How balanced are you? Bilingualism and the development of attentional control in English-Mandarin preschool children

Chan, Clara Gek Hoon

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**HOW BALANCED ARE YOU?
BILINGUALISM AND THE DEVELOPMENT OF
ATTENTIONAL CONTROL IN
ENGLISH-MANDARIN PRESCHOOL CHILDREN**

CHAN GEK HOON, CLARA

School of Social Sciences

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	ii
TABLE OF CONTENTS	iv
LIST OF TABLES	ix
LIST OF FIGURES	xii
ABSTRACT	xiii
CHAPTER 1. INTRODUCTION	1
1.1 Outline of the thesis.....	4
CHAPTER 2. LITERATURE REVIEW.....	5
2.1 Bilingualism Shapes Cognitive Control	5
2.1.1 How Does The Brain Manage Two Languages? Review Of Current Theories	5
2.1.1.1 Earlier Theories.....	6
2.1.1.2 The Adaptive Control Hypothesis.....	7
2.1.2 Does Bilingual Experience Benefit General Cognitive Control?.....	12
2.1.3 Bilingualism Balance And Its Association With Cognitive Control.....	17
2.1.4 Theoretically, How Would Bilingualism Balance Relate To Cognitive Control?	18
2.1.4.1 Previous Perspective: Inhibition Based	19
2.1.4.2 Proposed Perspective: Contextual-based Attention Control.....	20
2.1.5 Previous Studies.....	23

2.1.5.1 Issues In Measurement	33
2.1.5.1.1 Measurement Of Bilingual Proficiency	33
2.1.5.1.2 Measurement Of Bilingual Balance	35
2.2 Attention: A Key Component Of Cognitive Control	37
2.2.1 The Attention Network Model	38
2.2.1.1 The Attention Network Test (ANT)	40
2.2.2 The Role Of Attention in the Relation Between Bilingualism And Cognitive Control	43
2.2.3 How Is Bilingualism Expected To Relate To The Attention Network?	44
2.3 The Present Paper: Bilingualism Balance And Attentional Control..	46
2.3.1 Research Aim 1: To Examine Whether Vocabulary Tests Represent Language Experience	47
2.3.2 Research Aim 2: To Examine How Different Bilingual Balance Aspects Relate To Different Attention Networks	48
2.3.3 Research Aim 3: To Examine the Mechanism Behind Bilingualism Balance And Attentional Control	50
2.3.4 Present Population: Preschoolers In Singapore	52
2.4 Summary	55
CHAPTER 3. STUDY 1	57
3.1 Rationale of the Present Study	57
3.2 Methods	58
3.2.1 Participants	58
3.2.2 Measures	59
3.2.2.1 Parental Report Questionnaire	60

3.2.2.2 Peabody Picture Vocabulary Test (PPVT)	60
3.2.2.3 Expressive Vocabulary Test-2 (EVT)	61
3.2.3 Procedure	62
3.3 Results	63
3.3.1 Preliminary Calculations.....	63
3.3.2 Demographic Variables	68
3.3.3 Correlations.....	68
3.4 Discussion.....	74
CHAPTER 4. STUDY 2	80
4.1 Rationale of the Present Study	80
4.2 Methods	83
4.2.1 Participants.....	83
4.2.2 Measures	83
4.2.2.1 Demographic Questionnaires.....	84
4.2.2.2 Peabody Picture Vocabulary Test (PPVT) and Expressive Vocabulary Test-2 (EVT)	84
4.2.2.3 Child Attention Network Task – Shortened (ANT)	84
4.2.2.4 Kaufman Brief Intelligence Test-2 (KBIT)	87
4.2.3 Procedure	88
4.3 Results	89
4.3.1 Preliminary Analyses.....	89
4.3.2 Demographic Variables	90
4.3.3 Language Measures	91
4.3.4 Preliminary ANT Analyses.....	92
4.3.4 Correlations.....	98

