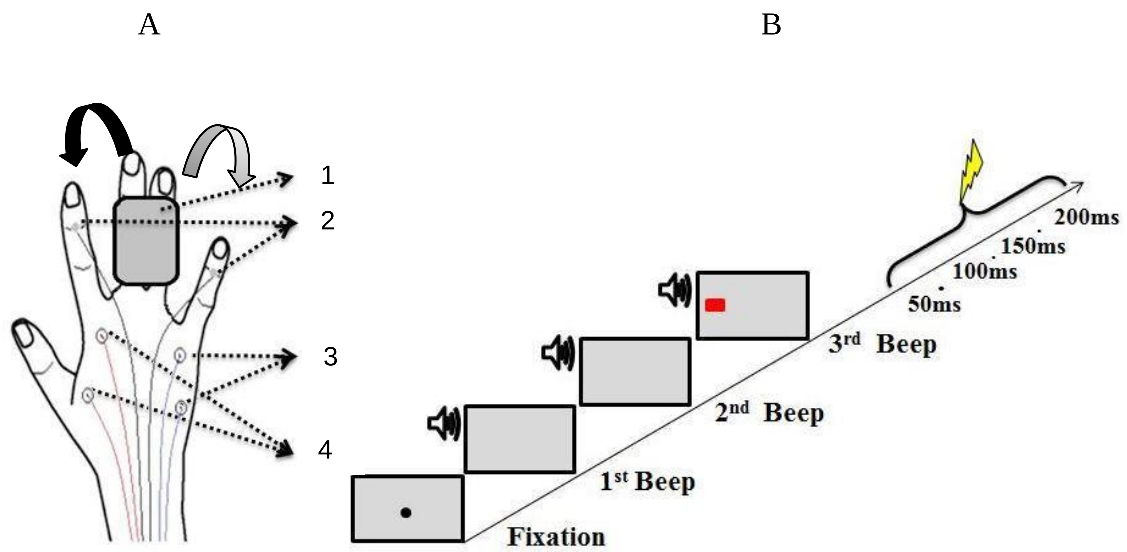


Figure 3.1. Electrode placement and trial sequence. (A) Right-hand fixed with Optotrak sensors, EMG electrodes and target location over the index finger (i.e., shaded area) [1- Velcro; 2 - Optotrak Sensors; 3 - EMG electrodes over ADM; 4 - EMG electrodes over FDI]. (B) Trial sequence of target presentation and single-pulse TMS time points.

3.2.5 Transcranial Magnetic Stimulation

Single-pulse TMS was first performed to establish participants resting motor threshold (RMT) using a Magstim Rapid stimulator (Magstim model 200, Magstim, Whitland, UK). The stimulation was conducted using a 70 mm figure-8 coil. The coil was positioned tangentially to the skull with the handle pointing occipitally over the primary motor cortex in the left hemisphere at the optimal site for obtaining an MEP in the muscles. This optimal site was marked on the scalp for each participant to ensure identical placement of the coil throughout the experiment proper. RMT was defined as the stimulus intensity that elicited responses of at least 50 mV peak-to-peak in 3 out of 5 successive trials. Stimulus intensities were adjusted individually for every participant at 120 percent of RMT to ensure that TMS stimulation was equally effective in all participants. During the experiment proper, single-pulse TMS was applied for 1 ms at four different SSAs (50 ms, 100 ms, 150 ms and 200 ms) following target onset. MEP control values were obtained in three baseline blocks that were interspersed throughout the experimental blocks, which is further explained below.

3.2.6 Design and Procedure

The within-subject factors manipulated in this study were Trial Type (compatible, neutral, incompatible), SSAs (50 ms, 100 ms, 150 ms, 200 ms), and Response Effector (responding effector, non-responding effector). The between-subject factors manipulated in this study were Response Assignment (index finger – red target, little finger – red target) and groups (monolingual, bilingual). The experiment consisted of 416 trials. There were 64 practice trials, 256 experimental trials, and 96 baseline trials in which no response was required. The baseline trials were blocked and interspersed amongst the experimental blocks.

As illustrated in Figure 3.1B, each trial began with a fixation dot that was presented for 500 ms. The fixation dot was followed after 500 ms, 900 ms and 1200 ms by three beeps. The target was presented simultaneously with the third beep for 300 ms in one of four locations: left, right, up or down. Hence, participants were instructed to initiate their movement with the final third beep. Specifically, half of the participants were instructed to abduct the right-hand *index* finger when they saw a red target and right-hand *little* finger when they saw a green target. Therefore, the target response assignment could be compatible (e.g., a red target presented on the left, which requires moving the finger that is most leftward), neutral (e.g., a red target presented either up or down, but nevertheless requires a leftward response), or incompatible (e.g., a red target presented on the right, but requires a leftward response). We instructed the other half of participants to respond using the reverse assignment. The trial sequence ended after 4000 ms. In each trial, the response initiation had a response time window of 850 ms (i.e., 100 ms before and 750 ms after the onset of the third beep). The trial was terminated with an audio buzz, and visual feedback was presented on the screen (e.g., “Too Early!” or “Too Late!”) when participants failed to move within this response-locked window. Participants were provided with feedback about their accuracy.

3.2.7 MEP Data Analysis

MEP amplitude was defined as the peak-to-peak amplitude within a window of 10 ms to 175 ms following TMS applied to the left hemisphere motor cortex. The mean normalized MEP amplitude, which is represented as the percentage of baseline, is calculated by dividing the average MEP amplitudes recorded during the experimental blocks with the average MEP amplitudes from the baseline blocks. The MEP data recorded from the practice trials and incorrect trials were excluded from the following analyses. The offline MEP data analysis was performed using a custom-made Matlab script (The MathWorks, Inc., Natick, USA).

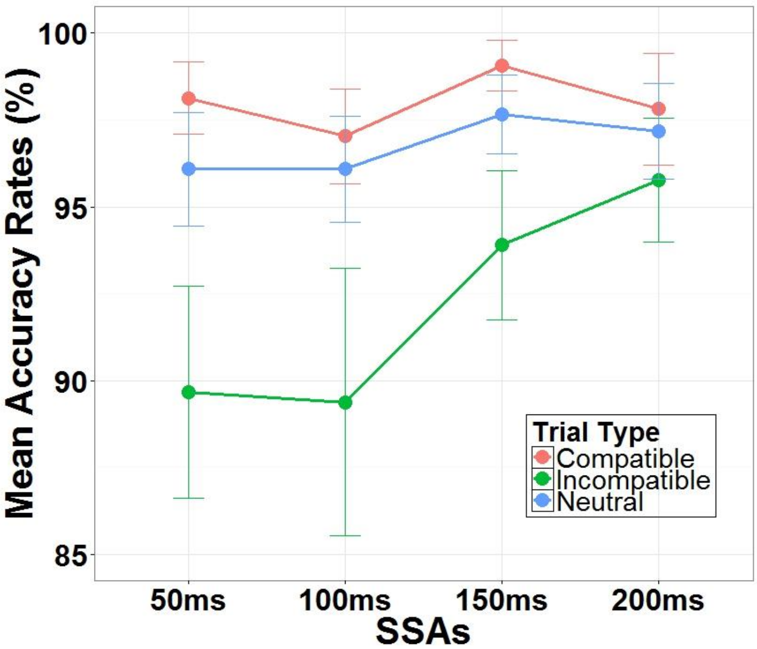


Figure 3.2. Mean accuracy rates (%) across SSA for trial types. The error bars indicate confidence intervals.

3.3 Results

3.3.1 Accuracy Rate (%)

We conducted a 3 x 4 x 2 x 2 ANOVA with trial type (compatible, neutral, incompatible) and SSA (50 ms, 100 ms, 150 ms, 200 ms) as within-subject factors, and response assignment (index finger for red vs. little finger for red) and groups (Bilingual, Monolingual) as between-subject factors. The analysis revealed a significant main effect of trial type, F (2, 72) = 33.88, $p < .001$, $\eta_G^2 = .153$, and SSA, F (3, 108) = 11.53, $p < .001$, $\eta_G^2 = .040$. The main effects were qualified by a two-way interaction between trial type and SSA, F (6, 216) = 5.22, $p < .001$, $\eta_G^2 = .03$. We conducted pairwise comparisons to explore the nature of this interaction (see Figure 3.2). Overall, the accuracy rates were higher on compatible trials relative to incompatible trials. This, suggests that the Simon effect (as indexed by reduced accuracy in incompatible trials as compared to compatible trials) was present across all SSAs (all *p's* < .001). No other significant effects were found in the omnibus analysis (all *F's* < 2.10).

3.3.2 Motor Evoked Potentials

The dependent variable was mean normalised MEPs on correct trials. A 3 x 4 x 2 x 2 x 2 repeated-measures ANOVA was conducted with trial type (compatible, neutral, incompatible), SSA (50 ms, 100 ms, 150 ms, and 200 ms), and response effector (responding effector, non-responding effector) as within-subject factors, and groups (bilinguals, monolinguals) and response assignment (index finger for red, little finger for red) as between-subjects factors. The analysis revealed a significant main effect of SSA, F (3, 108) = 5.24, $p < .005$, $\eta_G^2 = .004$. There was also a significant two-way interaction between trial type and response effector, F (2, 72) = 17.70, $p < .001$, $\eta_G^2 = .004$, and also between response effector and SSA, F (3, 108) = 3.28, $p < .05$, $\eta_G^2 = .000$. Importantly, the results revealed a significant three-way interaction between trial type, SSA and response effector, F (6, 216) = 10.49, p <

.001, η_G^2 = .007 (see Figure 3.3). No other comparisons were significant (all *p's* > .05). We conducted pairwise comparisons to investigate the nature of the SSA main effect using FDR (false discovery rate) corrections to adjust for multiple comparisons. This analysis revealed that the normalized mean MEPs were significantly higher at the 200 ms SSA (*M* = 1.39, *SD* = 0.52) relative to the 50 ms SSA (*M* = 1.30, *SD* = 0.42), *t* (19) = 2.66, *p* < .05, 100 ms SSA (*M* = 1.32, *SD* = 0.41), *t* (19) = 2.71, *p* < .05, and 150 ms SSA (*M* = 1.34, *SD* = 0.47), *t* (19) = 2.61, *p* < .05.

To examine the nature of the three-way interaction, we conducted an ANOVA with trial type and response effector as factors for each level of SSA. This analysis enabled us to ascertain, the point in time at which trial type modulates MEP amplitudes for each effector. No other effects were significant (all *F's* < 2.49). Importantly, there was no four-way interaction between trial type, SSA, response effector and group, *F* (6, 216) = 0.40, *p* = .87, η_G^2 = .0002, suggesting similar MEPs across groups (see Figure 3.4).

3.3.2.1 At 50 ms SSA. A 3 x 2 ANOVA was conducted on mean normalized MEPs in the 50ms SSA condition with trial type (compatible, neutral, incompatible) and response effector (responding effector, non-responding effector) as within-subjects factors. The results revealed a significant main effect of response effector, *F* (1, 19) = 7.19, *p* < .05, η_G^2 = .003, which indicated higher mean MEP amplitudes over the non-responding effector (*M* = 1.33, *SD* = 0.43) as compared to the responding effector (*M* = 1.29, *SD* = 0.42). No other effects were significant (all *Fs* < 2.01). Importantly, there was no interaction between trial type and response effector, *F* (2, 38) = 2.01, *p* = .147, η_G^2 = .002. This pattern of results suggests that the magnitude of MEP amplitudes at each level of trial type were no different for each effector when TMS is delivered 50 ms after target onset; that is, there is no evidence of a Simon effect at the level of the motor cortex within this time point.

3.3.2.2 At 100 ms SSA. We performed the same ANOVA as above on MEPs obtained at the 100 ms SSA. The results revealed no significant main effects (all *F's* < 2.80). Again, there was no interaction between trial type and response effector, F (2, 38) = 0.21, p = .81, η_G^2 = .000. This pattern of results suggests that the magnitude of MEP amplitudes at each level of trial type were no different for both the responding and non-responding effector when TMS is delivered 100 ms after target onset; that is, there is no evidence of a Simon effect at the level of the motor cortex within this time point.

3.3.2.3 At 150 ms SSA. The results of the same 3 x 2 ANOVA for mean MEP amplitudes at the 150 ms SSA revealed a significant interaction between trial type and response effector, F (2, 38) = 10.19, p < .001, η_G^2 = .023. No other effects in this analysis were significant (all *F's* < 2.46). We conducted FDR corrected paired t-tests, for each response effector to investigate the nature of this interaction (see Figure 3.3). The analysis for the responding effector revealed a significantly higher MEP amplitude on compatible trials (*M* = 1.45, *SD* = 0.53) relative to incompatible trials (*M* = 1.27, *SD* = 0.40), t (19) = 4.15, p < .005. This finding is suggestive of the emergence of a Simon effect at the level of the motor cortex. Furthermore, the MEP amplitudes were higher on compatible trials than neutral trials (*M* = 1.34, *SD* = 0.46), t (19) = 3.66, p < .01, which reveals the emergence of a response-facilitation effect. There was also a trend towards a difference in MEPs attained on neutral trials relative to incompatible trials, t (19) = 2.26, p = .07, which suggests an emerging response-suppression effect. For the non-responding effector, however, there were no MEP amplitude differences between levels of trial type at this SSA (all *p's* > 0.10). This pattern of results suggests that the stimulus' information was effective in facilitating participants' responses over responding effector but, interestingly, did not lead to reliably greater levels of activation of the non-responding effector.

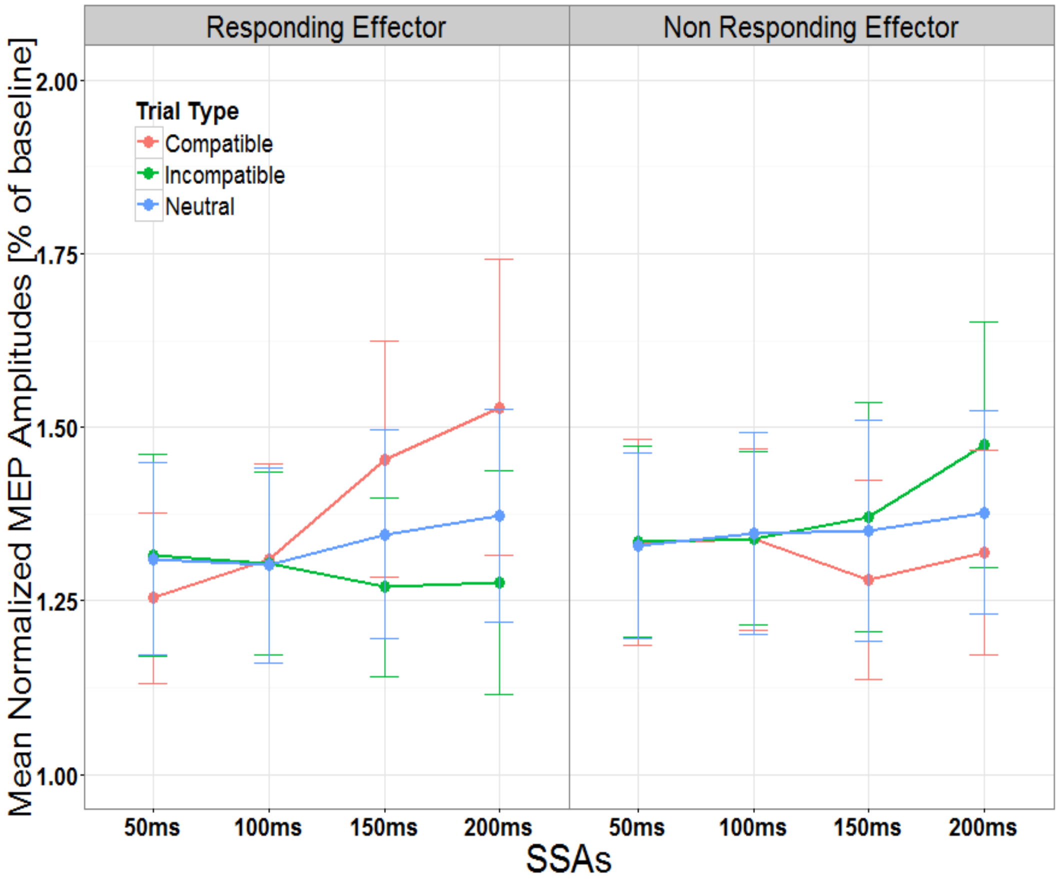


Figure 3.3. Mean MEP amplitudes over responding and non-responding effector for trial type trials across SSAs. The error bars indicate confidence intervals.

3.3.2.4 At 200 ms SSA. We again performed the same ANOVA as above on MEPs obtained at the 200 ms SSA. The results revealed a significant interaction between trial type and response effector, F (2, 38) = 14.17, $p < .001$, $\eta_G^2 = .046$. No main effects were significant (all *F's* < 1.53). We ran paired t-tests adjusted with FDR to investigate the nature of the interaction effect (see Figure 3.3). For the responding effector, the MEP amplitudes were significantly higher on compatible trials (M = 1.52, SD = 0.53) relative to incompatible trials (M = 1.27, SD = 0.40), t (19) = 4.44, $p < .01$, which suggests the presence of a Simon effect even at 200ms after target onset. Furthermore, the MEP amplitudes on compatible trials were higher than neutral trials MEP amplitudes (M = 1.37, SD = 0.46), t (19) = 3.17, $p < .05$, which suggests a continued facilitation of response activation over the responding effector.

Moreover, the MEP amplitudes were significantly lower on incompatible trials relative to neutral trials, t (19) = 3.21, $p < .05$, which suggests the suppression of response activation over the responding effector. For the non-responding effector, the pattern is reversed. That is, at the 200 ms SSA we found significantly higher MEP amplitudes on incompatible trials (M = 1.47, SD = 0.51) than compatible trials (M = 1.31, SD = 0.46), t (19) = 3.19, $p < .05$, which is a reverse Simon effect. The only source that is driving this reverse Simon effect over the non-responding effector is the response activation from the spatial information. Furthermore, to support this claim, there was a trend of significant difference in MEP amplitudes between incompatible and neutral trials (M = 1.37, SD = 0.45), t (19) = 1.96, p = .08, indicating facilitation from the spatial information over the non-responding effector. Also, a trend of significance between the neutral and compatible trials, t (19) = 1.78, p = .090, indicating suppression of response activation over the non-responding effector. This pattern of results at 200ms after target onset suggests that spatial information is very effective in driving motor activation over the non-responding effector on incompatible trials.

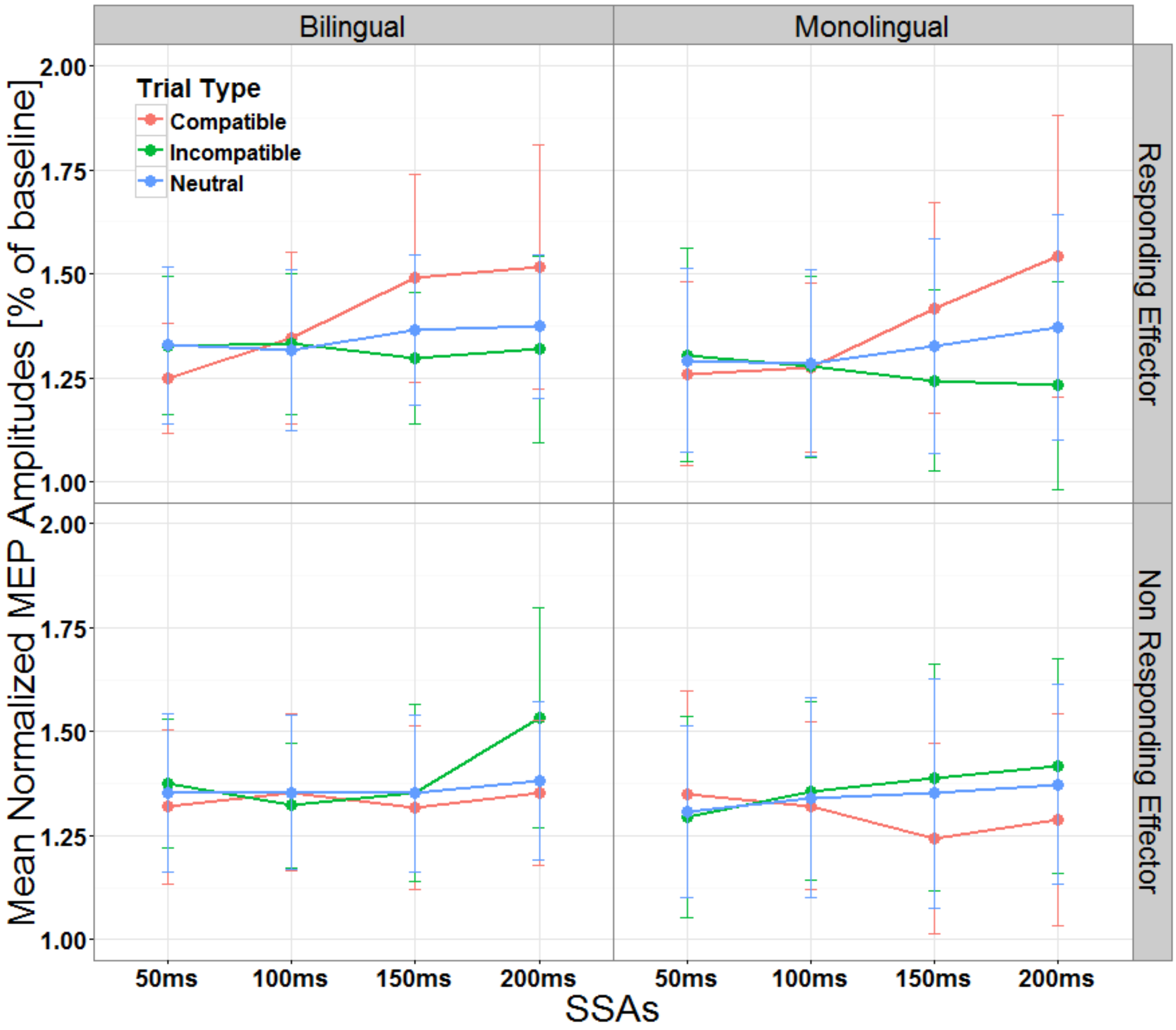


Figure 3.4. Mean MEP amplitudes over responding and non-responding effector across bilinguals (left-side panel) and monolinguals (right-side panel). The error bars indicate confidence intervals.

3.4 Discussion

The primary purpose of the present study was to investigate the temporal dynamics of motor cortex excitability for task-irrelevant and task-relevant information in the Simon task. We further extended this aim by examining the manner in which bilingualism might affect the time course of motor cortex excitability in a Simon task. To investigate these two objectives, we delivered single-pulse TMS at four different SSA's (50 ms, 100 ms, 150 ms, 200 ms) while participants performed the Simon task. The MEP modulation relative to stimulus presentation time allowed us to track the time course of activation by task-irrelevant (spatial) and relevant (colour) stimulus information for each language group.

The behavioural data are consistent with the classic findings of higher accuracy on compatible trials relative to neutral and incompatible trials (e.g., Acosta & Simon, 1976; De Jong et al., 1994; Lu & Proctor, 1995; Simon & Rudell, 1967; Umiltá et al., 1999; Wallace, 1972; Wiegand & Wascher, 2007). Additionally, the MEP data revealed higher activation on compatible trials as compared to neutral and incompatible trials for the responding effector, whilst the reverse was true for the non-responding effector. This pattern of results not only replicated previous studies utilising MEPs in the Simon task (Stürmer et al., 2000; van Campen et al., 2014), but also resembled the response latency findings observed in other studies (i.e., faster responses on compatible vs. incompatible trials; Hedge & Marsh, 1975; Lu & Proctor, 1995 for review). Indeed, these results indicate that participants are preparing a motor response for the correct effector on compatible trials and the incorrect effector on incompatible trials. The consistency between our behavioural and MEP findings with that of others validates our task.

The three major findings obtained from the MEP data to be discussed further include: response-facilitation over responding effector on compatible trials, reverse Simon effect over non-responding effector on incompatible trials and response-suppression over responding effector on incompatible trials.

First, over the responding effector at 150 ms and 200 ms after target onset we observed the response-facilitation effect (i.e., the difference in MEP amplitude between compatible and neutral trials). Stürmer et al. (2000) argued for task-irrelevant spatial information activation for the response-facilitation effect, however, in contrast to their claims, we attribute the onset of response-facilitation to the combination of response activation from both stimulus location and stimulus colour dimension over the same response code on compatible trials. This is in line with the assumptions of dual-route accounts, in which both direct and indirect route processes activate the same response code leading to faster responses on compatible trials (De Jang et al., 1994; Kornblum, Hasbroucq, & Osman, 1990; Ridderinkhof, 2002). Hence, it was difficult to tease apart whether the MEP responses on compatible trials were driven by stimulus location information or stimulus colour information in the Simon task. The findings were similar to Stürmer et al. (2000), which revealed a strong response-facilitation over the responding effector, and, simultaneously, on the same set of trials the motor activation was not suppressed over the non-responding effector relative to the neutral trials activation levels.

Second, over the non-responding effector, at 200 ms after target onset, the MEP responses were higher on incompatible trials relative to compatible trials. There was also an emerging trend of higher MEPs on incompatible trials relative to neutral trials. The only source of information that is directing higher motor cortex excitability on incompatible trials is the response activation from the task-irrelevant dimension over the non-responding effector. We attribute the pattern of results at this time point to the evolution of early motor preparation processes triggered by the stimulus location information on incompatible trials. These early motor preparation processes are similar to the early waveform deflection of the lateralized readiness potential (LRP), reported in the Simon task at ~ 200 ms after target onset (De Jong et al., 1994; Leuthold, 2011). The LRP is an event-related potential that is the difference in ERP activity from the contralateral and ipsilateral motor cortex of the responding effector (i.e., interhemispheric design). The negative deflection of the LRP on incompatible trials reflects the higher cortical activation over the ipsilateral motor cortex of the responding effector, which is attributed to the response activation from the task-irrelevant stimulus location dimension (Burle et al., 2002; Eimer, 1995; Leuthold, 2011; Valle-Inclán, 1996; Wascher et al., 2001). Thus, we propose that the higher MEP amplitude on incompatible trials over the non-responding effector corresponds to the early motor cortex preparation driven by the task-irrelevant spatial information from the fast direct route processes (De Jong et al., 1994; Stürmer et al., 2000; Stürmer, Redlich, Irlbacher, & Brandt, 2007). Furthermore, these results are in line with Stürmer et al. (2000) at 200 ms after target onset, where they argue for spatial information activation over the non-responding effector on incompatible trials. However, in comparison to van Campen et al. (2014) study, the emergence of reverse Simon effect was significant in the present study.

The third major finding to be discussed in MEP data is that, at 200 ms after target onset, the data suggested response-suppression effect (i.e., the difference between incompatible and neutral trials MEP amplitude) over the responding effector. The only information that is suppressing motor cortex excitability on incompatible trials over the responding effector is the task-irrelevant information activation over the non-responding effector. Unlike previous studies (Stürmer et al., 2000; van Campen et al., 2014), we recorded MEPs simultaneously from the responding and non-responding effector on the same trial. The location information activation on the non-responding effector at 200 ms after target onset might have significantly suppressed the motor cortex excitability of the responding effector. The pattern is similar to computational models of the Simon effect (Zorzi & Umiltá, 1995) and interhemispheric motor inhibition accounts (Di Lazzaro et al., 1999; Schnitzler et al., 1996), which states that “the transcranial stimulation of the motor cortex of one side in man evoke activity in transcallosal pathway producing an inhibition of the contralateral motor cortex” (Di Lazzaro et al., 1999, p.524). The results were inconsistent with Stürmer et al. (2000) for response-suppression over the responding effector at least for the MEP responses recorded from left motor cortex stimulation. However, they do report response-suppression on incompatible trials whey they delivered single-pulse TMS over the right motor cortex.

The above motor cortex excitability results are in line with dual-route accounts, according to which, a fast direct route of response selection is suggested to activate responses that spatially correspond to the stimulus location at an early stage of stimulus processing. This is followed by response activation from a slow indirect route on the basis of the task-relevant stimulus colour information at later stages of stimulus processing (De Jang et al., 1994; Kornblum, Hasbroucq, & Osman, 1990; Ridderinkhof, 2002). In the present study, we were able to capture the evolution of fast and early response activation from the direct route for the task-irrelevant spatial information at 200 ms after target onset. In contrast to our predictions for task-relevant information activation, we did not find higher MEP responses over neutral trials relative compatible trials over the responding effector. We were able to report a combined effect of response activation from task-relevant and task-irrelevant dimension on compatible trials. However, we were not able to capture the exact time point of response activation for the task-relevant information. This might be due to the slow and late emergence of the task-relevant information in the Simon task (Burle et al., 2002; Finkbeiner & Heathcote, 2016; Hasbroucq, Possamaï, Bonnet, & Vidal, 1999; see Burle, Vidal, Tandonnet, & Hasbroucq, 2004 for review). Hence, the time interval between target onset and the TMS pulse (50 ms to 200 ms) to record MEPs in the current study might be limited to capture the response activation for the task-relevant information from the indirect route.

Unlike previous studies who explored the motor cortex status of responding and non-responding effectors on different trials (i.e., interhemispheric design; Stürmer et al., 2000; van Campen et al., 2014), in the present study we probed the responding and non-responding effector motor cortex status simultaneously by applying single-pulse TMS (i.e., intrahemispheric design). The intrahemispheric design provides deeper insight in understanding the interactive mechanism between the responding and non-responding effector response within hemispheres (e.g., for incompatible trials in which the RED colour square presented on the right visual field, recording responses simultaneously from both the right-hand index finger, i.e., responding effector, and the right-hand little finger, i.e., non-responding effector).

Furthermore, in the present study, we explored whether the so-called bilingual cognitive advantage (if present) is due to bilinguals' ability to control response activation of task-irrelevant information or whether it is due to bilinguals' ability to activate response activation of task-relevant information. To achieve this, we captured the time course of task-irrelevant and task-relevant information in the Simon task. Interestingly, there was no evidence for a group difference in the MEP responses, even though the MEP data demonstrated the response activation of task-irrelevant information at 200 ms over the non-responding effector. This suggests that the consequences of bilingualism are absent for response activation of stimulus information at the level of the motor cortex.

Additionally, we captured the magnitude of the Simon effect at similar response time points (at 50 ms, 100 ms, 150 ms, and 200 ms) across bilinguals and monolinguals by delivering single-pulse TMS. This procedure allowed us to eliminate the reaction time distribution differences between the language groups to measure the magnitude of the Simon effect. The overall data indicated the onset of the Simon effect at 150ms after target onset over the responding effector. However, in contrast to our prediction, there was no effect of bilingualism on the magnitude or the time course of the Simon effect in the MEP data. These findings suggest that the benefits of bilingualism on conflict resolution may be absent in the early motor preparation stage (~200 ms) at the level of the motor cortex.

To our knowledge, none of the previous studies investigating bilingual cognitive control have specifically looked into the response activation for stimulus information at the level of motor cortex by recording MEPs in the Simon task. Reaction time measures have been commonly used to measure group differences in the cognitive control tasks, which represents the end point of cognitive decision making (e.g., Bialystok et al., 2004; Bialystok, 2006; see Hilchey & Klein, 2011; Paap & Sawi, 2014; Zhou & Krott, 2015). This mean that the results of previous studies are difficult to compare with the results of the current study.

Recently, Kousaie and Phillips (2012) investigated bilinguals' and monolinguals' performance on the Simon task by measuring the P300 component. Their results demonstrated a smaller amplitude of P300 in bilinguals relative to monolinguals. Kousaie and Phillips (2012) argued the evidence of smaller magnitude in bilinguals for higher resource allocation while performing the task. It is possible that the effect of bilingualism in the Simon task is not evident in the earliest stages of motor preparation. Such a possibility would indicate that bilinguals exhibit differences in cognitive control at the point where stimulus information reaches the later response decision system. Indeed, this possibility would be consistent with findings from electrophysiological studies (e.g., Coderre, & van Heuven, 2014; Heidlmayr, Hemforth, Moutier, & Isel, 2015; Kousaie & Phillips, 2012).

There are other possible reasons that could explain why we did not observe an effect of bilingualism. For instance, the small sample size ($n = 20$) may have reduced statistical power to the point where it would be difficult to observe group differences. However, previous studies reporting language group differences have found effects with the same number of participants (e.g., Bialystok et al., 2004; Bialystok et al., 2005; Bialystok et al., 2008; Yang, Yang, & Lust, 2011). Additionally, the interplay between bilingualism and cognitive control might not have been picked up in the young adults due to the ceiling effect or peak age of cognitive functioning (e.g., Bialystok, Craik, & Luk, 2005; Paap & Greenberg, 2013; Salvatierra & Rosselli, 2011). However, researchers recruiting young adults have shown a bilingual advantage on various other cognitive control tasks (e.g., Blumenfeld & Marian, 2014; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa, Hernández, & Sebastián-Gallés, 2008; Hernández et al., 2010; Prior & Gollan, 2011; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011).

In summary, the purpose of this study was to investigate the time course of task-irrelevant and task-relevant information in the Simon task at the level of motor cortex. The

MEPs coupled with the temporal resolution offered by TMS, promises to shed new light on the exact time point at which the stimulus information is activated at an early motor preparation stage. The results illustrated that task-irrelevant spatial information is activated earlier than task-relevant colour information, thereby supporting dual-route theories of the Simon effect (e.g., De Jong et al., 1994). We also explored the effect of bilingualism on the time course of stimulus information. Specifically, we investigated whether bilinguals are better at suppressing the response activation from the task-irrelevant information, or, whether bilinguals are faster at activating the task-relevant information. The lack of evidence for motor cortex excitability differences between language groups for the stimulus information and the Simon effect challenges the notion of a bilingual cognitive advantage in the early motor preparation stage for the bilinguals selected in the present study. To conclude, the effect of bilingualism on a cognitive control task were absent in the early stages of motor preparation.

References

Acosta Jr, E., & Richard Simon, J. (1976). The effect of irrelevant information on the stages of processing. *Journal of Motor Behavior*, *8*(3), 181-187. doi:10.1080/00222895.1976.10735070

Aisenberg, D., & Henik, A. (2012). Stop being neutral: Simon takes control! *The Quarterly Journal of Experimental Psychology*, *65*(2), 295-304. doi: 10.1080/17470218.2010.507819

Bialystok, E. (2006). Effect of bilingualism and computer video game experience on the Simon task. *Canadian Journal of Experimental Psychology*, *60*(1), 68-79. doi: 10.1037/cjep2006008

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and Aging*, *19*(2), 290-303. doi: 10.1037/0882-7974.19.2.290

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859-873. doi: 10.1037/0278-7393.34.4.859

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism*, *9*(1), 103-119. doi: 10.1177/13670069050090010701

Blumenfeld, H. K., & Marian, V. (2014). Cognitive control in bilinguals: Advantages in Stimulus–Stimulus inhibition. *Bilingualism: Language and Cognition*, *17*(03), 610-629. doi: 10.1017/S1366728913000564

Burle, B., Possamaï, C. A., Vidal, F., Bonnet, M., & Hasbroucq, T. (2002). Executive control in the Simon effect: an electromyographic and distributional analysis. *Psychological Research*, *66*(4), 324-336. doi:10.1007/s00426-002-0105-6

Burle, B., Vidal, F., Tandonnet, C., & Hasbroucq, T. (2004). Physiological evidence for response inhibition in choice reaction time tasks. *Brain and Cognition*, *56*(2), 153-164. doi: 10.1016/j.bandc.2004.06.004

Coderre, E. L., & van Heuven, W. J. (2014). Electrophysiological explorations of the bilingual advantage: evidence from a Stroop task. *PLos one*, 9(7). doi: 10.1371/journal.pone.0103424

Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition*, *106*(1), 59-86. doi: 10.1016/j.cognition.2006.12.013

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don't. *Cognition*, *113*(2), 135-149. doi:10.1016/j.cognition.2009.08.001

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: a dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(4), 731-750. doi: 10.1037/0096-1523.20.4.731

Di Lazzaro, V., Oliviero, A., Profice, P., Insola, A., Mazzone, P., Tonali, P., & Rothwell, J. C. (1999). Direct demonstration of interhemispheric inhibition of the human motor cortex produced by transcranial magnetic stimulation. *Experimental Brain Research*, *124*(4), 520-524. doi:10.1007/s002210050648

Eimer, M. (1995). Stimulus-response compatibility and automatic response activation: evidence from psychophysiological studies. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(4), 837-854. doi:10.1037/0096-1523.21.4.837

Finkbeiner, M. & Heathcote, A. (2016). Distinguishing the time- and magnitude-difference accounts of the Simon effect. *Attention, Perception and Psychophysics, 78,* 848-867. doi: 10.3758/s13414-015-1044-9

Hasbroucq, T., Possamaï, C. A., Bonnet, M., & Vidal, F. (1999). Effect of the irrelevant location of the response signal on choice reaction time: An electromyographic study in humans. *Psychophysiology*, *36*(4), 522-526. doi: 10.1017/S0048577299001602

Hedge, A., & Marsh, N. W. A. (1975). The effect of irrelevant spatial correspondences on two-choice response-time. *Acta psychologica*, *39*(6), 427-439. doi: 10.1016/0001-6918(75)90041-4

Heidlmayr, K., Hemforth, B., Moutier, S., & Isel, F. (2015). Neurodynamics of executive control processes in bilinguals: evidence from ERP and source reconstruction analyses. *Frontiers in Psychology*, *6*. doi: 10.3389/fpsyg.2015.00821

Hernández, M., Costa, A., Fuentes, L. J., Vivas, A. B., & Sebastián-Gallés, N. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Bilingualism: Language and Cognition*, *13*(03), 315-325. doi: 10.1017/S1366728909990010

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625-658. doi: 10.3758/s13423-011-0116-7

Keel, J. C., Smith, M. J., & Wassermann, E. M. (2001). A safety screening questionnaire for transcranial magnetic stimulation. *Clinical Neurophysiology*, *112*(4), 720. doi:10.1016/S1388-2457(00)00518-6

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: cognitive basis for stimulus-response compatibility--a model and taxonomy. *Psychological Review*, *97*(2), 253-270. doi: 10.1037/0033-295X.97.2.253

Kousaie, S., & Phillips, N. A. (2012). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research*, *1446*, 71-90. doi: 10.1016/j.brainres.2012.01.052

Leuthold, H. (2011). The Simon effect in cognitive electrophysiology: a short review. *Acta Psychologica*, *136*(2), 203-211. doi:10.1016/j.actpsy.2010.08.001

Lu, C. H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*(2), 174-207. doi: 10.1016/j.actpsy.2010.08.001

Marian, V., Blumenfeld, H. K., &Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech, Language, and Hearing Research, 50,* 940–967. doi:10.1044/1092-4388(2007/067)

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113. doi: 10.1016/0028-3932(71)90067-4

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232-258. doi: 1016/j.cogpsych.2012.12.002

Paap, K. R., & Sawi, O. (2014). Bilingual advantages in executive functioning: problems in convergent validity, discriminant validity, and the identification of the theoretical constructs. *Frontiers in Psychology*, *5*(962), 2. doi: 10.3389/fpsyg.2014.00962

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(04), 682-691. doi: 10.1017/S1355617711000580

Raven, J., Raven, J. C. & Court, J. H (1998). Raven manual: Section 4, Advanced Progressive Matrices, 1998 edition. Oxford, UK: Oxford Psychologists Press Ltd.

Ridderinkhof, R. K. (2002). Micro-and macro-adjustments of task set: Activation and suppression in conflict tasks. *Psychological research*, *66*(4), 312-323. doi: 10.1007/s00426-002-0104-7

Salvatierra, J. L., & Rosselli, M. (2011). The effect of bilingualism and age on inhibitory control. *International Journal of Bilingualism*, *15*(1), 26-37. doi:10.1177/1367006910371021.

Schnitzler, A., Kessler, K. R., & Benecke, R. (1996). Transcallosally mediated inhibition of interneurons within human primary motor cortex. *Experimental brain research*, *112*(3), 381-391. doi:10.1007/BF00227944

Simon, J. R., & Rudell, A. P. (1967). Auditory SR compatibility: the effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*(3), 300-304. doi:10.1037/h0020586

Stürmer, B., Redlich, M., Irlbacher, K., & Brandt, S. (2007). Executive control over response priming and conflict: a transcranial magnetic stimulation study. *Experimental Brain Research*, *183*(3), 329-339. doi:10.1007/s00221-007-1053-6

Stürmer, B., Siggelkow, S., Dengler, R., & Leuthold, H. (2000). Response priming in the Simon paradigm. *Experimental Brain Research*, *135*(3), 353-359. doi: 10.1007/s002210000529

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology*, *2*. doi: 10.3389/fpsyg.2011.00123

Terao, Y., & Ugawa, Y. (2002). Basic mechanisms of TMS. *Journal of Clinical Neurophysiology*, *19*(4), 322-343.