4.3.5 Regressions	102
4.4 Discussion.....	114
CHAPTER 5. STUDY 3	121
5.1 Rationale of the Present Study	121
5.2 Methods	127
5.2.1 Participants.....	127
5.2.2 Measures	127
5.2.2.1 Demographic Questionnaires.....	127
5.2.2.2 Peabody Picture Vocabulary Test (PPVT)	127
5.2.2.3 Kaufman Brief Intelligence Test-2 (KBIT)	128
5.2.2.4 Child Attention Network Task – Shortened (ANT)	128
5.2.2.4 Picture Identification Task.....	128
5.2.3 Procedure	132
5.3 Results	133
5.3.1 Pilot Test Results.....	133
5.3.2 Preliminary Analyses.....	134
5.3.3 Demographic Analyses (Across Conditions).....	135
5.3.4 Picture Identification Task Performance	137
5.3.5 Preliminary ANT Analyses (All Participants)	139
5.3.6 ANT Performance Across Conditions.....	141
5.4 Discussion.....	152
CHAPTER 6. GENERAL DISCUSSION.....	161
6.1 Summary of Results	161
6.2 Key Research Findings	163

6.2.1 Vocabulary Ratio Scores as Representations of Bilingualism Balance	163
6.2.2 The Relations Between Bilingualism Balance Exposure and Production with Alerting and Conflict Attention Network.....	165
6.2.3 Examining the Mechanism Behind Bilingualism Balance and Attentional Control: The Importance of Context.....	166
6.2.3 Additional Finding: The Independence of ANT Components	168
6.3 Limitations and Future Directions	169
6.4 Implications	173
6.4.1 Theoretical Implications	173
6.4.2 Practical Implications	175
6.5 Conclusion	176
REFERENCES	178
APPENDICES	193
Appendix A. Sample Survey Items	193
Appendix B. List of Items for Picture Identification Task	195

LIST OF TABLES

TABLE 1. Summary of the Adaptive Control hypothesis: Control Processes, the Associated Neural Areas, and Relative Demands of Each Context on the Processes	10
TABLE 2. Summary of Previous Research on Bilingualism Balance and Cognitive Control	27
TABLE 3. Means, Standard Deviations, Skewness and Kurtosis values for parent reported language exposure and production, PPVT, EVT, and all derived scores	66
TABLE 4. Correlations among parent reported proficiency, PPVT, EVT, and all derived scores	69
TABLE 5. Correlations among parent reported language exposure and production quantities, PPVT, EVT, and all derived scores	71
TABLE 6. Mean, Standard Deviation, Skewness and Kurtosis for PPVT, EVT and KBIT scores	92
TABLE 7. Means, Standard Deviations, Skewness and Kurtosis of Accuracy and RT for Each Cue and Flanker Condition in ANT	93
TABLE 8. Means, Standard Deviations, Skewness and Kurtosis of Accuracy, Error Rate (ER) and RT for Attention Network Scores (Original and New Methods of Calculation	96
TABLE 9A. Correlations Among Age, PPVT, EVT, KBIT, ANT Overall Accuracy (Acc) and Reaction Times (RT), Controlling for Income	98

TABLE 9B. Correlations Among ANT Network Scores Accuracy (Acc), Error Rates (ER), and Reaction Times (RT), Both Original (old) and New Calculations, Controlling for Income.....	99
TABLE 9C. Correlations Between Age, PPVT, EVT, KBIT, ANT Accuracy (Acc), Error Rates (ER), Reaction Times (RT), Against ANT Network Scores, Controlling for Income.....	100
TABLE 10. Original ANT Error Rates (ER) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 1 (Receptive Vocabulary)...	105
TABLE 11. Original ANT Error Rates (ER) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 2 (Expressive Vocabulary) .	106
TABLE 12. Original ANT Alerting Reaction Time (RT) And Conflict Error Rate (ER) Hierarchical Regression Analyses Using Combined Model (Receptive & Expressive Vocabulary).....	107
TABLE 13. Original ANT Conflict Error Rate (ER) Hierarchical Regression Analyses By Flanker, Using Model 2 (Expressive Vocabulary).....	108
TABLE 14. New ANT Accuracy (Acc) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 1 (Receptive Vocabulary)	111
TABLE 15. New ANT Error Rates (ER) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 2 (Expressive Vocabulary).....	112
TABLE 16. New ANT Alerting Reaction Time (RT) and Conflict RT Hierarchical Regression Analyses Using Combined Model (Receptive & Expressive Vocabulary)	113
TABLE 17. Summary/Mean And Standard Deviations Of Demographics By Condition	136