Umiltá, C., Rubichi, S., & Nicoletti, R. (1999). Facilitation and interference components in the Simon effect. *Archives italiennes de Biologie*, *137*(2), 139-149.

Valle-Inclán, F. (1996). The locus of interference in the Simon effect: an ERP study. *Biological Psychology*, *43*(2), 147-162. doi: 10.1016/0301-0511(95)05181-3

van Campen, A. D., Keuken, M. C., van den Wildenberg, W. P., & Ridderinkhof, K. R. (2014). TMS over M1 reveals expression and selective suppression of conflicting action impulses. *Journal of Cognitive Neuroscience*, *26*(1), 1-15. doi:10.1162/jocn_a_00482

Wallace, R. J. (1972). Spatial SR compatibility effects involving kinesthetic cues. *Journal of Experimental Psychology*, *93*(1), 163-168. doi: 10.1037/h0032462

Wascher, E., Schatz, U., Kuder, T., & Verleger, R. (2001). Validity and boundary conditions of automatic response activation in the Simon task. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(3), 731-751. doi: 10.1037/0096-1523.27.3.731

Wassermann, E. M., Pascual-Leone, A., & Hallett, M. (1994). Cortical motor representation of the ipsilateral hand and arm. *Experimental Brain Research*, *100*(1), 121-132. doi: 10.1007/BF00227284

Wiegand, K., & Wascher, E. (2007). The Simon effect for vertical S–R relations: changing the mechanism by randomly varying the S–R mapping rule? *Psychological Research*, *71*(2), 219-233. doi:10.1007/s00426-005-0023-5

Wühr, P., & Ansorge, U. (2005). Exploring trial-by-trial modulations of the Simon effect. *The Quarterly Journal of Experimental Psychology*, *58*(4), 705-731. doi: 10.1080/02724980443000269

Yang, S., Yang, H., & Lust, B. (2011). Early childhood bilingualism leads to advances in executive attention: Dissociating culture and language. *Bilingualism: Language and Cognition*, *14*(03), 412-422. doi: 10.1017/S1366728910000611

Zorzi, M., & Umiltá, C. (1995). A computational model of the Simon effect. *Psychological Research*, *58*(3), 193-205. doi: 10.1007/BF00419634

Zhou, B., & Krott, A. (2015). Data trimming procedure can eliminate bilingual cognitive advantage. *Psychonomic Bulletin & Review*, 1-10. doi:10.3758/s13423-015-0981-6

Chapter 4

Differences in the Time Course of Conflict Resolution in Bilinguals and Monolinguals: Evidence from the Forced-Reading Stroop Task

Manjunath Narra[1, 2, 3] & Matthew Finkbeiner[1, 2, 3]

[1] Perception in Action Research Centre, Macquarie University, Australia

[2]Department of Cognitive Science, Macquarie University, Australia

[3]ARC Centre of Excellence in Cognition and its Disorders, Macquarie University, Australia

Abstract

Previous studies have shown that in the Stroop task, participants respond faster when the ink colour and the word meaning are the same, i.e., compatible trials, than when they are different, i.e., incompatible trials. The response time difference between compatible and incompatible trials is referred to as the Stroop effect and its magnitude is thought to reflect one's ability to resolve conflict between word reading and the ink colour dimension. Interestingly, some studies have shown that bilinguals outperform monolinguals in the Stroop task, with overall faster response times and smaller Stroop effects. To understand the cognitive processes of a bilingual advantage, in the present study, we investigated the time course of conflict resolution between the word reading and ink colour information in bilinguals and monolinguals. We employed a *reach-to-touch* version of the forced-reading Stroop task coupled with the response-signal procedure to uncover the magnitude of Stroop effect in these two populations. Participants initiated their reaching responses across a wide range of stimulus viewing times, allowing us to determine when the Stroop effect first emerges. Surprisingly, our results show that the Stroop effect emerged earlier in bilinguals than monolinguals. This finding suggests that bilinguals are not better at controlling interference from the task-irrelevant information in the forced-reading Stroop task. The findings challenge the notion of a bilingual cognitive advantage in linguistic cognitive control tasks.

Differences in the Time Course of Conflict Resolution in Bilinguals and Monolinguals: Evidence from the Forced-Reading Stroop Task

4.1 Introduction

The Stroop colour word task (Stroop, 1935) is a commonly used cognitive control task to investigate response conflict (see MacLeod, 1991 for review). In this task, participants were asked to respond to the ink colour of a word (the task-relevant dimension) by simultaneously ignoring the word reading (the task-irrelevant dimension). Participants respond faster and more accurately when the word meaning and the ink colour are the same (compatible trials; e.g., the word RED presented in red ink) than when they are different (incompatible trials; e.g., the word RED presented in green ink). The response time difference between compatible and incompatible trials is referred to as the Stroop effect and its magnitude corresponds to one's ability to control interference from task-irrelevant word reading to respond accurately to the ink colour dimension. The Stroop effect has been accounted for by parallel distributed processing models (Cohen, Dunbar, & McClelland, 1990; MacLeod, 1991) that are based upon magnitude difference accounts. According to these models, it is proposed that both the task-irrelevant (word reading) and task-relevant pathways (ink colour) are activated at the same time. However, the relative magnitude of the task-irrelevant pathway is higher in the initial stages (MacLeod & McClelland, 2000). The faster responses on compatible trials are attributed to the same response activation from the word reading and the ink colour dimensions (Roelofs, 2010). On the other hand, the slower responses on incompatible trials are attributed to conflict resolution between the automatic word reading dimension and the ink colour dimension.

The Stroop task has been used to investigate the interaction between cognitive control and language processing abilities in bilinguals (e.g., Dyer, 1971; Mägiste, 1984; Rosselli et al., 2002; Zied et al., 2004). Studies investigating the Stroop effect in bilinguals (in L1 and

L2), have reported larger Stroop effect in L1 compared to that of L2 (e.g., Heidlmayr et al., 2014; Rosselli et al., 2002; Zied et al., 2004). The smaller magnitude of the Stroop effect in bilinguals L2 has been attributed to reduced automaticity of word reading due to lower proficiency (e.g., Dijkstra & van Heuven, 2002; Gollan et al., 2005; for review see Kroll, Sumutka, & Schwartz, 2005). Interestingly, the asymmetrical difference in the Stroop effect between L1 and L2 is predominantly observed in unbalanced bilinguals (Mägiste, 1984; MacLeod, 1991) than the balanced bilinguals who are proficient in both languages (e.g., Lee & Chan, 2000; Naylor, Stanley, & Wicha, 2011; Tse & Altarriba, 2012). These studies suggest that proficiency in the Stroop task stimuli language significantly influences the magnitude of the Stroop effect in bilinguals (e.g., MacLeod, 1991; Marian et al., 2013).

In the past decade, the Stroop task has also been used to investigate the cognitive control abilities of both bilinguals and monolinguals (e.g., Bialystok, Craik, & Luk, 2008; Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010; Heidlmayr, Hemforth, Moutier, & Isel, 2015; Yow & Li, 2015). Interestingly, studies have reported a smaller magnitude of Stroop and interference effects in bilinguals relative to monolinguals (e.g., Badzakova-Trajkov, 2008; Bialystok, Craik, & Luk, 2008; Coderre & van Heuven, 2014; Coderre, van Heuven, & Conklin, 2013; Heidlmayr, Moutier, Hemforth, Courtin, Tanzmeister, & Isel, 2014; Sabourin & Vinerte, 2015). A number of recent studies however failed to replicate previous findings of a bilingual advantage (e.g., Duñabeitia et al., 2014; Kousaie & Phillips, 2012a; Rosselli, Ardila, Lalwani, & Vélez-Uribe, 2016; von Bastian, Souza, & Gade, 2016). The mixed findings between bilinguals and monolinguals on cognitive control tasks across studies have also been attributed to differences in matching bilingual and monolingual participants on various confounding factors, including: socioeconomic status, nonverbal intelligence, video game playing and computer usage (see Dong & Li, 2015; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Paap, Sawi, Dalibar, Darrow, & Johnson, 2015; Valian, 2015 for review).

Using the classic Stroop colour word naming task, Bialystok, Craik, and Luk (2008) investigated the interaction between bilingualism and cognitive control in a mixed group of young and older bilinguals (low vocabulary scores in stimulus language) and monolinguals. The task consisted of four different types of trials presented in a blocked design (neutral-colour, neutral-word, compatible, incompatible). On neutral-colour trials participants named the ink colour of target letters (e.g., a series of Xs presented in red ink). On neutral-word trials, participants read the word displayed in black ink (e.g., the word 'RED' presented in black ink). They measured the Stroop effect from the compatible and incompatible trials. Despite similar behavioural performance between bilinguals and monolinguals on neutral trials (i.e., colour naming and word reading), the results revealed a smaller Stroop effect in bilinguals compared to monolinguals. Additionally, the bilinguals showed a smaller interference effect, the response time difference between incompatible and neutral-colour trials and a larger facilitation effect, the response time difference between compatible and neutral-colour trials than their monolingual counterparts (Bialystok, Craik, & Luk, 2008). However, in early bilinguals with high proficiency in the stimulus language, Kousaie and Phillips (2012b) failed to replicate a smaller interference effect, instead observed overall faster reaction times than monolinguals, supporting an overall speed advantage for bilinguals (e.g., Incera & MacLennan, 2016). These studies suggest that the bilingual advantage varied across stimuli language proficiency between bilinguals and monolinguals.

Additionally, when there was no evidence for a behavioural difference between bilinguals (early, late bilinguals) and monolinguals in the mean reaction time, the event-related potentials (ERPs) such as N200 (Kousaie & Phillips, 2012a), P300 (Kousaie & Phillips, 2012a) and N400 (Coderre, van Heuven, & Conklin, 2013; Heidlmayr, Hemforth, Moutier, & Isel, 2015) were sensitive enough to capture neural processing differences in the Stroop task. In their seminal work, Kousaie and Phillips (2012a) investigated the different electrophysiological responses in the colour word Stroop task between early bilinguals and monolinguals. In their study, the early bilinguals demonstrated smaller N200 amplitude and early peak latency of P300 relative to monolinguals. In a similar line of research, Heidlmayr et al. (2015) measured the Stroop effect for N200 and N400 components between late bilinguals and monolinguals. In contrast to Kousaie and Phillips (2012a), Heidlmayr et al. (2015) reported no evidence for language group differences for the N200 component. For the N400 component, the results revealed a smaller Stroop effect size in late bilinguals than the monolinguals. In addition to behavioural studies, the ERP data suggest that neural processing differences between bilinguals (early, late) and monolinguals emerge at different time windows. However, it is difficult to interpret neurophysiological differences as an index to represent a bilingual advantage, due to their varied interpretation across studies and inconsistency with the behavioural data (e.g., Liu, Yao, Wang, & Zhou, 2014; Paap et al., 2015).

Coderre, van Heuven, and Conklin (2013) investigated the influence of lexical processing speed and cognitive control in the Stroop colour word task in late bilinguals (English-Chinese, Chinese-English) and monolinguals (English). In their task, the *word* (task-irrelevant dimension) and *colour* (task-relevant dimension) were presented at five different SOA's (± 400, ± 200, 0) to track lexical processing speed and cognitive control. In negative SOAs, the *word* was presented before the *colour* dimension, whereas, in positive SOAs the *colour* dimension was presented before the *word* dimension. They predicted earlier peak onset of the interference effect (in negative SOAs) in bilinguals relative to monolinguals with similar magnitude indicating delayed lexical processing speed. They also predicted a lower magnitude of peak interference effect in bilinguals compared to monolinguals suggesting enhanced cognitive control abilities at the same SOA across groups. Their results showed, that the English (L1) - Chinese (L2) bilinguals and monolinguals performed similarly for L1 (English) Stroop task, suggesting that when the proficiency is similar across groups in the stimuli language, then there was no evidence for a bilingual advantage.

Further, in the Coderre, van Heuven, and Conklin (2013) study, the Chinese (L1)-English (L2) bilinguals showed the smaller magnitude of peak interference effect for L2 (English) compared to monolinguals at - 200ms. Coderre, van Heuven, and Conklin (2013) argued that this was evidence for an enhanced cognitive control abilities in bilinguals since there was no group difference in the timing of peak interference effect (same lexical processing speed). Additionally, in contrast to their prediction, for the Chinese version, the results demonstrated later onset of peak interference effect in bilinguals relative to monolinguals, which was argued for script variability. Coderre, van Heuven, and Conklin (2013) results indicate that higher proficiency in the stimulus (English) language, the more similar the behavioural performance across groups and lower proficiency in the testing (English) language, the lower the magnitude of the interference effect in late bilinguals. These results are inconsistent with either delayed lexical processing speed or enhanced cognitive control abilities in bilinguals, which might be due to the influence of language proficiency, the age of second language acquisition and the language script differences across groups.

The automaticity of word reading has been shown to influence the magnitude of the Stroop effect in studies investigating cognitive control in bilinguals and monolinguals. It has been argued that in the Stroop colour word task, wherein participants are asked to respond to the ink colour of the word, it is possible that participants miss the automatic word reading on some trials and directly respond to the ink colour (e.g., Algom et al., 1996; Eidels, Ryan, Williams, & Algom, 2014; Kane & Engle, 2002; 2003). In this case, missing automatic word reading modulates the magnitude of Stroop effect (and interference effect) within trials, across participants and experiments. This might also contribute to inconsistent results across studies investigating bilingual cognitive control when the two groups are compared. Recently, Eidels et al. (2014) developed a forced-reading Stroop task, in which the participants were instructed to recognise the word (colour vs. non-colour) before making a correct response choice. In colour word trials, the participant’s task was to respond to the ink colour of the word, whereas, in non-colour word trials, (e.g., ROD, QUEEN) participants were asked to withhold the response. The forced-reading task design maximised the probability of trials in which both the word reading and ink colour dimensions were activated simultaneously. In turn, increasing the complexity of interference between the word reading and ink colour dimensions in the Stroop task. Eidels, Ryan, Williams, and Algom, (2014; Experiment 2) reported increased interference between word reading and ink colour by demonstrating a larger Stroop effect in the forced-reading Stroop task (122 ms) compared to the standard Stroop task (37 ms). In the present study, we used the forced-reading Stroop task to investigate the cognitive processes of resolving conflict between the word reading and ink colour dimensions in bilinguals and monolinguals.

The review of studies suggests that the interaction between bilingualism and cognitive control in the Stroop colour word task is intrinsically connected to bilingual language history and other confounding factors. To pursue this further, in our study, we carefully matched bilingual and monolingual participants for testing stimuli language proficiency, nonverbal intelligence, socioeconomic status, handedness, video game playing and computer usage. Nevertheless, how the cognitive processes that underlie the ability of both bilingual and monolingual participant's to resolve the conflict between word reading and colour naming emerge across stimulus processing time is still an open question. In the present study, to understand the cognitive processes of a bilingual advantage in the Stroop task, we investigated the time course of the conflict effect (i.e., interference effect, Stroop effect) in early bilinguals and monolinguals.

To understand the time course of conflict control in the Stroop task, one needs to track the emergence of the conflict effect (the Stroop effect, interference effect) in the Stroop task. To achieve this, a continuous behavioural paradigm (such as a reach-to-touch measure), would be more appropriate to uncover the temporal dynamics of conflict resolution. Due to its high temporal resolution, in recent years these techniques have been used to study the real-time unfolding of cognitive processes and motor response at early stages of information processing while the participants are still processing the stimulus information (e.g., Finkbeiner et al., 2008; Finkbeiner, Coltheart, & Coltheart, 2014; Finkbeiner & Heathcote, 2016; Quek & Finkbeiner, 2013; 2014; Spivey, Grosjean, & Knoblich, 2005; Song & Nakayama, 2008).

In the present study, we take full advantage of the high temporal resolution offered by the reach-to-touch paradigm (Finkbeiner & Heathcote, 2016) to uncover the dynamics of conflict resolution between word reading and ink colour across bilinguals and monolinguals. In the reach-to-touch version of the forced-reading Stroop task, participants categorised the target stimulus by reaching out and touching the appropriate response panel (Tillman, Eidels, & Finkbeiner, 2014). We compared the initial x-velocity profiles (which is the dependent measure in the reach-to-touch paradigm) of specific trial types as a function of stimulus viewing time across language groups. If bilinguals are less susceptible to interference from the word reading dimension then we would expect a late onset of the conflict effect (i.e., interference and Stroop effect) in bilinguals compared to monolinguals. The late onset of a conflict effect would be consistent with the notion that the enhanced cognitive ability of bilinguals allows suppression of the task-irrelevant dimension and greater ability to respond accurately on the task-relevant dimension. On the other hand, if bilinguals are more susceptible to interference in word reading, then we predict an early onset of the conflict effect in bilinguals compared to monolinguals. The early onset of a conflict effect may be suggestive of poor cognitive control to suppress the task-irrelevant word reading dimension and respond accurately to the task-relevant ink colour dimension.

4.2 Method

4.2.1 Participants

Nineteen monolinguals and 19 bilinguals in the age range of 18 to 36 years were recruited from Macquarie University's psychology participant pool and received credit points for their participation. All participants completed a Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian, Blumenfeld, & Kaushanskaya, 2007) (see Appendix A), Edinburgh Handedness Inventory (Oldfield, 1971) (see Appendix B), and Raven's Advanced Progressive Matrices-Set I (Raven, Raven, & Court, 1998) (see Appendix C) before the actual experiment. Table 4.1 presents detailed descriptions of the participants' demographic information.

Based on the self-reported general language background questionnaire (see Appendix D), participants were allocated into either the bilingual group (mean age = 22.21 years, SD = 5.21; females = 10) or the monolingual group (mean age = 21.21 years, SD = 5.10; females = 9). The monolingual participants spoke only English and they were not exposed to any other language. The bilingual participants spoke English and another language: Mandarin (n = 3), Cantonese (n = 2), Korean (n = 2), Serbian (n = 2), Tamil (n = 1), Kannada (n = 1), Hindi (n = 1), Punjabi (n = 1), Bengali (n = 1), Vietnamese (n = 1), Burmese (n = 1), Greek (n = 1), Italian (n = 1), and French (n = 1). Monolingual and bilingual participants were matched across self-reported English language proficiency ratings, age, years of education, handedness, nonverbal intelligence, video game playing and socioeconomic status (all p's > .05). None of the participants reported any speech, hearing, and neurological disorders. All participants were right-handed and had normal or corrected-to-normal vision. The study was approved by the Macquarie University Human Research Ethics Committee (see Appendix E). Before testing, informed consent was obtained from all the participants (see Appendix F).

Table 4.1.

Demographic information for participant groups.

Variables	**Monolinguals Mean (SD)**	**Bilinguals Mean (SD)**	**Sig.**
Age (in years)	21.21 (5.10)	22.21 (5.21)	$p > .05$
Formal Education (in years)	14.3 (2.28)	15.10 (3.03)	$p > .05$
Edinburgh's Handedness Scores	79.67 (17.33)	86.14 (17.35)	$p > .05$
Ravens Score's	10.31 (1.41)	10.10 (2.05)	$p > .05$
Video Game Playing (Playing hrs/week)	1.89 (3.68)	0.73 (2.35)	$p > .05$
Average Parental Education (5 point rating scale)	2.8 (1.14)	3.68 (1.27)	$p > .05$
Computer Usage (hrs/day)	3.89 (2.10)	6.36 (2.81)	$p < .05$
	English	**English**	**Non-English**
Age of Acquisition (in years)	0.73 (0.78)	2.89 (2.20)	2.05 (2.15)
Language Usage (in %)	100	65.78 (14.27)	27.63 (14.27)
Proficiency Rating (10 point scale)			
Speaking	9.57 (0.6)	9.15 (1.05)	8.4 (1.11)
Understanding	9.68 (0.47)	9.23 (1.03)	8.6 (1.30)
Reading	9.57 (0.6)	9.34 (1.00)	7.0 (2.44)

4.2.2 Task Design

The target stimulus was a centrally presented word (colour word, non-colour word) or a series of Xs that were either red or green in colour. In the reach-to-touch paradigm, participants classified the target stimulus by reaching out and touching the appropriate response panel (see Figure 4.1). Based on the combination of the semantic meaning of the word and its ink colour, the task consisted of four different trial types (compatible, incompatible, neutral-colour and neutral-word).