TABLE 18. Means and Standard Deviations of Accuracy and RT for Picture Identification Task	137
TABLE 19. Means, Standard Deviations, Skewness and Kurtosis of Accuracy and Median RT for Each Cue and Flanker Condition in ANT.....	139
TABLE 20. Means and Standard Deviations of ANT Cues and Flankers by Language Frame Condition	141
TABLE 21. Means and Standard Deviations of ANT Network Scores and Components by Language Frame Condition.....	147

LIST OF FIGURES

FIGURE 1. Overview of the Hypothesized Relationships in the Present Study	50
FIGURE 2. Q-Q plots of Exposure, Production, Parental Reported Language Proportion, PPVT ratio, EVT ratio, and Vocabulary Test Balance	67
FIGURE 3. Sequence of Each Trial of the Shortened Child ANT, with Illustrations on Cue and Target Conditions.....	85
FIGURE 4. ANT Accuracy Performance by Cue and Flanker Across Conditions.....	142
FIGURE 5. ANT RT Performance by Cue and Flanker Across Conditions...	143
FIGURE 6. Differences in ANT No and Center Cue Accuracy Across Conditions	149
FIGURE 7. Differences in ANT Spatial Cue Accuracy and RT Across Conditions	150
FIGURE 8. Differences in ANT Congruent and Incongruent Flanker Accuracy Across Conditions	151
FIGURE 9. Differences in ANT Overall Accuracy and RT Across Conditions	152

Abstract

In recent years, research interest on bilingualism and its relation to cognitive control has grown. Given that engaging in the cognitive processes of language management in the brain is likely to result in changes to the neural system to improve cognitive efficiency, bilingualism is expected to positively benefit cognitive control. However, the experience of bilingualism is varied. Some individuals are more comparable in their proficiency in both languages (more-balanced), while others are much more proficient in their dominant language than they are in their weaker language (less-balanced). The Adaptive Control hypothesis (Green & Abutalebi, 2013) is a theoretical framework proposed as to how bilinguals manage two languages in their minds. As part of the theory, they highlight the importance of context; three different bilingual conversational contexts were identified, and differing cognitive demands were attributed to those three contexts.

The main research question in the current thesis is to examine the relation between bilingualism balance and attentional control in preschool children. Young children have high levels of attentional plasticity; to examine the relation in this age group has far reaching implications both theoretically and practically. Previous studies have found a positive relationship between bilingualism balance and attentional control, with more-balanced bilinguals performing better on the attention task than the less-balanced bilinguals (e.g. Carlson & Meltzoff, 2008; Poarch & van Hell, 2012). However, there have been some research gaps. Firstly, due to the complex nature of measuring language proficiency and experience, there is yet to be a commonly accepted measure of bilingualism balance. Secondly, results comparing bilingualism

balance and attention have not been consistent across studies; there is a lack of information regarding which aspect of the bilingualism experience is related to which subcomponent of attention. Thirdly, there is also a lack of understanding of the mechanism underlying how bilingualism balance relates to attentional control. We propose a contextual-based attention control perspective as an underlying mechanism, by highlighting the importance of different language contexts and the role of attention in language monitoring and selection. We contend that, due to the differences in the contexts that a more-balanced bilingual experiences as compared to a less-balanced bilingual, the cognitive demands differ between them and therefore the more-balanced bilingual will have higher cognitive control than the less-balanced bilingual.