First, the compatible trials, in which the semantic meaning of the word was same as its ink colour (e.g., RED, GREEN). Second, the incompatible trials, in which the semantic meaning of the word was different with its ink colour (e.g., RED, GREEN). The responses on compatible and incompatible trials were used to note the Stroop effect. Third, the neutral-colour trials, in which the target stimulus was centrally presented series of X's that was either red or green in colour (e.g., XXXX, XXXX). The responses on neutral-colour trials relative to compatible trials were used to note the facilitation effect and; the responses over neutral-colour trials relative to incompatible trials were used to note the interference effect. Fourth, the neutral-word trials, in which the target stimulus was a centrally presented word that was either red or green in colour without any semantic meaning with its ink colour (e.g., ROD, BED, RENT, GREED, QUEEN, GRAIN). The target stimuli were presented on a black background in capitals, using the 'Arial' font, with font size 25.

Based on the target stimuli, the reaching responses were different across trial types. On a colour word (compatible, incompatible) and neutral-colour trials, participants were instructed to respond by reaching out and touching the left (or right) response panel appropriate to the ink colour. For example, for red ink colour word, to reach out and touch the left response panel and; for green ink colour word to reach out and touch the right response panel (see Figure 4.1). The colour-response panel was counterbalanced across participants within each group. On neutral-word trials, participants were instructed to reach out and touch a centrally placed response panel on the table, which was fixed between the left and right response panel (see Figure 4.1). The experiment began with a block of practice trials (n = 60) and followed by four blocks of experimental trials (n = 432). The experiment was presented in a mixed factorial design.

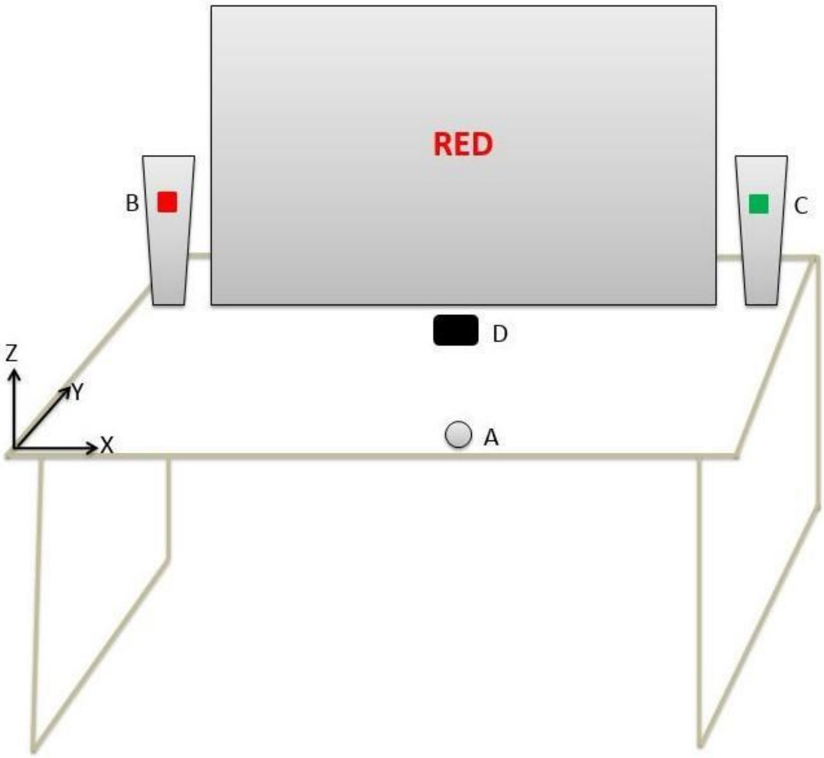


Figure 4.1. Target stimulus presentation and response panel setup. Participants place their right index finger at the start position (A) to initiate trial sequence and then respond by reaching out and touching the appropriate response panel depending on the trial type (B: Left response panel; C: Right response panel; D: Central response panel). For example, on compatible trial in the figure, in which the colour word '**RED**' presented in red ink, requires a reaching response towards the left response panel.

4.2.3 Procedure

Participants were seated at a viewing distance of about 90 cm from the 23″ LED monitor (1920 x 1080 x 32 pixels at 120 Hz) in a dimly lit room. Presentation® software (version 16.1, Neurobehavioral Systems) was used to deliver the stimulus. The reaching movements were recorded continuously from a sensor taped to the right index finger using a motion capture system (Polhemus Liberty, at 240 Hz) in three-dimensional space: x, y, and z. Participants commenced each trial sequence by moving their right index finger to the start position located on the middle edge of the desk (see Figure 4.1). On each trial, a central fixation cross was presented on the screen for 500 ms, followed by three beeps presented through headphones

(Sennheiser, HD 280 Pro). The target stimulus was presented for 300 ms at the centre of the computer screen (see Figure 4.1). The final beep, in the sequence of three beeps, served as an imperative go signal for which the participants were instructed to initiate their reaching movement (cf. Finkbeiner et al., 2014). The reach-to-touch version of the Stroop task was combined with the response-signal procedure (Finkbeiner et al., 2014). In this design, participants were required to initiate their reaching responses within a 300 ms response time window, which opened 100 ms before the imperative go signal and closed 200 ms after the go signal. The trial was stopped with a buzz and visual feedback was presented on the screen (e.g., “Too Early!” or “Too Late!”) if participants failed to initiate their response movement within the response time window of 300 ms. Further, the imperative signal and target stimulus was presented at three different SOAs: at 0 ms (the target and the response-signal presented simultaneously), 70 ms (the target was presented 70 ms before the response-signal), and 150 ms (the target was presented 150 ms before the response-signal). The SOA modulations allowed us to elicit reaching movements across a wide range of stimulus viewing times (~ 350 ms). The time in milliseconds (ms) between stimulus onset and the response initiation is referred to as the movement initiation time (MIT). This fine-grained analysis allowed us to determine how much the participant knew about the target stimulus information at the time of movement initiation.

4.2.4 Data Analysis

The response movement speed was calculated along x- and y-axis, based on the location of the corresponding response panel (see Figure 4.1). On colour word (compatible and incompatible) and neutral-colour trials, the appropriate response panels were on either side of the screen. Thus, on these trials, the responses were measured in the left-right direction, i.e., along the x-axis, which is referred to as *x-velocity*. On neutral-word trials, the appropriate response panel was at the centre of the screen. Hence, on these trials, the responses were measured in the forward direction, i.e., along the y-axis, which is referred to as *y-velocity*.

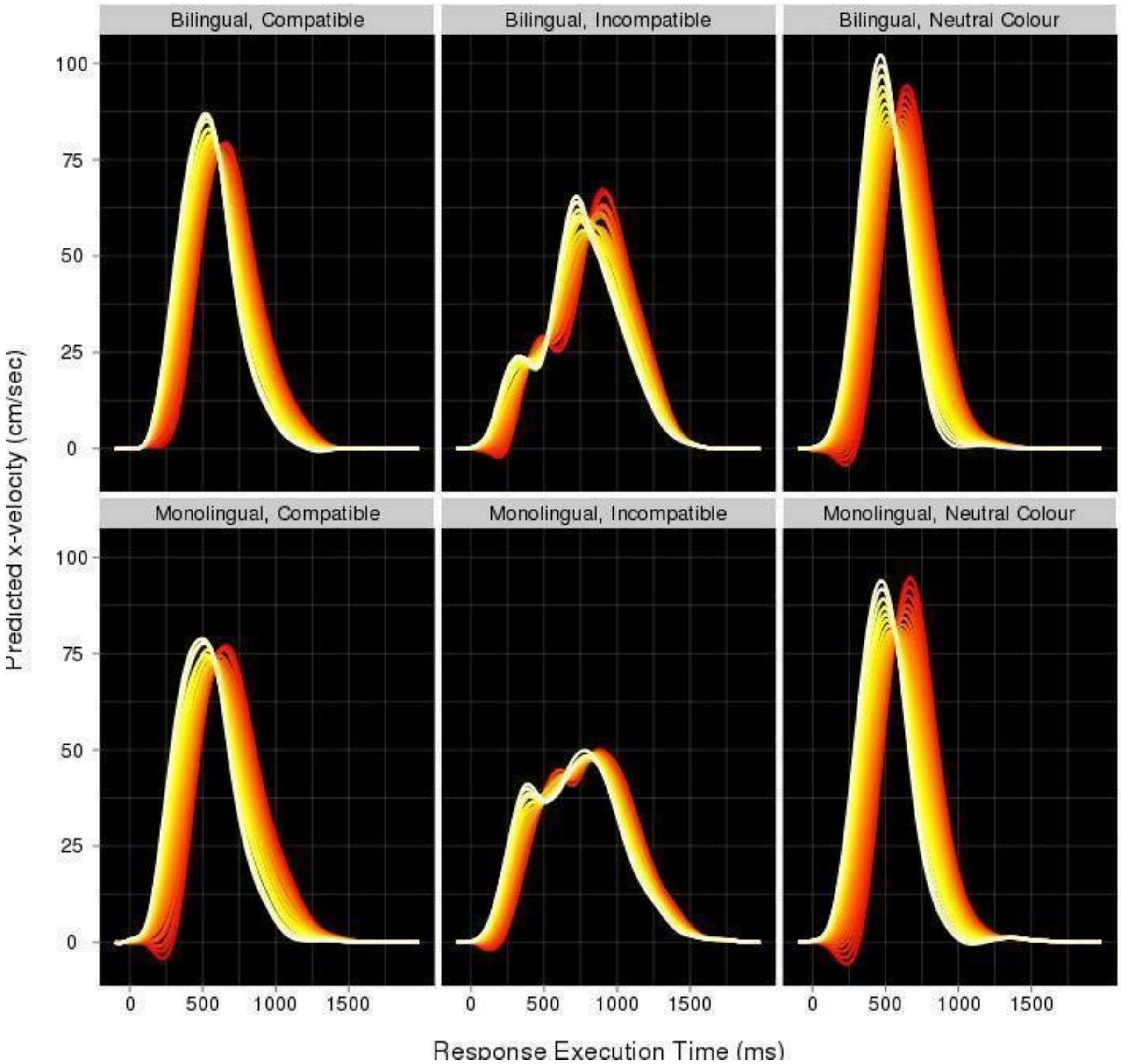


Figure 4.2. Predicted x-velocity profiles as a function of response execution time (ms) for bilinguals and monolinguals across 20 MIT quantiles on the compatible, incompatible and neutral-colour trials. The zero on the y-axis represents x-velocity of zero. The positive x-values above zero indicate reaching movements in the correct direction and the negative x-values below zero indicate reaching movements in the incorrect direction. The reddish lines correspond to reaching responses initiated in the earlier MITs and the yellowish lines correspond to reaching responses in the later MIT's. The reaching responses suggests that longer the stimulus viewing time faster the positive peak velocity as in later MITs.

Practice trials and the erroneous trials (5.5 % for bilinguals; 8.14 % for monolinguals) were eliminated from further data analysis. We followed Finkbeiner and colleagues (see Finkbeiner et al., 2014; Finkbeiner & Heathcote, 2016; Quek & Finkbeiner, 2013; 2014) protocol to analyse the time course of reaching responses over stimulus viewing time across trials. The data analyses steps to extract predicted x-velocity profiles were similar to that reported in Chapter 2 (Experiment 1b; Method section). Figure 4.2 illustrates the mean predicted x-velocity profiles across 20 MIT quantiles on compatible, incompatible and neutral-colour trials for bilingual and monolingual participants. The longer the participants wait to initiate their movement, the faster the peak x-velocity of reaching responses in the correct direction. Figure 4.3 illustrates the *predicted y-velocity* profiles (along the y-axis) on neutral-word trials across groups.

4.2.5 Statistical Analyses

The data was analysed with a linear mixed-effect model (LMM) (Bates, 2005; Baayen, Davidson, & Bates, 2008) implemented in R statistical analysis software with the lmer4 package (Bates, Maechler, & Bolker, 2012). The LMM analysis allowed us to consider both random and fixed factors simultaneously. In each case, test values (AIC, BIC, log likelihood) were used to indicate the preferred model. These values provided a measure of goodness-of-fit, penalising for the number of free parameters to prevent over-fitting. Our incremental model included subject as a random factor, together with fixed factors of trial type (compatible, incompatible, neutral-colour and neutral-word), MIT quantile (1 to 20), group (monolingual, bilingual). The fixed factors were added selectively across dependent measures (accuracy rate, movement initiation time, initial x-velocity and initial y-velocity). As is typical in LMM analyses, the coefficient magnitude of at least twice the standard error was taken as the criteria for significance. We further report coefficients (b), standard errors (SE), and t-values for the resulting model selected.

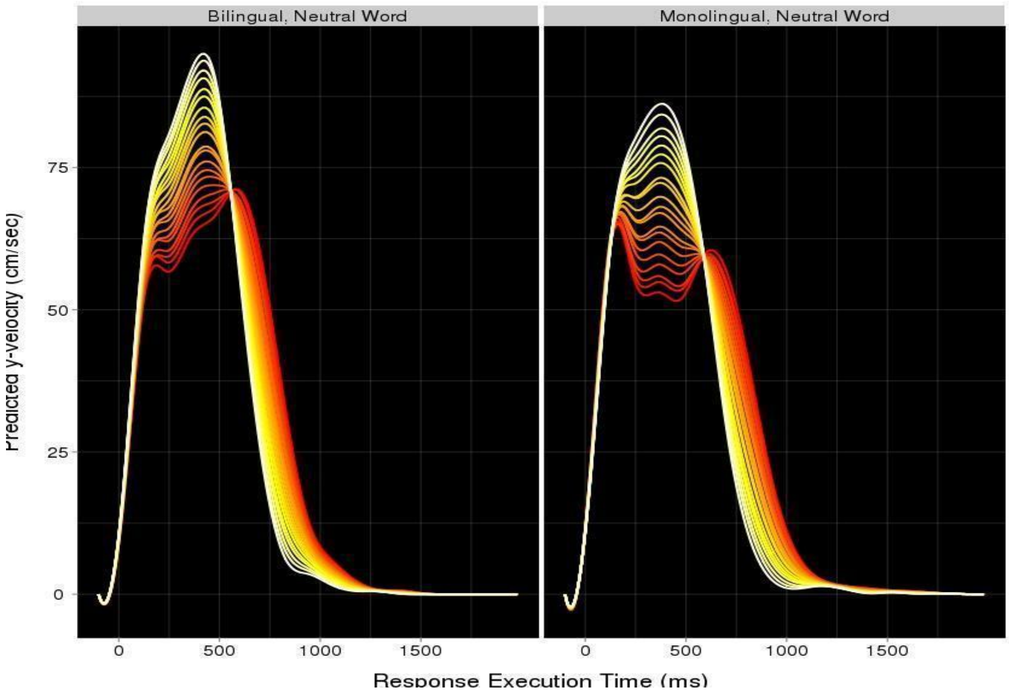


Figure 4.3. Predicted y-velocity as a function of response execution time (ms) for neutral-word trials across groups.

4.3 Results

4.3.1 Accuracy Rate (%)

In line with the previous studies, the accuracy rates were very high (overall ~ 97%) in the reach-to-touch paradigm (Finkbeiner et al., 2014; Quek & Finkbeiner, 2013; 2014). This is due to a long duration of the reaching responses, which provided the participants an opportunity to recognize errors and correct motor program mid-flight (Finkbeiner et al., 2014). We ran LMM analysis with subject as a random factor. Trial type (compatible, incompatible, neutral-colour and neutral-word) and group (bilingual, monolingual) were added as fixed factors. The main effect of trial type was significant, χ^2 (3) = 50.26, $p < .001$, indicating that the responses were more accurate on compatible trials (*M* = 99.26 %, *SD* = 1.1) than incompatible trials (*M* = 95.87 %, *SD* = 4), *b* = - 3.39, *SE* = 0.67, *t* = - 5.06 and neutral-word trials (*M* = 95.7 %, *SD* = 3.7), *b* = - 3.55, *SE* = 0.67, *t* = - 5.3. There was no reliable difference between compatible and neutral-colour trials (*M* = 99.73 %, *SD* = 0.3), *b* = 0.47, *SE* = 0.67, *t* = 0.7. Further, including group as a factor did not significantly improve the fit of the model, χ^2 (1) = 0.49, *p* = .48 nor did the interactions between trial type and group, χ^2 (3) = 1.5, *p* = .68, suggesting similar accuracy rates across groups in the Stroop task.

4.3.2 Movement Initiation Time

Movement initiation time (ms) is the time from the target onset until the participant released the start button and began their reaching movement. Figure 4.4 illustrates the distribution of movement initiation times relative to the target onset across trial types. We further ran LMM analysis with subject as a random factor and trial type (compatible, incompatible, neutral-colour and neutral-word) and group (bilingual, monolingual) as fixed factors. The results revealed that the fixed effect of trial type, χ^2 (3) = 5.62, *p* = .13 and group, χ^2 (1) = 2.6, *p* = .10 did not contribute to the fit of the model nor the interaction between trial type and group, χ^2 (3) = 1.6, *p* = .65. The data indicates that the responses were initiated at similar response time window relative to the imperative go signal (3rd beep) across trial types and groups, which is critical for interpreting the reaching responses to note experimental effects. This suggests that the bilinguals and monolinguals response distributions were similar across stimulus viewing time.

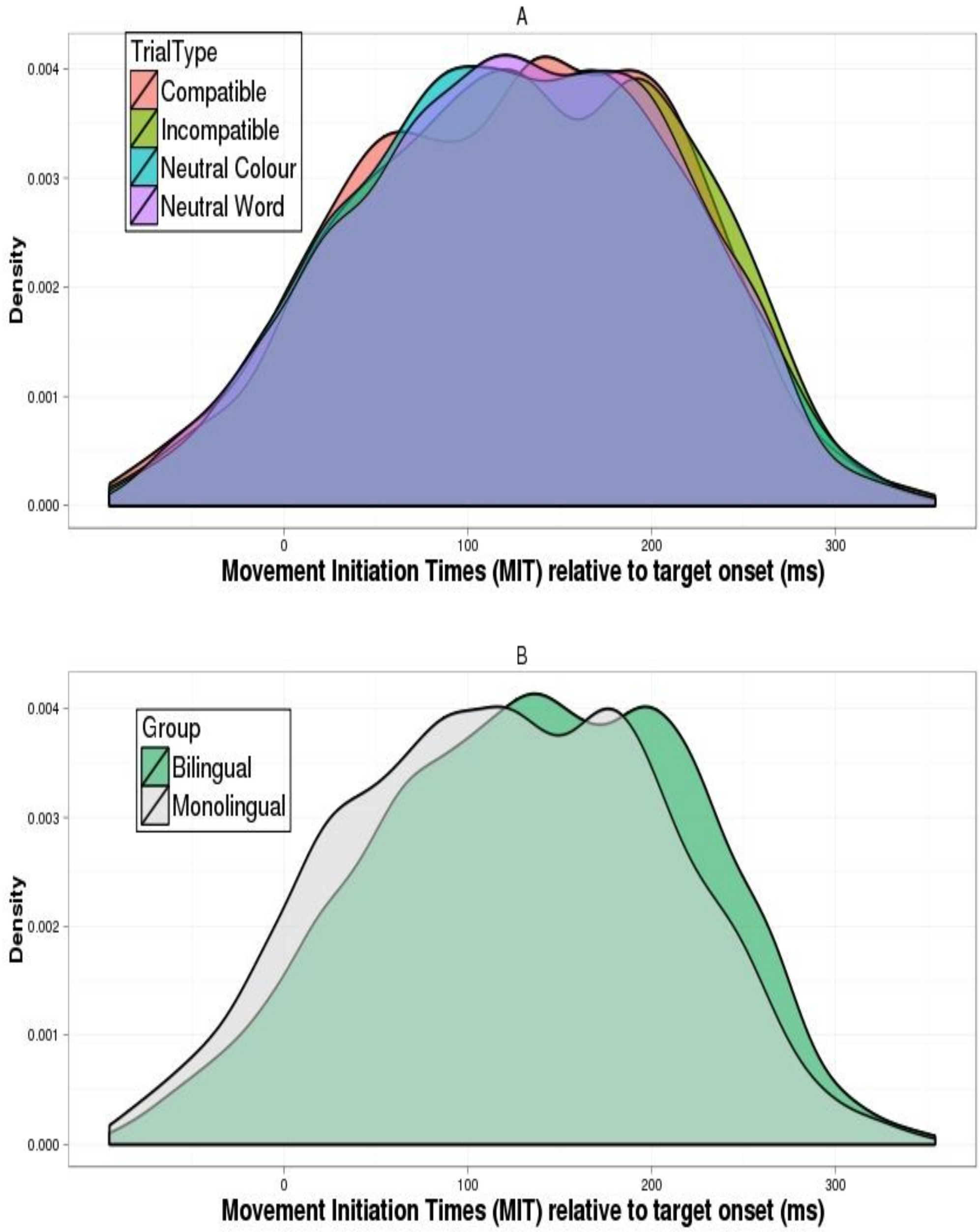


Figure 4.4. Distribution of movement initiation times relative to the target onset across trial types (A) and groups (B).