In response to the research gaps, we conducted three studies. In Study 1, we set out to determine the real-world bilingual experience correspondence of our chosen index of bilingualism balance: vocabulary tests ratios. We compared parental reported exposure and use of each language with receptive and expressive vocabulary scores. Results showed moderately strong correlations between parental reported scores and the vocabulary tests ratios, supporting the use of this balance index in the subsequent studies. In Study 2, we examined the relation between bilingualism balance and attentional control. Using the ratio of receptive vocabulary across languages as a proxy for language exposure, and expressive vocabulary ratio as a proxy for language production, we compared the vocabulary ratios to different network performances on the Attention Network Test (ANT). Results indicated that in general, more-balanced bilinguals (higher ratio) performed better on the ANT as compared to the less-balanced ones. Specifically, both aspects of language

experience (exposure and production) were related to two of the attentional networks (alerting and conflict). Study 3 was designed to endeavor to understand the mechanism behind how bilingualism balance affects attentional control. To investigate the importance of different linguistic contexts, the aspect we proposed to be what more and less-balanced bilinguals differ on, we experimentally induced different language contexts to see the subsequent performance on the ANT. Participants were randomly assigned them to one of three conditions: before completing the ANT, they had to complete a picture-recognition task either (1) in their dominant language, (2) in their weaker language, or (3) in a mixture of the two languages (to simulate language-switching). It was found that the children who completed the language task in their weaker language and the language switching condition showed higher overall accuracy in the subsequent ANT compared to those who completed the task in their dominant language.

Taken together, the studies suggest that more-balanced bilingual children (as compared to less-balanced ones) exhibit better attentional control, and this difference may be due to the differences in exposure to their languages between these two groups; the less-balanced bilinguals are exposed mostly to their dominant language, and since that context does not require as much cognitive demands, they are less likely to practice attentional control, as compared to being in a highly bilingual environment, which is more common in more-balanced bilinguals. Given the cultural and societal differences inherent in bilingualism all over the world, caution needs to be taken when generalizing the conclusions, but the results have both theoretical and practical implications on

promoting balanced bilingualism among young bilinguals to benefit their attentional control.

CHAPTER 1

INTRODUCTION

To be bilingual – to know and understand two (or more) languages – is a phenomenon that develops together with globalization. As different parts of the world become more interconnected, bilingualism arises both out of necessity and demand. Now, many countries have become linguistically diverse, making bilingualism more of the norm than the exception (Bialystok, Craik, Green, & Gollan, 2009).

In recent years, research interest on bilingualism and its relation to cognitive control has grown. Green and colleagues have proposed and refined over the years a number of theories to explain how bilinguals manage two languages in their minds, the most recent being the Adaptive Control hypothesis (Green & Abutalebi, 2013). In it, they identified three different kinds of interactional contexts bilinguals undergo: a single language context where one language is only used in one situation, with a language switch only in a different situation; a dual language context in which both languages are used in the same setting but usually with different people; and a dense code-switching context in which the bilingual engages in frequent language changes in one utterance. Additionally, they also identified eight cognitive control processes involved when the bilingual is in conversation, and suggested that each of the three interactional contexts varied in the demand on those eight cognitive processes. Specifically, the dual language context is seen as the most demanding, followed by the single language context, and finally the dense code-switching context. Given that engaging in these cognitive processes are more likely to result in changes to the neural system to improve cognitive

efficiency (Abutalebi & Green, 2007), bilingualism is expected to then positively benefit cognitive control.