4.3.3 Initial x-velocity Profile

Figure 4.5 illustrates the initial x-velocity profiles across trial types between bilinguals and monolinguals at four different time points of reaching trajectories. In the preliminary analysis, experimental effects did not emerge until the first 450 ms of reaching trajectories. So, only the first 450 ms of the x-velocity profiles were analysed to note the time course of experimental effects across stimulus viewing time (see Figure 4.5D). We refer to this dependent measure as *initial x-velocity*. The initial x-velocity measure is critical to test the hypothesis predicted in the introduction.

For LMM analyses on initial x-velocity, we included subject as a random factor. Trial type (compatible, incompatible, and neutral-colour) and group (bilinguals, monolinguals) were added as fixed factors. The coefficients for the trial type and group factor used the compatible trials and the bilingual group as a baseline so that the negative coefficient values indicate smaller velocities relative to the compatible trials and bilingual group. The results revealed a main effect of MIT quantiles, χ^2 (3) = 7416.87, p < .001, indicating increasing x-velocity in the correct direction relative to the stimulus viewing time, b = 351.99, SE = 11.33, t = 31.04. The main effect of trial type was significant, χ^2 (2) = 705.17, p < .001, suggesting higher x-velocity on compatible trials relative to incompatible trials, b = - 3.78, SE = 0.18, t = - 20.6. Additionally, the x-velocity was lower on compatible trials than the neutral-colour trials, b = 0.55, SE = 0.15, t = 3.69. No main effect of group was significant, χ^2 (1) = 0.78, p = .37. Further, there was also a significant two-way interaction between MIT quantiles and group, χ^2 (3) = 335.80, p < .001, trial type and group, χ^2 (2) = 91.76, p < .001 and; trial type and MIT quantiles, χ^2 (6) = 1080.01, p < .001. These two-way interactions were evident in a three-way interaction between MIT quantiles, trial type, and group, χ^2 (6) = 51.37, p < .001, indicating increasing x-velocity across MIT quantiles for compatible trials relative to incompatible trials (b = - 162.92, SE = 24, t = - 6.78) and neutral-colour trials (b = -110.61, SE = 19.58, t = - 5.64) in bilinguals relative to monolinguals.

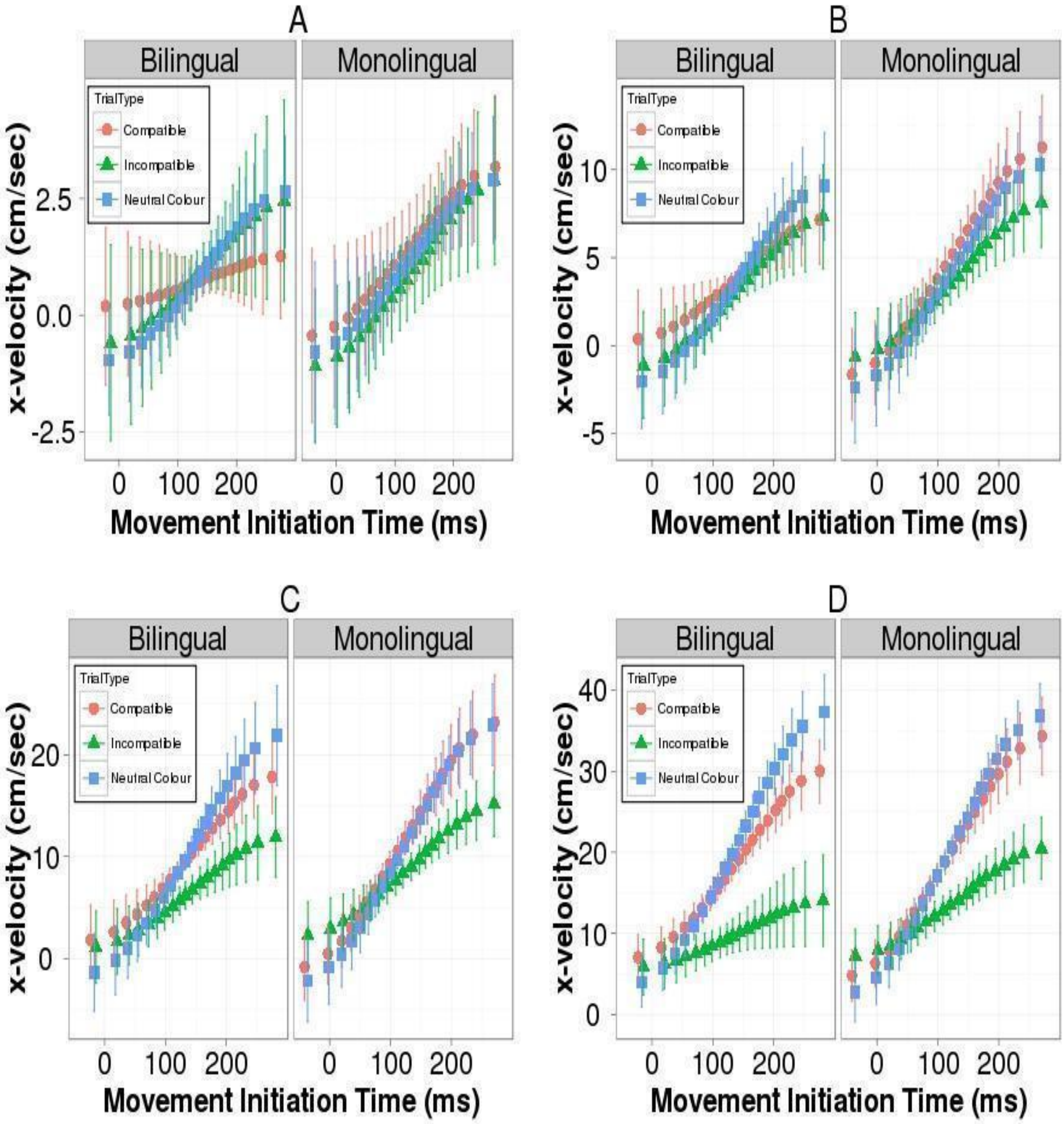


Figure 4.5. Initial x-velocity as a function of movement initiation time obtained from different reaching trajectory time points across trial type by groups. The x-axis represents the movement initiation time (ms) relative to the target onset, which is a proxy for stimulus viewing time. The zero on y-axis indicates the net velocity of zero. The x-velocity values above zero (on the y-axis) indicate reaching movements in the correct direction and x-values below zero (on the y-axis) indicate reaching movements in the incorrect direction. (A) first 150 ms of reaching responses, (B) first 250 ms of reaching responses, (C) first 350 ms of reaching responses, and; (D) first 450 ms of reaching responses. The reaching responses were almost overlapping across trial types in the initial three figures (A, B, C). Whereas in the figure D, the reaching responses emerged differently across trials types over stimulus viewing time. The steady increase in the initial x-velocity across trial types clearly indicates that as the stimulus viewing time increased, the reaching responses were in the correct direction towards correct response panel. Error bars calculated using 95 % confidence intervals.

To further examine the nature of the three-way interaction, within each group we ran LMM as described earlier, with subject as a random factor and trial type as a fixed factor. The final LMM model results revealed a significant increase in initial x-velocity with MIT quantiles for the bilinguals, *b* = 424.09, *SE* = 8.94, *t* = 47.41 and for the monolinguals, *b* = 561.97, *SE* = 8.71, *t* = 64.45. Also, the initial x-velocity was significantly higher on compatible colour word trials than the incompatible colour word trials for the bilinguals, *b* = - 7.88, *SE* = 0.18, *t* = - 42.10 and for the monolinguals, *b* = - 5.49, *SE* = 0.18, *t* = - 29.89. In contrast, the initial x-velocity was significantly lower on compatible colour word trials relative to neutral-colour trials only for the bilinguals, *b* = 1.57, *SE* = 0.15, *t* = 10.24 and not for the monolinguals, *b* = 0.04, *SE* = 0.15, *t* = 0.28. Further, an interaction between trial type and MIT quantiles was significant, suggesting that the initial x-velocity significantly changed across MIT quantiles for incompatible trials (bilinguals: *b* = - 232.86, *SE* = 13.31, *t* = - 17.48; monolinguals: *b* = - 297.81, *SE* = 13.01, *t* = - 22.88) and neutral trials (bilinguals: *b* = 188.33, *SE* = 10.91, *t* = 17.26; monolinguals: *b* = 67.64, *SE* = 10.63, *t* = 6.36) relative to compatible trials reaching responses.

Figure 4.5D illustrates the two-way interaction between MIT quantiles and trial type within each group. To further test this interaction, we ran a series of one-sample t-tests corrected for multiple comparisons with FDR over specific trial type pairs within each language group to note the time course of experimental effects, i.e., the Stroop effect, facilitation effect and interference effect. In the present study, the onset of the Stroop effect was referred to the target viewing time point when the reaching response difference between the compatible and incompatible colour word trials emerged for the first time. The Stroop effect emerged from the 10^{th} MIT quantiles ($p < .05$) at 132 ms of target viewing time for the bilinguals, whereas for the monolinguals the difference was not significant ($p > .05$) for the time window investigated in the present study. Further, the onset of the interference effect was related to the target viewing time point when the reaching response difference between the incompatible colour word and neutral-colour trials was significant. The interference effect emerged from the 8th MIT quantile (p < .05) at 109 ms of target viewing time for the bilinguals, and from 16th MIT quantile (p < .05) at 188 ms for the monolinguals. Finally, the onset of the facilitation effect was referred to the target viewing time point when the reaching response difference between the compatible colour word and neutral-colour trials was observed. The results revealed that there was no evidence for the facilitation effect, across groups for the time window investigated in the present study (p > .05).

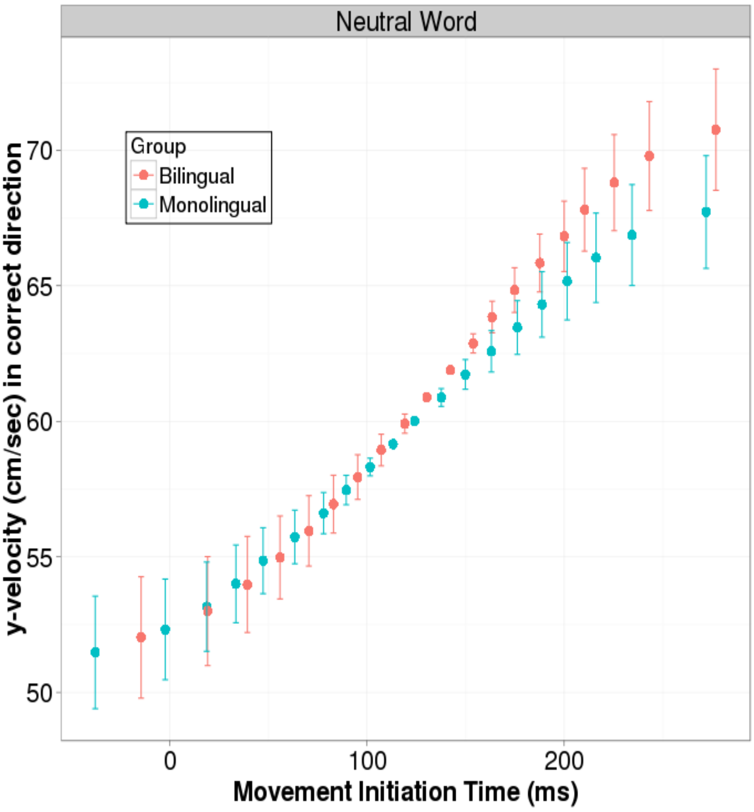


Figure 4.6. Initial y-velocity as a function of movement initiation time (ms) for bilinguals and monolinguals on neutral-word trials. The x-axis represents the movement initiation time (ms) relative to the target onset. The y-axis represents the initial y-velocity. Higher mean initial y-velocity values at the earliest stimulus viewing time clearly indicates that the reaching responses were in the correct direction towards the response panel within the first 450ms of reaching responses. Error bars calculated using 95 % confidence intervals.

4.3.4 Initial y-velocity Profile

The *initial y-velocity* refers to the first 450 ms of the reaching responses on neutral-word trials along the y-axis (see Figure 4.6). We ran a LMM analysis, similar to that of the initial x-velocity profile analysis, with subject as a random effect and; MIT quantiles (1 to 20) and group (bilingual, monolingual) as fixed factors. We reported coefficients (b), standard errors (SE), and t-values for the resulting model selected. The coefficients for the group factor used the bilingual group as a baseline so that negative coefficient values indicate smaller velocities relative to the bilingual group. The results revealed a significant effect of MIT quantiles, χ^2 (3) = 8336.34, p < .001, indicating increasing y-velocity with increasing stimulus viewing time, b = 376.38, SE = 3.34, t = 112.35. No main effect of group was significant, χ^2 (1) = 0.78, p = .37. The two-way interaction between group and MIT quantiles was significant, χ^2 (3) = 101.44, p < .001, suggesting increasing y-velocity over stimulus viewing time for bilinguals relative to the monolingual group, b = - 48.14, SE = 4.75, t = - 10.12. However, on further analysis with t-test corrected for multiple comparisons with FDR, there were no differences between groups across individual MIT quantiles (p > .05), suggesting similar information processing for neutral-word trials over stimulus viewing time.

4.4 Discussion

The goal of the current study was to investigate conflict resolution across bilinguals and monolinguals in the forced-reading Stroop task. To achieve this, we measured the time course of conflict effects (interference effect, Stroop effect) across groups using a reach-to-touch paradigm. The reaching paradigm was coupled with the response-signal procedure (e.g., Finkbeiner et al., 2014) in which the responses were time locked with an imperative go signal. With this design, the reaching responses were compared across similar response quantiles across language groups over a wide range of stimulus viewing time points. The reaching responses revealed an early emergence of the interference and Stroop effect in bilinguals relative to monolinguals.

The initial x-velocities were significantly greater than the zero horizontal line (see Figure 4.5D) in both language groups. The finding indicates that the responses were in the correct direction towards the appropriate response panel within the first 450 ms of the reaching responses. However, the information processing for an overt response was different across trial types. On compatible trials (e.g., RED, GREEN), the initial x-velocities were higher in the correct direction relative to the incompatible trials (e.g., RED, GREEN). This difference corresponds to the faster accumulation of evidence for the task-relevant colour dimension on compatible trials (Incera & McLennan, 2016). The reaching responses are consistent with button press measures (accuracy and reaction time) in the Stroop task, in which responses are faster and more accurate on compatible trials than incompatible trials (MacLeod, 1991; McLeod & MacDonald, 2000). Thus, these findings validate the reach-to-touch version of the forced-reading Stroop task.

The fine-grained analysis of initial x-velocity over stimulus processing time revealed a different temporal window of conflict effect emergence across language groups. The interference effect, which is the difference in initial x-velocities between the neutral-colour and incompatible trials, emerged earlier for the bilinguals than for the monolinguals (at ~ 109 ms for bilinguals; ~ 188 ms for monolinguals). The Stroop effect, which is the difference between the compatible and incompatible trials, emerged at ~ 132 ms of stimulus viewing time for the bilinguals. Whereas, for the monolinguals, the corrected t-tests never reached significance at any of the MIT quantiles. As predicted, if bilinguals selected in the present study were better at resolving conflict in the Stroop task, then they should have shown a later onset of interference and Stroop effect, indicating enhanced cognitive control abilities. The data demonstrated early onset of the conflict effect (interference and Stroop effect) in bilinguals, suggesting a failure to resolve conflict in the forced-reading Stroop task.

In the forced-reading Stroop task, the probability of trials with 'missing word reading processes' is reduced to zero, thus increasing the complexity of conflict interference (Eidels et al., 2014). The automaticity of word reading is at maximum for both the groups. Furthermore, it is suggested that in the forced-reading Stroop task word reading is more intentional and involves a deeper depth of processing, than the standard Stroop task (Eidels, Ryan, Williams, & Algom, 2014). The high probability of automaticity of word reading and the deeper depth of word processing, might have had a greater impact on the bilinguals, than the monolinguals. If bilinguals are good at conflict resolution, then we would expect them to show a later onset of the conflict effect. The results, however, suggest that our bilinguals were more susceptible to interference in the forced-reading Stroop task than the monolinguals.

There is a lot of variability across studies investigating a bilingual advantage in the Stroop task because of the involvement of linguistic and other factors, which make it even more complex to compare with other studies. Some of the factors are: different linguistic profiles between bilinguals and monolinguals for stimuli language, confounding variables across groups, combined usage of two different stimuli languages, and variability of automaticity of word reading processes across trials. However, we address major issues which are relevant to the present study. The current findings are in contrast to studies reporting a smaller magnitude of the conflict effect in late bilinguals relative to monolinguals (e.g., Bialystok et al., 2008 for English-Other; Coderre & van Heuven, 2014 for Chinese-English bilinguals; Coderre, van Heuven, & Conklin, 2013 for Chinese-English bilinguals; Heidlmayr, Moutier, Hemforth, Courtin, Tanzmeister, & Isel, 2014 for Chinese-English bilinguals). We suggest that these differences may be due to the language profiles of bilingual participants, rather than a pure cognitive control difference between groups, including proficiency in stimuli language, age of second language acquisition, and the frequency of language usage.

Careful consideration of previous studies reporting similar behavioural performance between language groups indicates that when language proficiency is similar between bilinguals and monolinguals in the stimuli language, there is no evidence for a bilingual advantage in the conflict effect (e.g., Coderre, van Heuven, & Conklin, 2013 for English-Chinese bilinguals; Duñabeitia et al., 2014; Kousaie & Phillips, 2012b for English-French bilinguals; Rosselli, Ardila, Lalwani, & Vélez-Uribe, 2016; von Bastian, Souza, & Gade, 2016). In contrast to the above-mentioned studies, we reported an early onset of the conflict effect in bilinguals relative to monolinguals. The inconsistency between studies may be due to the differences in the task design used in the present study. The forced-reading Stroop task requires word reading on all trials, this in turn, might be more linguistically challenging for the bilinguals to resolve the conflict and respond accurately to the ink colour.

Furthermore, in the current study, we matched bilingual and monolingual participants across nonverbal intelligence, handedness, video game playing and socioeconomic status. These variables have shown to play a major role in modulating the group differences in cognitive control abilities (e.g., Hilchey & Klien, 2011; Rosselli, Ardila, Lalwani, & Vélez-Uribe, 2016; Valian, 2015;). However, previous studies have failed to match bilingual and monolingual participants for the above confounding variables (e.g., Bialystok, Craik, & Luk, 2008; Coderre & van Heuven, 2014; Incera & McLennan, 2016; Yow & Li, 2015). This could also be a possible factor explaining the contrasting findings.

There is no evidence for the emergence of a facilitation effect within language groups, which is the reaching response difference between the compatible trials and neutral-colour trials over stimulus viewing time. The absence of a facilitation effect suggests that the information processing is similar between compatible and neutral-colour trials across stimulus viewing time points. We suppose that the facilitation from the task-irrelevant and task-relevant information on compatible trials (e.g., 'RED' presented in red ink; MacLeod & MacDonald, 2000; Roelofs, 2010) and the minimal interference from the word reading processes on neutral-colour trials (e.g., a series of Xs presented in red ink) would have contributed to similar information processing. Thus, the difference between the compatible and neutral-colour trials possibly faded out due to the relative speed of the task-relevant stimulus information across trials. Hence, we suggest that the facilitation effect was not sensitive enough to capture any differences between bilinguals and monolinguals selected in the present study for the forced-reading Stroop task.

Additionally, the reaching response revealed no group differences in the neutral-word trials across stimulus viewing time (e.g., ROD, QUEEN). Nevertheless, it is tempting to attribute this to similar word reading speeds in bilinguals and monolinguals. However, we avoid claiming this as, reaching responses were always initiated towards the central panel, irrespective of trial type. Depending on the trial type, reaching response patterns vary over stimulus viewing time as evidence accumulates for stimulus information. In our design, for neutral-word trials, the target response panel was positioned centrally, so the tendency to reach towards the central response panel was always high and the same across groups. Therefore our interpretation of group performance on these trials may not be reasonable. In spite of this, it serves the purpose of monitoring word reading in the forced-reading Stroop task.

The current study emphasizes firstly, the need to consider the linguistic profiles in the stimuli language when investigating the conflict effect in language based cognitive control tasks in bilinguals and monolinguals. Secondly, the relevance of using reaching responses coupled with the response-signal procedure to uncover the time course of conflict resolution across language groups. Future studies should take advantage of investigating conflict resolution between bilinguals (early, late bilinguals) and monolinguals in nonlinguistic Stroop task. On a nonlinguistic numerical version of the Stroop task, Hernández et al. (2010), reported both a reaction time and a conflict effect advantage in early bilingual young adults relative to their monolingual counterparts. We suppose that the nonlinguistic task might reduce the chances of interference from linguistic information and provide an opportunity to study cognitive control abilities across language groups.

To sum up, the present study investigated how the bilinguals and the monolinguals recruit cognitive control processes to resolve conflict over stimulus processing time in the forced-reading Stroop task. The reaching data provide a deeper insight into the time course of experimental effects across bilinguals and monolinguals. The results revealed an early onset of the conflict effect in bilinguals relative to monolinguals. To conclude, the results demonstrated that the bilinguals, selected for the present study, had poorer conflict control on a linguistically based cognitive control task.

References

Algom, D., Dekel, A., & Pansky, A. (1996). The perception of number from the separability of the stimulus: The Stroop effect revisited. *Memory & Cognition*, *24*(5). doi: 557-572.0.3758/BF03201083

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modelling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390-412. doi: 10.1016/j.jml.2007.12.005

Badzakova-Trajkov, G. (2008). *A behavioural and functional imaging investigation of Stroop task performance in late proficient bilinguals* (Unpublished doctoral thesis). The University of Auckland, Auckland, New Zealand. doi: 2292/3365

Bates, D. (2005). Fitting linear mixed models in R. R news, 5(1), 27-30.

Bates, D., Maechler, M., & Bolker, B. (2012). lme4: Linear mixed-effects models using S4 classes (2011). R package version 0.999375-42.

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, memory, and cognition*, *34*(4), 859-873. doi: 10.1037/0278-7393.34.4.859

Coderre, E. L., & van Heuven, W. J. (2014). Electrophysiological explorations of the bilingual advantage: evidence from a Stroop task. *PLos one*, *9*(7). doi: 10.1371/journal.pone.0103424

Coderre, E. L., Van Heuven, W. J., & Conklin, K. (2013). The timing and magnitude of Stroop interference and facilitation in monolinguals and bilinguals. *Bilingualism: Language and Cognition, 16(02),* 420-441. doi: 10.1017/S1366728912000405

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*(3), 332-361. doi: 10.1037/0033-295X.97.3.332

Dijkstra, T., & Van Heuven, W. J. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language and cognition*, *5*(03), 175-197. doi: 10.1017/S1366728902003012

Dong, Y., & Li, P. (2015). The cognitive science of bilingualism. *Language and Linguistics Compass*, *9*(1), 1-13. doi:10.1111/lnc3.12099

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited. *Experimental Psychology, 61*(3), 234-251. doi: 10.1027/1618-3169/a000243

Dyer, F. N. (1971). Color-naming interference in monolinguals and bilinguals. *Journal of Verbal Learning and Verbal Behavior*, *10*(3), 297-302. doi: 10.1016/S0022-5371(71)80057-9

Eidels, A., Ryan, K., Williams, P., & Algom, D. (2014). Depth of Processing in the Stroop Task. *Experimental Psychology, 61(5), 385-393*. doi: 10.1027/1618-3169/a000259

Finkbeiner, M. & Heathcote, A. (2016). Distinguishing the time- and magnitude-difference accounts of the Simon effect. *Attention, Perception and Psychophysics, 78,* 848-867. doi: 10.3758/s13414-015-1044-9

Finkbeiner, M., Coltheart, M., & Coltheart, V. (2014). Pointing the way to new constraints on the dynamical claims of computational models. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 172. doi: 10.1037/a0033169

Finkbeiner, M., Song, J. H., Nakayama, K., & Caramazza, A. (2008). Engaging the motor system with masked orthographic primes: A kinematic analysis. *Visual Cognition*, *16*(1), 11-22. doi: 10.1080/13506280701203838

Gollan, T. H., Montoya, R. I., Fennema-Notestine, C., & Morris, S. K. (2005). Bilingualism affects picture naming but not picture classification. *Memory & Cognition*, *33*(7), 1220-1234. doi:10.3758/BF03193224

Heidlmayr, K., Hemforth, B., Moutier, S., & Isel, F. (2015). Neurodynamics of executive control processes in bilinguals: evidence from ERP and source reconstruction analyses. *Frontiers in Psychology*, *6*, 821. doi: 10.3389/fpsyg.2015.00821

Heidlmayr, K., Moutier, S., Hemforth, B., Courtin, C., Tanzmeister, R., & Isel, F. (2014). Successive bilingualism and executive functions: The effect of second language use on inhibitory control in a behavioural Stroop Colour Word task. *Bilingualism: Language and Cognition*, *17*(03), 630-645. doi: 10.1017/S1366728913000539

Hernández, M., Costa, A., Fuentes, L. J., Vivas, A. B., & Sebastián-Gallés, N. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Bilingualism: Language and Cognition*, *13*(03), 315-325. doi: 10.1017/S1366728909990010

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625-658. doi:10.3758/s13423-011-0116-7

Incera, S., & McLennan, C. T. (2016) Mouse tracking reveals that bilinguals behave like experts. *Bilingualism: Language and Cognition*, *19*(3). doi: 10.1017/S1366728915000218

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review*, *9*(4), 637-671. doi: 10.3758/BF03196323

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, *132*(1), 47-70. doi: 10.1037/0096-3445.132.1.47

Kousaie, S., & Phillips, N. A. (2012a). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research, 1446*, 71-90. doi:10.1016/j.brainres.2012.01.052

Kousaie, S., & Phillips, N. A. (2012b). Ageing and bilingualism: Absence of a “bilingual advantage” in Stroop interference in a nonimmigrant sample. *The Quarterly Journal of Experimental Psychology, 65*(2), 356-369. doi:10.1080/17470218.2011.604788

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology, 25*(5), 497-514. doi:10.1080/20445911.2013.799170

Kroll, J. F., Sumutka, B. M., & Schwartz, A. I. (2005). A cognitive view of the bilingual lexicon: Reading and speaking words in two languages. *International Journal of Bilingualism, 9*(1), 27-48. doi: 10.1177/13670069050090010301

Lee, T. M., & Chan, C. C. (2000). Stroop interference in Chinese and English. *Journal of Clinical and Experimental Neuropsychology, 22*(4), 465-471. doi:10.1076/1380-3395(200008)22:4;1-0;FT465

Liu, C., Yao, R., Wang, Z., & Zhou, R. (2014). N450 as a candidate neural marker for interference control deficits in children with learning disabilities. *International Journal of Psychophysiology, 93*(1), 70-77. doi:10.1016/j.ijpsycho.2014.05.007

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: an integrative review. *Psychological Bulletin, 109*(2), 163-203. doi: 10.1037/0033-2909.109.2.163

MacLeod, C. M., & MacDonald, P. A. (2000). Interdimensional interference in the Stroop effect: Uncovering the cognitive and neural anatomy of attention. *Trends in Cognitive Sciences, 4*(10), 383-391. doi:10.1016/S1364-6613(00)01530-8

Mägiste, E. (1984). Stroop tasks and dichotic translation: The development of interference patterns in bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10*(2), 304-315. doi: 10.1037/0278-7393.10.2.304

Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech, Language, and Hearing Research*, *50*(4), 940-967. doi:10.1044/1092-4388(2007/067)

Marian, V., Blumenfeld, H. K., Mizrahi, E., Kania, U., & Cordes, A. K. (2013). Multilingual Stroop performance: Effects of trilingualism and proficiency on inhibitory control. *International Journal of Multilingualism*, *10*(1), 82-104. doi:10.1080/14790718.2012.708037

Naylor, L. J., Stanley, E. M., & Wicha, N. Y. (2011). Cognitive and electrophysiological correlates of the bilingual Stroop effect. *Frontiers in Psychology*, *3*, 81. doi: 10.3389/fpsyg.2012.00081

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113. doi:10.1016/0028-3932(71)90067-4

Paap, K. R., Sawi, O. M., Dalibar, C., Darrow, J., & Johnson, H. A. (2015). Beyond panglossian optimism: larger N2 amplitudes probably signal a bilingual disadvantage in conflict monitoring. *AIMS Neuroscience*, *2*(1), 12-17. doi:10.3934/Neuroscience.2015.1.1

Quek, G. L., & Finkbeiner, M. (2013). Spatial and temporal attention modulate the early stages of face processing: behavioural evidence from a reaching paradigm. *PLos one*, *8*(2). doi: 10.1371/journal.pone.0057365

Quek, G. L., & Finkbeiner, M. (2014). Face-sex categorization is better above fixation than below: Evidence from the reach-to-touch paradigm. *Cognitive, Affective, & Behavioral Neuroscience*, *14*(4), 1407-1419. doi: 10.3758/s13415-014-0282-y

Raven, J., Raven, J. C. & Court, J. H (1998). Raven manual: Section 4, Advanced Progressive Matrices, 1998 edition. Oxford, UK: Oxford Psychologists Press Ltd.

Roelofs, A. (2010). Attention and facilitation: converging information versus inadvertent reading in Stroop task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(2), 411. doi: 10.1037/a0018523

Rosselli, M., Ardila, A., Lalwani, L. N., & Vélez-Uribe, I. (2016). The effect of language proficiency on executive functions in balanced and unbalanced Spanish–English bilinguals. *Bilingualism: Language and Cognition, 19*(3). doi: 10.1017/S1366728915000309

Rosselli, M., Ardila, A., Santisi, M. N., Arecco, M. R., Salvatierra, J., Conde, A., & Lenis, B. (2002). Stroop effect in Spanish-English bilinguals. *Journal of the International Neuropsychological Society*, *8*(6), 819-827. doi:10.1017/S1355617702860106

Sabourin, L., & Vinerte, S. (2015). The bilingual advantage in the Stroop task: simultaneous vs. early bilinguals. *Bilingualism: Language and Cognition*, *18*(2), 350-355. doi: 10.1017/S1366728914000704

Song, J. H., & Nakayama, K. (2008). Numeric comparison in a visually-guided manual reaching task. *Cognition*, *106*(2), 994-1003. doi:10.1016/j.cognition.2007.03.014

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(29), 10393-10398. doi: 10.1073/pnas.0503903102

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643-662. doi: 10.1037/0096-3445.121.1.15

Tillman, G., Eidels, A., & Finkbeiner, M. (2014). *A reach-to-touch investigation on the nature of reading in the Stroop task*. Talk presented at the annual meeting of the Australasian Society for Experimental Psychology, Brisbane, Australia.

Tse, C. S., & Altarriba, J. (2012). The effects of first-and second-language proficiency on conflict resolution and goal maintenance in bilinguals: Evidence from reaction time distributional analyses in a Stroop task. *Bilingualism: Language and Cognition*, *15*(03), 663-676. doi: 10.1017/S1366728912000077.

Valian, V. (2015). Bilingualism and cognition. *Bilingualism: Language and Cognition*, *18*(01), 3-24. doi: 10.1017/S1366728914000522

von Bastian, C. C., Souza, A. S., & Gade, M. (2016). No Evidence for Bilingual Cognitive Advantages: A Test of Four Hypotheses. *Journal of Experimental Psychology*, *145*(2), 246-258. doi: 10.1037/xge0000120

Yow, W. Q., & Li, X. (2015). Balanced bilingualism and early age of second language acquisition as the underlying mechanisms of a bilingual executive control advantage: why variations in bilingual experiences matter. *Frontiers in Psychology*, *6*, 164. doi:10.3389/fpsyg.2015.00164

Zied, K. M., Phillipe, A., Karine, P., Valerie, H. T., Ghislaine, A., & Arnaud, R. (2004). Bilingualism and adult differences in inhibitory mechanisms: Evidence from a bilingual Stroop task. *Brain and Cognition*, *54*(3), 254-256. doi:10.1016/j.bandc.2004.02.036

Chapter 5

General Discussion

General Discussion

5.1 Introduction

The impact of bilingualism on cognitive functions is one of the most debated topics in cognitive science (e.g., García-Pentón et al., 2016; Paap, Johnson, & Sawi, 2015; Valian, 2015). As reviewed in the Introduction (Chapter 1), the research suggests that the evidence for a bilingual cognitive advantage in reaction time and conflict effect is inconsistent and sometimes absent (for review see Hilchey & Klein, 2011; Zhou & Krott, 2015). Even if it is assumed that there are positive effects of bilingualism on cognitive control, the reaction time advantage appears to be more robust than the conflict effect advantage. Previous research has compared the magnitude of the conflict effect between groups at two different response times because of differences in the reaction time distributions. In the current thesis, I investigated the magnitude of the conflict effect in bilinguals and monolinguals across the same response time bins in the Simon task and in the Stroop task. To achieve this, I used the response-signal procedure combined with the reach-to-touch paradigm, in which the participants' reaching responses were time locked with an imperative go signal (Chapters 2 and 4). In addition I used the stimulation of the motor cortex procedure, in which the participants' motor evoked potential (MEP) responses were elicited at predefined response time points (Chapter 3).

In all the studies (Chapters 2, 3, and 4), the bilingual and monolingual participants were matched across age, years of education, socioeconomic status, handedness, nonverbal intelligence, and video game playing. These variables have been reported to affect cognitive control performance (e.g., Dong & Li, 2015; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Paap, Sawi, Dalibar, Darrow, & Johnson, 2015; Valian, 2015). The participants in the bilingual group were: exposed to both languages early in childhood (before the age of 6 years), highly proficient in both languages (rating greater than 7 on a 10 point rating scale), and reported a daily language usage that was unbalanced (English ~ 65 % usage; other language ~ 30 % usage). The monolingual group included participants with only English language exposure and no history of proficiency in a second language.

In this chapter, I will present the main findings observed across all the studies in the present thesis. I will discuss the findings in relation to theories of bilingual cognitive advantage as well as in relation to the contributions to the field of bilingualism and cognitive control.

5.2 Summary of Findings

In Chapter 2 (Experiment 1a), I used the button press version of the Simon task to investigate the decision processing mechanism in bilinguals and monolinguals. In this study, participants were instructed to press the response button appropriate to the stimulus colour with either their left index finger or right index finger. The accuracy and reaction time data were fitted to the linear ballistic model (LBA) (Brown & Heathcote, 2008). This is the first study to investigate the effect of bilingualism on the decision processing mechanism (for drift rate and response threshold parameters) using the evidence accumulation model in the Simon task. The LBA model results indicated a higher drift rate in bilinguals relative to monolinguals, suggesting faster evidence accumulation for an overt response in bilinguals. On the other hand, there was no interaction between language groups and trial types for the drift rate and the response threshold parameters. Additionally, for the button press measures, the results showed similar behavioural performance in the reaction time and the magnitude of the Simon effect.

In Chapter 2 (Experiment 1b), I used the reach-to-touch paradigm combined with the response-signal procedure with the same set of participants as in experiment 1a (Chapter 2). The response-signal procedure (e.g., Finkbeiner et al., 2014) was employed to compare group differences in regard to the magnitude of the Simon effect at similar response bins. In the reach-to-touch version of the Simon task, participants were asked to classify the colour of the stimulus by reaching out and touching the appropriate response panel kept on either side of the screen from the right-hand index finger (Finkbeiner & Heathcote, 2016). Additionally, the response activation of task-relevant information (colour) and task-irrelevant information (location) was also captured across language groups. To my knowledge, this is the first study that has used the reach-to-touch paradigm in the Simon task that has reported the time course of task-relevant and task-irrelevant information in bilinguals and monolinguals. The results showed that there was no difference between language groups for the onset and decay of the Simon effect in the reaching responses, suggesting a similar pattern of conflict resolution in bilinguals and monolinguals. Further, the results revealed that the bilinguals required a shorter stimulus viewing time for formulating an overt response on compatible and neutral trials relative to monolinguals. In particular, on the neutral trials, the bilinguals were faster at activating the task-relevant (colour) information relative to monolinguals. In contrast, on the incompatible trials, bilinguals were better at suppressing the activation of task-irrelevant information initially, but then required more stimulus viewing time to formulate an appropriate response.

In Chapter 3, I investigated the magnitude of the Simon effect by recording MEPs across the language groups. The reaction time distribution differences were eliminated by delivering single-pulse transcranial magnetic stimulation (TMS) over the motor cortex at predefined response time points. In this study, bilingual and monolingual participants were asked to move their right-hand index and right-hand little finger in response to the appropriate target colour. The single-pulse TMS was delivered at four different SSAs relative to the target onset in order to capture the motor cortex excitability for the task-relevant and task-irrelevant dimension. This study is the first of its kind to investigate the consequences of bilingualism in the Simon task at the level of motor cortex. Overall, the MEP responses revealed that the onset of the Simon effect was at 150 ms and that the task-irrelevant information activation was observed at 200 ms after target onset. On the other hand, there was no evidence of bilingualism affecting motor cortex excitability, neither for the magnitude of the Simon effect nor for the task-irrelevant information activation.

In Chapter 4, I investigated the time course of the conflict effect in bilinguals and monolinguals in the linguistic cognitive control task: the Stroop task. In this study, I used the reach-to-touch paradigm combined with the response-signal procedure in order to reduce the reaction time distribution differences between bilinguals and monolinguals and thus to measure the magnitude of the conflict effect at same response time bins. I employed the forced-reading Stroop task in order to increase the probability of trials in which both the word reading and the ink colour dimensions were activated simultaneously. This modulation increased the complexity of the interference in the task (Eidels et al., 2014). Participants classified the target stimulus by reaching out and touching the appropriate response panel. The results demonstrated an early onset of the Stroop effect and interference effect in bilinguals relative to monolinguals.

In the following section, I will discuss the above findings in the context of understanding the broader framework of a bilingual cognitive advantage in cognitive control tasks. Finally, the limitations and future directions of these findings will also be addressed.

5.3 Theories of Bilingual Cognitive Advantage

To briefly summarise what was discussed in the Introduction (Chapter 1), the bilingual cognitive advantage has been explained in terms of the bilingual inhibitory control advantage hypothesis (BICA) and the bilingual executive processing advantage hypothesis (BEPA). The BICA hypothesis was proposed to account for the smaller magnitude of the conflict effect in bilinguals as compared to monolinguals; this hypothesis is based on the inhibitory control model of language processing (Green, 1998; Hilchey & Klein, 2011). The BEPA hypothesis was proposed to account for the overall faster reaction time in bilinguals relative to monolinguals; this hypothesis is based on the conflict monitoring abilities in language processing (Costa et al., 2009; Hilchey & Klein, 2011). If the bilingual advantage stems from the BICA, then I predicted that bilinguals would show a later onset of the conflict effect indicating better control in the resolution of the conflict between the task-relevant and task-irrelevant dimensions. Additionally, I predicted that bilinguals would perform faster on the incompatible trials. On the other hand, if the bilingual advantage stems from the BEPA, then I predicted that the bilinguals would perform faster on all the trials (compatible, neutral and incompatible) as compared to monolinguals.

BICA: In the button press paradigm, there was no evidence in the LBA model parameter estimates and reaction time measures to support a bilingual advantage in conflict resolution. In the reach-to-touch version of the Simon task, the findings suggested that the bilinguals and monolinguals resolved the conflict similarly. In the TMS paradigm, there was no evidence for group differences in the magnitude and the time course of the Simon effect. In the reach-to-touch version of the Stroop task, the bilinguals were poorer in resolving the conflict from the task-irrelevant information. Overall, the findings do not support the BICA hypothesis across tasks (linguistic and nonlinguistic) nor across measures (LBA parameter estimates, reaction time, reaching responses, MEP responses). The results suggest that after controlling for reaction time distribution differences between language groups, there is no evidence of an advantage in the magnitude of the conflict effect.

BEPA: In the button press paradigm, the bilinguals and monolinguals showed similar mean reaction times in the Simon task. For the LBA parameter estimate (i.e., for drift rate), results indicated faster evidence accumulation in bilinguals relative to monolinguals. When the same set of participants completed the reach-to-touch version of the Simon task, the results demonstrated faster responses for bilinguals relative to monolinguals only on neutral and compatible trials. These findings partially support the BEPA hypothesis demonstrating faster responses in bilinguals relative to monolinguals only for the drift rate and in the non-response conflict trials. If bilinguals are better in regard to the monitoring system, they should have shown a more efficient ability with faster responses across all the parameter estimates relative to monolinguals. For the reaching responses on incompatible trials, the bilinguals should have performed better and faster than monolinguals as suggested by previous studies (e.g., Costa et al., 2009). Additionally, there was no evidence for faster responses in either MEP measures or in the reaching responses in the Stroop task to support for the BEPA hypothesis. Overall, the findings add to the literature demonstrating only partial support for the efficient monitoring system in bilinguals. Even if the group differences are observed, the difference is subtle and required a fine-grained analysis in order to capture the effects of bilingualism on cognitive functions.