However, the experience of bilingualism is varied; every bilingual uses both of their languages to different proportions of time, and individually they all differ in proficiency in both of their languages. Some individuals are more comparable in their proficiency in both languages (more-balanced), while others are much more proficient in their dominant language than they are in their weaker language (less-balanced). Given that the experience of bilingualism is what shapes cognitive abilities, it is important that these variations in bilingual balance are taken into account when examining the relation between bilingualism and cognitive control.

Hence, drawing from the focus on language contexts identified in the Adaptive Control hypothesis (Green & Abutalebi, 2013) as well as the proposal by Bialystok (2015, 2017) regarding the importance of attention, we highlight the importance of contextual-based attentional control in understanding the relationship between bilingualism balance and cognitive control. We contend that, due to the differences in the contexts that a more-balanced bilingual experiences (proportionally more weaker language in both single and dual language contexts) as compared to a less-balanced bilingual (more dominant language in both contexts), the cognitive demands differ between them and therefore the more-balanced bilingual will have higher cognitive control than the less-balanced bilingual.

Given its importance, we focus on one of the most fundamental aspects of cognitive control: attentional control (Bialystok, 2015, 2017). Attentional control is also proposed to underlie much of the management of language in the

bilingual brain (Costa, Hernandez, & Sebastian-Galles, 2006). Hence, our overarching research question for this thesis is to examine the relationship between bilingualism balance and attentional control in preschool children. We have chosen to work with preschool children due to their relative lack of formal education, which would allow us to examine the effects of non-formal education based bilingualism environment on attentional control.

Previous studies have found a positive relationship between bilingualism balance and attentional control, with more-balanced bilinguals performing better on the attention task than the less-balanced bilinguals (e.g. Carlson & Meltzoff, 2008; Poarch & van Hell, 2012). However, there have been some research gaps. Firstly, due to the complex nature of measuring language proficiency and experience, there is yet to be a commonly accepted measure of bilingualism balance. Secondly, results comparing bilingualism balance and attention have not been consistent across studies; there is a lack of consistency regarding which aspect of the bilingualism experience is related to which subcomponent of attention. Thirdly, there is also a lack of understanding of the mechanism underlying how bilingualism balance relates to attentional control; given that we have proposed a contextual-based attention control mechanism, it would be important to examine its relevance in this relation.

Thus, we set out to address three research aims in this thesis. Firstly, we aim to examine how well our selected measure of bilingualism balance, the receptive and expressive vocabulary ratios, correspond to parent reported language experiences of the bilingual child, in order to justify the use of that indicator in the future studies. To do this, in Study 1, we collected receptive and expressive vocabulary test scores, as well as parent reported levels of exposure

and production of each language of their child, and compared the correlations between them.

Secondly, we aim to understand how different bilingual balance aspects (language exposure and production) relate to attentional control. This was addressed in Study 2, where we collected data regarding children's receptive (used to represent language exposure) and expressive (to represent language production) vocabulary, and compared it with their performance on the Attention Network Task (ANT).

Thirdly, we aim to examine the mechanism underlying bilingualism balance and attentional control, in order to better understand this relationship. Having proposed that differing level of bilingualism balance is associated with different language contexts, we manipulated language contextual frames to see if these language frames would affect performance on the subsequent ANT.

Outline of the Thesis

Chapter 2 provides an overview of the literature available in the field, including theories on how bilingualism and bilingualism balance are related to cognitive and attentional control, as well as previous studies that show support for these theories. Chapters 3, 4 and 5 show the three studies conducted to address the three research aims above, and Chapter 6 comprises of the general discussion; included within are a summary of all findings, limitations, future directions, implications and the conclusion.

CHAPTER 2

LITERATURE REVIEW

In this chapter, we review the existing literature on how the bilingual experience and its variability are theorized to affect general cognitive control and hence attentional control, the empirical findings behind these relationships and the gaps present in the current state of research.