5.4 Theoretical and Methodological Contributions

The present findings have made several theoretical and methodological contributions to understanding the interaction between bilingualism and cognitive control. At a theoretical level, the findings lend empirical support to interpreting the dual-route assumptions of the Simon effect (De Jong et al., 1994; Ridderinkhof, 2002). According to dual-route models, it is proposed that the task-irrelevant (spatial) dimension is activated earlier by the fast direct route processes, and the task-relevant (colour) dimension is activated later by the slow indirect route processes. The responses from the reach-to-touch paradigm (Chapter 2, Experiment 1b) and the TMS paradigm (Chapter 3) show an early activation of task-irrelevant information in the Simon task, this is then followed by the task-relevant information. In accordance with Finkbeiner and Heathcote (2016), the reaching responses and the MEP responses provide direct evidence for the dual-route theories of the Simon task. Moreover, this model-driven experimental design provides a deeper insight into the underlying mechanisms of the group differences in the Simon task. The bilinguals were faster at processing the task-relevant dimension on the neutral trials from the slow indirect route processes relative to the monolinguals. On the other hand, the monolinguals were faster at activating the task-irrelevant dimension on incompatible trials from the fast direct route processes and recovered faster from the interference than the bilinguals.

The methodological contribution of the present thesis is in its design that allows the investigation of the magnitude of the conflict effect across the same response bins between bilinguals and monolinguals. This is achieved by implementing two independent approaches: a response-signal procedure combined with the reach-to-touch responses and a transcranial magnetic stimulation procedure combined with the MEP responses. Furthermore, using these approaches I was able to minimize the reaction time distribution differences (mean and variance) across the groups. If this was not done, it would have led to the measurement of the magnitude of the conflict effect between a fast responding group and a slow responding group (Abutalebi et al., 2015; Calabria et al., 2011; Calabria et al., 2015; Pratte et al., 2010; Speckman et al., 2008).

The manipulation of the target onset and the imperative go signal (or stimulation) allowed a deeper insight into the time course of the conflict effect over stimulus viewing time. The data obtained from all the studies (MEP responses, reaching responses and reaction time responses) allowed the uncovering of the temporal dynamics of the conflict effect across the language groups over a broad temporal window of stimulus information processing. The MEP responses correspond to the earliest stages of motor preparation (~ 200 ms), the reaching responses correspond to the intermediate stage of cognitive processes and motor action (~ 450 ms), and the mean reaction time correspond to the final end point of cognitive decision making (~ 600 ms). The results demonstrated no differences between the groups in regard to the magnitude of the Simon effect in any of the time points: MEP responses, reaching responses and reaction time responses.

Studies have reported that the bilinguals demonstrate a smaller magnitude of the conflict effect indicating better conflict resolution (e.g., Bialystok et al., 2004; Bialystok et al., 2008; Costa et al., 2008; Hernández et al., 2010; Prior & MacWhinney, 2010; Schroeder & Marian, 2012). Based on this findings, we predicted late onset of the Simon effect in bilinguals as compared to monolinguals. This late onset in bilinguals indicates better control of interference from the task-irrelevant spatial information. However, contrary to our predictions, the overall evidence from all the studies challenges the BICA hypothesis (Hilchey & Klein, 2011), demonstrating similar magnitude and the time course of the Simon effect in bilinguals and monolinguals.

5.5 Limitations and Future Directions

There are some limitations in the present study that are important to address in regard to the findings. The first limitation concerns the diversity of linguistic and background profiles of the bilingual participants selected across all the studies (Chapters 2, 3, and 4). The bilingual group was a heterogeneous language sample: apart from English they spoke a variety of other languages. The bilinguals did not use both of their languages equally on a daily basis; most of the bilingual speakers used English (L2) more frequently (~ 65 %) than the other language (~ 30 %). The bilingual group consisted of participants who had been in Australia for more than 6 years, and the majority of the bilingual participants were not immigrants (~ 75 %). These mixed sociolinguistic and sociocultural profiles might have limited the ability of this study to replicate previous findings (e.g., Costa et al., 2008; Costa et al., 2009). The heterogeneous sample was included due to the necessity of selecting highly proficient bilinguals in all the components of language skills (speaking, understanding, reading, and writing). This forced the inclusion of bilinguals who use different languages. Further, the findings from the heterogeneous bilingual sample would be generalised to the experience of bilingualism *per se*, instead of specific language combination experience (e.g., Bialystok, Martin, & Viswanathan, 2005; Paap, Johnson, & Sawi, 2014; Prior & Mac Whinney, 2010; von Bastian, Souza, & Gade, 2016). It was also unlikely that bilingual participants with a balanced daily usage of L1 and L2 would have been found; this is because these studies were conducted in a country where English is the dominant language. In addition, matching bilinguals and monolinguals with absolute certainty on all variables was not possible due to the multidimensional aspect of bilingualism and the life experiences of the participants (e.g., Kaushanskaya & Prior, 2015).

The second limitation is that the non-significant findings across studies might have also been due to the participation of young adults (e.g., Valian, 2015). Similar behavioural performance in bilingual and monolingual young adults has been attributed to the ceiling effect or peak age of cognitive functioning which might have masked the bilingual language experience on cognition (e.g., Bialystok et al., 2005; Bialystok, Craik, & Luk, 2012; Salvatierra & Rosselli, 2011). Nevertheless, it is interesting to note that the majority of studies in the literature were carried out on young adults (see Hilchey & Klein, 2011; Paap et al., 2014; Zhou & Krott, 2015 for review). Further, the previous research investigating the effect of bilingualism on cognitive control tasks in young adults demonstrated mixed results, with some reporting an advantage (e.g., Costa et al., 2008; Costa et al., 2009; Hernández et al., 2010; Tao et al., 2011) and others failing to find an advantage (e.g., Bialystok et al., 2005; Bialystok, Craik, & Luk, 2012; Paap & Greenberg, 2013; Salvatierra & Rosselli, 2011).

Future studies are required and recommended in order to validate and replicate the present findings. It would be of interest to investigate the effect of bilingualism on other cognitive control tasks (such as the flanker task, the attentional network task) using a similar design to measure the magnitude of the conflict effect. Furthermore, the studies investigating the consequences of bilingual experience on cognitive function have demonstrated that children and old-aged bilinguals are better at resolving conflict in cognitive control tasks than their age-matched monolinguals (e.g., Abutalebi et al., 2015; Bialystok et al., 2004; Bialystok, Craik, & Luk, 2008; Martin-Rhee & Bialystok, 2008; Salvatierra & Rosselli, 2011; Schroeder & Marian, 2012; for review see Hilchey & Klein, 2011; Zhou & Krott, 2015). Employing the response-signal (or similar methodological) procedure in this population would allow the comparison of the magnitude of the conflict effect at similar response bins. If the positive benefits of bilingualism are indeed present, then this will be indicated by the smaller magnitude and later onset of the conflict effect in bilinguals relative to age-matched monolinguals.

Another recommendation is to consider implementing the present study design in order to investigate the intense language processing experience on the sequential effects in cognitive control tasks, i.e., the influence of a previous trial on the current trial response (Botvinick et al., 2001; Hilchey & Klein, 2011). For example, an incompatible trial leads to an elevated level of cognitive control to resolve the conflict. When this trial is followed by another incompatible trial, the level of interference experienced is lower due to the already activated cognitive control system which monitors the conflict effect. However, when a compatible trial is followed by an incompatible trial, the interference level is higher due to the minimal activation of the cognitive control system to monitor the conflict on the compatible trial. Thus, investigating the sequential effects might help to better understand how the language groups engage conflict monitoring processes in order to resolve the response conflict on a trial-by-trial basis at similar response bins (e.g., incompatible-incompatible, compatible-incompatible). The effect of bilingualism on the conflict monitoring system might be strongly indicated by a smaller magnitude and later onset of the conflict effect in bilinguals relative to monolinguals when incompatible trials are preceded by compatible trials. The sequential effects might also be more relevant to explore the conflict monitoring system across the language groups as compared with relying only on the reaction time responses in specific trial types.

5.6 Conclusions

In summary, the findings in this thesis have made several contributions to the field of bilingualism and cognitive control. The use of the response-signal procedure in reaching responses and the TMS procedure in MEP responses indeed provide a deeper insight of the magnitude of the conflict effect at similar response bins (or quantiles) between bilinguals and monolinguals by eliminating the reaction time distribution differences. The findings across studies provide a comprehensive understanding of conflict resolution at different stages of stimulus information processing across the language groups. First, in the LBA parameter estimates, by fitting reaction time and accuracy data to the model I found no difference in the decision processing mechanism between bilinguals and monolinguals. Only for drift rate, I observed a difference in bilinguals as compared with monolinguals. Second, in the reach-to-touch version of the Simon task, I found that the conflict resolution is similar between bilinguals and monolinguals. In the same study, I observed that the bilinguals were slower to recover from the task-irrelevant information interference on incompatible trials than the monolinguals. Additionally, I showed that in the Simon task the bilinguals were faster in activating task-relevant information on neutral trials relative to the monolinguals.

Third, in the TMS version of the Simon task, by recording MEP responses I found no difference between the language groups in the magnitude of the Simon effect at the early motor preparation stage. Furthermore, I found no evidence for group differences in the response activation for task-irrelevant and task-relevant information in the Simon task at the level of the motor cortex. Fourth, in the reach-to-touch version of the forced-reading Stroop task, I found that the bilinguals were more susceptible to interference from the task-irrelevant word dimension than the monolinguals. I hope that the findings reported here will guide future studies attempting to investigate the effect of bilingualism on cognitive control tasks in children and elderly adults.

References

Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P. A., Parris, B. A., & Weekes, B. S. (2015). Bilingualism provides a neural reserve for aging populations. *Neuropsychologia*, *69,* 201-210. doi:10.1016/j.neuropsychologia.2015.01.040

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: consequences for mind and brain. *Trends in Cognitive Sciences*, *16*(4), 240-250. doi: 10.1016/j.tics.2012.03.001

Bialystok, E., Craik, F. I., Grady, C., Chau, W., Ishii, R., Gunji, A., & Pantev, C. (2005). Effect of bilingualism on cognitive control in the Simon task: Evidence from MEG. *NeuroImage*, *24*(1), 40-49. doi: 10.1016/j.neuroimage.2004.09.044

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and Aging*, *19*(2), 290-303. doi: 10.1037/0882-7974.19.2.290

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859-873. doi: 10.1037/0278-7393.34.4.859.

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism*, *9*(1), 103-119. doi: 10.1177/13670069050090010701

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624. doi: 10.1037/0033-295X.108.3.624

Brown, S. D., & Heathcote, A. (2008). The simplest complete model of choice response time: linear ballistic accumulation. *Cognitive Psychology*, *57*(3), 153-178. doi: 10.1016/j.cogpsych.2007.12.002

Calabria, M., Branzi, F. M., Marne, P., Hernández, M., & Costa, A. (2015). Age-related effects over bilingual language control and executive control. *Bilingualism: Language and Cognition*, *18*(01), 65-78. doi:10.1017/S1366728913000138

Calabria, M., Hernández, M., Martin, C. D., & Costa, A. (2011). When the tail counts: the advantage of bilingualism through the ex-Gaussian distribution analysis. *Frontiers in Psychology*, *2*, 250. doi: 10.3389/fpsyg.2011.00250

Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition*, *106*(1), 59-86. doi:10.1016/j.cognition.2006.12.013

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don't. *Cognition*, *113* (2), 135–149. doi:10.1016/j.cognition.2009.08.001

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: a dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(4), 731-750. doi: 10.1037/0096-1523.20.4.731

Dong, Y., & Li, P. (2015). The cognitive science of bilingualism. *Language and Linguistics Compass*, *9*(1), 1-13. doi: 10.1111/lnc3.12099

Eidels, A., Ryan, K., Williams, P., & Algom, D. (2014). Depth of Processing in the Stroop Task. *Experimental Psychology, 61*(5)*, 385-393*. doi: 10.1027/1618-3169/a000259

Finkbeiner, M. & Heathcote, A. (2016). Distinguishing the time- and magnitude-difference accounts of the Simon effect. *Attention, Perception and Psychophysics, 78,* 848-867. doi: 10.3758/s13414-015-1044-9

Finkbeiner, M., Coltheart, M., & Coltheart, V. (2014). Pointing the Way to New Constraints on the Dynamical Claims of Computational Models. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 172-185. doi: 10.1037/a0033169

García-Pentón, L., Fernández García, Y., Costello, B., Duñabeitia, J. A., & Carreiras, M. (2016). The neuroanatomy of bilingualism: How to turn a hazy view into the full picture. *Language, Cognition and Neuroscience*, *31*(3), 303-327. doi: 10.1080/23273798.2015.1068944

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and cognition*, *1*(02), 67-81. doi: 10.1017/S1366728998000133

Hernández, M., Costa, A., Fuentes, L. J., Vivas, A. B., & Sebastián-Gallés, N. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Bilingualism: Language and Cognition*, *13*(03), 315-325. doi: 10.1017/S1366728909990010

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625-658. doi: 10.3758/s13423-011-0116-7

Kaushanskaya, M., & Prior, A. (2015). Variability in the effects of bilingualism on cognition: It is not just about cognition, it is also about bilingualism. *Bilingualism: Language and Cognition*, *18*(01), 27-28. doi: 10.1017/S1366728914000510

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology*, *25*(5), 497-514. doi: 10.1080/20445911.2013.799170

Martin-Rhee, M. M., & Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism Language and Cognition*, *11*(1), 81-93. doi: 10.1017/S1366728907003227

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232-258. doi:10.1016/j.cogpsych.2012.12.002

Paap, K. R., Johnson, H. A., & Sawi, O. (2014). Are bilingual advantages dependent upon specific tasks or specific bilingual experiences?. *Journal of Cognitive Psychology*, *26*(6), 615-639. doi: 10.1080/20445911.2014.944914

Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex*, *69*, 265-278. doi: 10.1016/j.cortex.2015.04.014

Paap, K. R., Sawi, O. M., Dalibar, C., Darrow, J., & Johnson, H. A. (2015). Beyond panglossian optimism: larger N2 amplitudes probably signal a bilingual disadvantage in conflict monitoring. *AIMS Neuroscience*, *2*(1), 12-17. doi:10.3934/Neuroscience.2015.1.1

Pratte, M. S., Rouder, J. N., Morey, R. D., & Feng, C. (2010). Exploring the differences in distributional properties between Stroop and Simon effects using delta plots. *Attention, Perception, & Psychophysics*, *72*(7), 2013-2025. doi: 10.3758/APP.72.7.2013.

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognition*, *13*(02), 253-262. doi:10.1017/S1366728909990526

Ridderinkhof, R. K. (2002). Micro-and macro-adjustments of task set: Activation and suppression in conflict tasks. *Psychological Research*, *66*(4), 312-323. doi:10.1007/s00426-002-0104-7

Salvatierra, J. L., & Rosselli, M. (2011). The effect of bilingualism and age on inhibitory control. *International Journal of Bilingualism, 15(1), 26-37.* doi:10.1177/1367006910371021

Schroeder, S. R., & Marian, V. (2012). A bilingual advantage for episodic memory in older adults. *Journal of Cognitive Psychology*, *24*(5), 591-601. doi: 10.1080/20445911.2012.669367

Speckman, P. L., Rouder, J. N., Morey, R. D., & Pratte, M. S. (2008). Delta plots and coherent distribution ordering. *The American Statistician*, *62*(3), 262-266. doi: 10.1198/000313008X333493

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology*, 2, 123, 83-101. doi: 10.3389/fpsyg.2011.00123

Valian, V. (2015). Bilingualism and cognition. *Bilingualism: Language and Cognition*, *18*(01), 3-24. doi: 10.1017/S1366728914000522

von Bastian, C. C., Souza, A. S., & Gade, M. (2016). No evidence for bilingual cognitive advantage: A test of four hypotheses. *Journal of Experimental Psychology: General, 145*(2), 246-258. doi: 10.1037/xge0000120

Zhou, B., & Krott, A. (2015). Data trimming procedure can eliminate bilingual cognitive advantage. *Psychonomic Bulletin & Review*, 1-10. doi:10.3758/s13423-015-0981

Appendices

Appendix A: Language Experience and Proficiency – Questionnaire (LEAP-Q)

Northwestern Bilingualism & Psycholinguistics Research Laboratory

Marian, Blumenfeld, & Kaushanskaya (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech Language and Hearing Research, 50* (4), 940-967.

Adapted to English for Australia pencil-and-paper by Agnes Au (James Cook University) & Marilyn Hall (Northwestern University)

Language Experience and Proficiency Questionnaire (LEAP-Q)

Last name		First name		Today's Date	
Age		Date of Birth		Male ☐	Female ☐

(1) Please list all the languages you know **in order of dominance**:

1	2	3	4	5

(2) Please list all the languages you know **in order of acquisition** (your native language first):

1	2	3	4	5

(3) Please list what percentage of the time you are *currently* and *on average* exposed to each language.
(*Your percentages should add up to 100%*):

List language here:					
List percentage here:					

(4) When choosing to read a text available in all your languages, in what percentage of cases would you choose to read it in each of your languages? Assume that the original was written in another language, which is unknown to you. (*Your percentages should add up to 100%*):

List language here:					
List percentage here:					

(5) When choosing a language to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each language? Please report percent of total time.
(*Your percentages should add up to 100%*):

List language here					
List percentage here:					

(6) Please name the cultures with which you identify. On a scale from zero to ten, please rate the extent to which you identify with each culture. (Examples of possible cultures include Caucasian, Chinese, Indigenous & Torres Strait Islander, Greek, Italian, Jewish-Orthodox, Pacific Islanders, etc.):

Culture: ______________

0	1	2	3	4	5	6	7	8	9	10
No identification	Very low identification				Moderate identification					Complete identification

Culture: ______________

0	1	2	3	4	5	6	7	8	9	10
No identification	Very low identification				Moderate identification					Complete identification

Culture: ______________

0	1	2	3	4	5	6	7	8	9	10
No identification	Very low identification				Moderate identification					Complete identification

Culture: ______________

0	1	2	3	4	5	6	7	8	9	10
No identification	Very low identification				Moderate identification					Complete identification

Culture: ______________

0	1	2	3	4	5	6	7	8	9	10
No identification	Very low identification				Moderate identification					Complete identification

(7) How many years of formal education do you have? ______________________________

Please check your highest education level (or the approximate Australian equivalent to a degree obtained in another country):

- ☐ Less than High School
- ☐ High School
- ☐ Senior Certificate
- ☐ TAFE
- ☐ Trade Certificate
- ☐ Undergraduate
- ☐ Masters
- ☐ Ph.D./M.D.
- ☐ Other:

(8) Date of immigration to Australia, if applicable ____

If you have ever immigrated to another country, please provide name of country and date of immigration here.

____

(9) Have you ever had a vision problem☐, hearing impairment☐, language disability☐, or learning disability ☐? (Check all applicable).

If yes, please explain (including any corrections):

____

Language:

This is my (**native** **second** **third** **fourth** **fifth**) language.

(1) Age when you…

began acquiring this language:	*became fluent in this language*:	*began reading in this language*:	*became fluent reading in this language*:

(2) Please list the number of years and months you spent in each language environment:

	Years	Months
A country where this language is spoken		
A family where this language is spoken		
A school and/or working environment where this language is spoken		

(3) Please circle your *level of* ***proficiency*** in speaking, understanding, and reading in this language:

Speaking

0	1	2	3	4	5	6	7	8	9	10
None	Very low	Low	Fair	Slightly less than adequate	Adequate	Slightly more than adequate	Good	Very good	Excellent	Perfect

Understanding spoken language

0	1	2	3	4	5	6	7	8	9	10
None	Very low	Low	Fair	Slightly less than adequate	Adequate	Slightly more than adequate	Good	Very good	Excellent	Perfect

Reading

0	1	2	3	4	5	6	7	8	9	10
None	Very low	Low	Fair	Slightly less than adequate	Adequate	Slightly more than adequate	Good	Very good	Excellent	Perfect

(4) Please circle how much the following factors contributed to you learning this language:

Interacting with friends

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Interacting with family

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Reading

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Language tapes/self-instruction

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

Listening to the radio

0	1	2	3	4	5	6	7	8	9	10
Not a contributor	Minimal contributor				Moderate contributor					Most important contributor

(5) Please circle to what extent you are currently exposed to this language in the following contexts:

Interacting with friends

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Interacting with family

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Watching TV

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Listening to radio/music

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Reading

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Language-lab/self-instruction

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

(6) In your perception, how much of a foreign accent do you have in this language?

0	1	2	3	4	5	6	7	8	9	10
None	Almost none	Very light	Light	Some	Moderate	Considerable	Heavy	Very heavy	Extremely heavy	Pervasive

(7) Please circle how frequently others identify you as a non-native speaker based on your <u>accent</u> in this language:

0	1	2	3	4	5	6	7	8	9	10
Never	Almost Never				Half of the time					Always

Appendix B: Edinburgh Handedness Inventory

Participants were asked to respond by a ‘++’ mark for a strong preference or a ‘+’ mark for equal preference for left and right-hand usage. The handedness scores were calculated for each participant by adding total ‘+’ marks under left and right column (i.e., Handedness Scores = (R-L/R+L)*100).

Surname_________________________ Given Name___________________

Date of Birth____________________________ Sex___________________

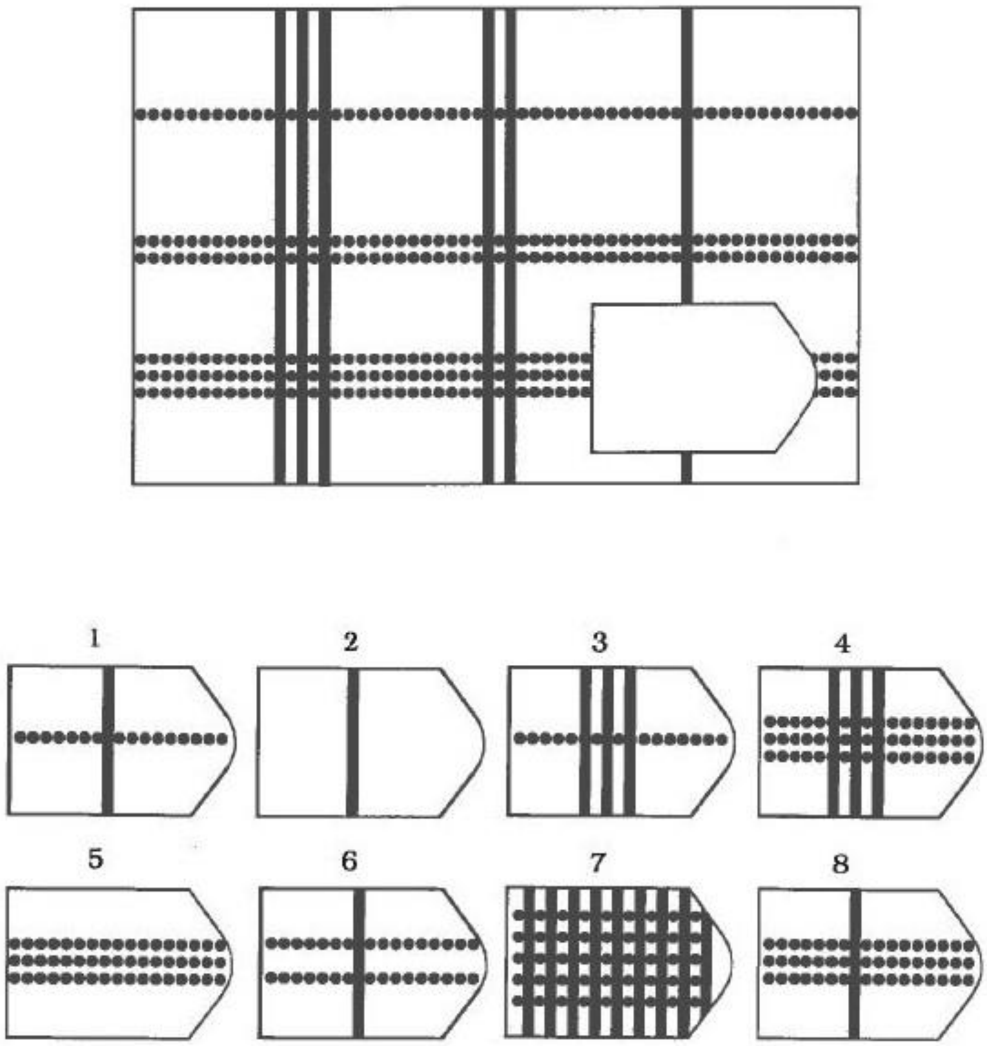
Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, *put ++*. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		

Participants completed a shortened version of the Raven's Advanced Progressive Matrices-Set I. The set I consisted of 12 items, and on an average took 12 minutes to complete the test. In this test, participants were asked to recognize a pattern from the list of eight options, that best fits the missing spot in the target item. Each correct answer was given a score of one, with a maximum total of 12. (Figure showing Item 1 from the test material).



Appendix D: Language, Education and Social Background Questionnaire

Note to the participant: Please take a few minutes to answer the following questions. Some of the questions below ask you to provide us with personal information. The responses you provide are for our research purposes only and will remain strictly confidential. You are free to stop participation at any time, and free to ask questions if you have any concerns whatsoever.

1. Please write down the name of the language in which you received instruction in school, for each of the schooling level?

   Primary school ___________________
   Junior high ___________________
   Senior high ___________________
   TAFE Certificate ___________________
   University Degree ___________________
   Postgraduate Degree ___________________

2. What is your dominant language for the last 5 years?______________________________

3. Rate your proficiency level in a scale of 0 to 10 for following activities in languages you know.

   (0= none; 1= very low; 2= low; 3= fair; 4= slightly less than adequate; 5= adequate; 6= slightly more than adequate; 7= good; 8= very good; 9= excellent; 10= perfect)

Language	English				
Writing					
Grammar					
Pronunciation					

4. For the languages you listed, please indicate below the place where you learned them and at what age, and if applicable, whether you learned them by formal lessons (e.g., at school or a course), or by informal learning (e.g., at home, at work, from friends).

Language	Country, Age (Years)	Lessons (yes/no)	Duration of lessons (per day or week)	Informal (yes/no)	Duration of informal learning
1					
2					
3					
4					
5					

5. Have you lived overseas? Yes/No.

   How long _____________________and where_____________________
   How long _____________________and where_____________________
   How long _____________________and where_____________________

6. Currently, how many hours do you spend on working on a computer every day.? _________

7. Do you play speeded computer video games? Yes/No
If yes,
Age of exposure to video games?______________
Years of experience?__________________
How many hours do you spend in a week (currently)?_________________

8. If you have taken a standardized test of proficiency for languages other than your native language (e.g., TOEFL or IELTS) please indicate the scores you received for each

Language	Scores	Name of the test

9. What languages do your parents speak?
Mother__________________________Father________________________________

10. Parental education level (Circle the number that best describes the highest education level obtained)

Parent: Mother/Father/Guardian Profession: ___________________

1.Did not graduate from high school	4. Earned a Bachelor's degree
2.Graduated from high school	5. Earned a graduate or professional degree
3.Attended college but did not earn a degree	

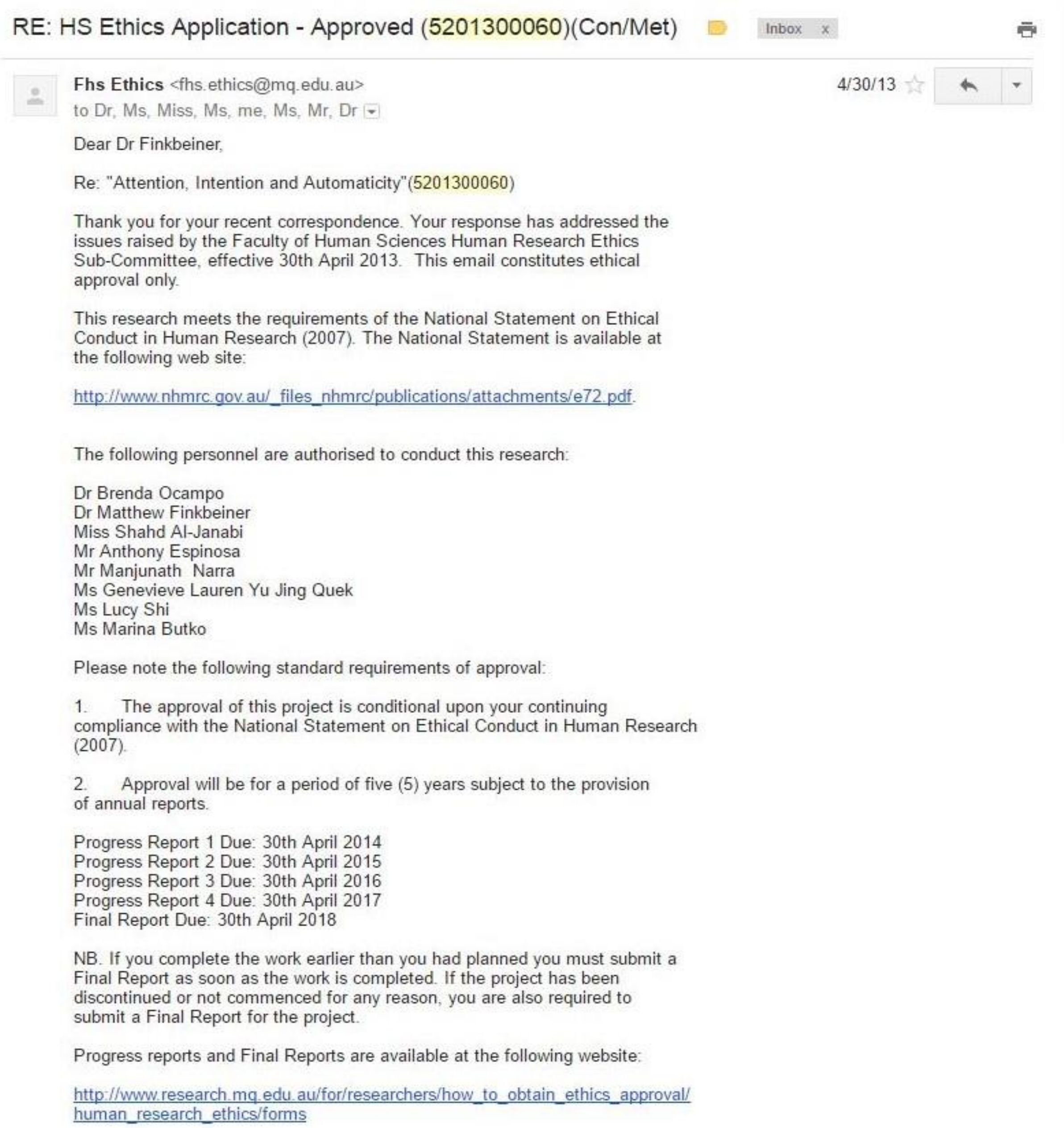
Parent: Mother/Father/Guardian Profession: ___________________

1.Did not graduate from high school	4. Earned a Bachelor's degree
2.Graduated from high school	5. Earned a graduate or professional degree
3.Attended college but did not earn a degree	

11. If you have anything else that you feel is interesting or important about your language history and use, please feel free to write them here.

Thank You !

Appendix E: Behavioural Experiments Ethics Approval



RE: HS Ethics Application - Approved (5201300060)(Con/Met) Inbox x

Fhs Ethics <fhs.ethics@mq.edu.au> 4/30/13
to Dr, Ms, Miss, Ms, me, Ms, Mr, Dr

Dear Dr Finkbeiner,

Re: "Attention, Intention and Automaticity"(5201300060)

Thank you for your recent correspondence. Your response has addressed the issues raised by the Faculty of Human Sciences Human Research Ethics Sub-Committee, effective 30th April 2013. This email constitutes ethical approval only.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:

Dr Brenda Ocampo
Dr Matthew Finkbeiner
Miss Shahd Al-Janabi
Mr Anthony Espinosa
Mr Manjunath Narra
Ms Genevieve Lauren Yu Jing Quek
Ms Lucy Shi
Ms Marina Butko

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).

2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 30th April 2014
Progress Report 2 Due: 30th April 2015
Progress Report 3 Due: 30th April 2016
Progress Report 4 Due: 30th April 2017
Final Report Due: 30th April 2018

NB. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

Appendix E: Behavioural Experiments Ethics Approval (continued)

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Sub-Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Sub-Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

5. Please notify the Sub-Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:

http://www.mq.edu.au/policy

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of approval to an external organisation as evidence that you have approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of ethics approval.

Yours sincerely,

Dr Peter Roger
Chair
Faculty of Human Sciences Ethics Review Sub-Committee
Human Research Ethics Committee

Faculty of Human Sciences - Ethics
Research Office
Level 3, Research HUB, Building C5C
Macquarie University
NSW 2109

Appendix F: Behavioural Experiments Participant Consent Form

Department of Cognitive Science
Faculty of Human Sciences
MACQUARIE UNIVERSITY NSW 2109

Phone: +61 (02) 9850 9599
Fax: +61 (02) 9850 6059

Email: cogsci@ mq.edu.au

INFORMATION AND CONSENT FORM

Project Name: *Attention, Intention, and Automaticity*

You are invited to participate in a study on the role of attention and intention in automatically elicited word and picture recognition processes.

This research, which is supported in part by the Australian Research Council and Macquarie University, is being conducted by Genevieve Quek (phone: 9850-4436; email: genevieve.quek@ mq.edu.au), Shahd Al-Janabi (phone: 9850-6729; email: shahd.al-janabi@mq.edu.au), Manjunath Narra (phone: 9850 2945; email: manjunath.narra@students.mq.edu.au), Samantha Parker (email: samantha.parker@students.mq.edu.au), Daniell Steinberg (email: daniell.steinberg@students.mq.edu.au), Marina Butko (phone: 9850 6858; email: marina.butko@mq.edu.au), and Irene Chork (email:irene.chork@students.mq.edu.au), under the supervision of A/Prof Matthew Finkbeiner (phone: 9850-6718; email: matthew.finkbeiner@mq.edu.au) of the Department of Cognitive Science, Macquarie University. It is also being conducted to fulfil partial requirements for a Doctor of Philosophy in Human Cognition and Brain Science for Genevieve Quek, Shahd Al-Janabi and Manjunath Narra, and Bachelor of Psychology (Honours) degree for Samantha Parker and Daniell Steinberg.

If you decide to participate, you will be asked to respond to stimuli by reaching out and touching the computer monitor. Measurements of your responses will be recorded by a camera system that tracks the position of light (infrared) emitting markers. The markers will be placed on your hand/finger with double-sided adhesive tape.

No personally identifying information will be collected in the course of this study. All data will only be kept in a de-identified form. All matters relating to your participation will be kept strictly confidential, and will be examined only by the researchers named above.

If you are enrolled in second year psychology, participation in this experiment will count towards your research participation for this course, and you will be credited for 1 hour of participation. If you are participating for pay, you will be compensated for your participation at the rate of $15.00 per hour.

If you decide to participate, you are free to withdraw from participation at any time without having to give a reason and without consequence. If you are participating in this study for course credit in second year psychology, this will not result in forfeit of course credit.

If you have any questions about any aspect of the research or your participation you are encouraged to contact the investigators (contact details given above).

I, ______________________ have read and understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time. I have been given a copy of this form to keep.

Participant's Name: ___________________________
(Block letters)
Participant's Signature: ___________________________ Date: ___________________
Investigator's Name: ___________________________
Investigator's Signature: ___________________________ Date: ___________________

The ethical aspects of this study have been approved by the Macquarie University Ethics Review Committee (Human Research). If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact Committee through the Director, Research Ethics (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

Appendix G: TMS Screening Form

Transcranial Magnetic Stimulation (TMS) is a method for producing an electric current in a small part of the brain. During TMS, a current passes through a copper coil that is wound inside a plastic casing and held over the participant's head. The current in the coil produces a magnetic field, which passes safely through the scalp and causes electrical activity in brain tissue.

Before receiving TMS, please read the following questions carefully and provide answers. For a small number of individuals, TMS may carry an increased risk of causing a seizure. The purpose of these questions is to make sure that you are not such a person. You have the right to withdraw from the screening and subsequent scanning if you find the questions unacceptably intrusive. The information you provide will be treated as strictly confidential and will be held in secure conditions.

If you are unsure of the answer to any of the questions, please ask the person who gave you this form or the person who will be performing the study. Definitions of some of technical terms are given overleaf.

	Please tick
Have you ever had an adverse reaction to TMS?	☐**Yes** ☐**No**
Do you experience claustrophobia?	☐**Yes** ☐**No**
Have you had a seizure?	☐**Yes** ☐**No**
Have you had a stroke?	☐**Yes** ☐**No**
Have you had a serious head injury (including neurosurgery)?	☐**Yes** ☐**No**
Do you have any metal in your head (outside the mouth) such as shrapnel, surgical clips, or fragments from welding or metalwork?	☐**Yes** ☐**No**
Do you have any implanted devices such as cardiac pacemakers, aneurysm clips, cochlear implants, medical pumps, deep brain stimulators, or intracardiac lines?	☐**Yes** ☐**No**
Do you suffer from frequent or severe headaches?	☐**Yes** ☐**No**
Have you ever had any other brain-related condition?	☐**Yes** ☐**No**
Have you ever had any illness that caused brain injury?	☐**Yes** ☐**No**
Are you taking any psychiatric or neuroactive medications, or do you have a history of drug abuse?	☐**Yes** ☐**No**
Are you pregnant?	☐**Yes** ☐**No**
Do you, or does anyone in your family, have epilepsy?	☐**Yes** ☐**No**
Do you hold a heavy goods vehicle driving license or bus license?	☐**Yes** ☐**No**

I have read and understood the questions above and have answered them correctly.

SIGNED………………………………… DATE…………………………

In the presence of ……………………………….. (Name) ……….………………….. (Signature)

Appendix H: TMS Experiment Ethics Approval

Fwd: Amendment HEMAY2009 RO660 | Inbox | ethics

Paul Sowman <paul.sowman@mq.edu.au> 7/23/13
to me, Erin, Margaret, Matthew, Shahd

---------- Forwarded message ----------
From: **Ethics Secretariat** <ethics.secretariat@mq.edu.au>
Date: Tue, Jul 23, 2013 at 9:35 AM
Subject: Re: Amendment HEMAY2009 RO660
To: Paul Sowman <paul.sowman@mq.edu.au>

Dear Paul

Thank you for your email and amendment request. The following amendment has been approved:

1. The addition of PhD student Mr Manjunath Narra from the study.

2. The removal of Ms Brenda Ocampo from the study.

Please do not hesitate to contact me if you have any questions.

Kind regards
Fran

On Fri, Jul 19, 2013 at 4:41 PM, Paul Sowman <paul.sowman@mq.edu.au> wrote:

> Dear ethics, we would like to amend the personnel on this ethics.
>
> Thanks, Paul
>
> --
> Paul F Sowman
> ARC DECRA Postdoctoral Fellow
> Department of Cognitive Science
> ARC Centre of Excellence for Cognition and its Disorders (CCD)
> MACQUARIE UNIVERSITY NSW 2109

--
--

Ethics Secretariat
Research Office
Level 3, Research Hub, Building C5C East
Macquarie University
NSW 2109 Australia
T: +61 2 9850 6848
F: +61 2 9850 4465
http://www.mq.edu.au/research

MACQUARIE University SYDNEY·AUSTRALIA

CRICOS Provider Number 00002J

Appendix I: TMS Experiment Participant Consent Form

MACQUARIE UNIVERSITY
SYDNEY ~ AUSTRALIA

CONSENT FORM

COMBINED TRANSCRANIAL MAGNETIC STIMULATION (TMS) AND ELECTROENCEPHALOGRAPHY (EEG) STUDIES OF ATTENTION AND COGNITIVE CONTROL IN THE HUMAN BRAIN

I ………………………………………………………. have read and understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this (*please check those modalities that you agree to*):

O Electroencephalography (EEG) research
O Transcranial Magnetic Stimulation (TMS) research

I know that I can withdraw at any time without having to give a reason and without penalty or loss of research credit. I have been given a signed copy of this form to keep.

Participant's name: …………………………………………………….(block letters)

Participant's signature……….……………………………………… Date………………..

Investigator's name ………………………………………………….…(block letters)

Investigator's signature ………………………………………………Date………………..

I would like to receive summary information about the overall outcome of this research project when it is completed: YES / NO

I am happy to be contacted with information about future research projects at Macquarie University: YES / NO

The ethical aspects of this study have been approved by the Macquarie University Ethics Review Committee (Human Research) Reference HEMAY2009 RO6600. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Ethics Review Committee through its Secretary (telephone 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.