Bilingualism Shapes Cognitive Control

One of the fundamental pillars of bilingualism and cognitive control research is the assumption that the bilingual experience causes some change in the cognitive control processes of an individual. In this section, we first highlight the proposed theories behind the way the brain copes with managing two languages, followed by how this experience is posited to be beneficial to cognitive control. Additionally, the variability in a bilingual's experiences, which we refer to as the extent of bilingualism balance, and the research on its impact on cognitive control is discussed.

How Does the Brain Manage Two Languages? Review of Current Theories

There have been a number of theories proposed to explain how multiple languages are represented and managed in the mind. For this thesis, we focus on theories proposed by Green and colleagues. Their work has been developed and refined over the years, and are influential in the field of bilingualism and cognition. We briefly address some of the earlier theories before elaborating on the Adaptive Control hypothesis (Green & Abutalebi, 2013), one of the main theories around which this thesis is centered.

Earlier Theories. At the foundation, it has been found that bilinguals have both languages constantly activated in their minds, to some degree. Behavioural studies (e.g. Colomé, 2001; Marian & Spivey, 2003) as well as neuroimaging studies (e.g. Martin, Dering, Thomas, & Thierry, 2009; Thierry & Wu, 2007) have consistently shown interference effects of bilingual participants' non-target language, indicating that there is joint activation of bilinguals' languages even in contexts where only one language is necessary.

The inhibitory control model was an early model proposed to address the control of language systems in a bilingual (Green, 1986). With regards to bilingual language interference, it was theorized that competition between word activations in a bilingual's mind is resolved by inhibiting any active, non-target language competitor. When speaking in one language, the activation of this target language and inhibition of the non-target language co-occurs. In a later update of the model (Green, 1998), the author suggested that there was a Supervisory Attentional System in the brain that was involved in a variety of processes in this model, including suppression of non-relevant language, as well as modification and monitoring of language task goals.

Abutalebi and Green (2007) subsequently proposed a single network model, in which they used functional neuroimaging and identified cortical and subcortical structures involved in the control of languages in a bilingual, which include the prefrontal cortex, anterior cingulate cortex (ACC), the inferior parietal lobule, and the basal ganglia (details on each structure will be presented under the Adaptive Control hypothesis). They established that there was one common neural network that served both languages, and controlling output in two different languages involved competing representations. Hence, they once

again highlighted the role of inhibition in the process of language selection and control. Using the illustration of lexical retrieval, upon activation, an interlinked web of representations to which a particular lexicon is connected to will be stimulated, of which only a small group of these are directly goal relevant. Hence, the inhibition of unnecessary peripheral concepts is essential to control the output, and this occurs not only within but also between languages. One important contribution of this proposed model was the role of the proficiency of the weaker language in the operation of this network; an increase in proficiency would see a shift of processing from a more controlled one to a more automatic one, which would then be associated with less prefrontal activity. When a speaker with low proficiency in one language (and much higher proficiency in the other) tries to engage in speech in the weaker¹ language, unnecessary lexical items from the dominant language provide high levels of competition, and hence controlled, rather than automatic, processing is engaged to deal with this conflict, showing activation in the prefrontal cortex. With growing proficiency in the weaker language, the speaker may be less in need to use such controlled processing due to reduced competition from the dominant language, resulting in more automatic processing and less prefrontal activity. More details will be provided in a later section on variability in bilingualism and its cognitive implications.

The Adaptive Control Hypothesis. More recently, acknowledging that the contexts in which bilinguals use their two languages would affect the

¹ In the literature, the non-dominant language is often denoted with “L2” and the dominant language with “L1”. However, in the present paper, we will refer to the two languages as the “weaker” and “dominant” language respectively. This is because the terms “L1” and “L2” also contain cultural inferences, which are not so clearly defined in our participant population – due to education policies, most ethnically Chinese children in Singapore are English dominant, with lower proficiency in Mandarin-Chinese despite simultaneously acquiring both languages.

cognitive processes involved, Green & Abutalebi (2013) proposed the Adaptive Control hypothesis. This hypothesis builds upon previous models, and includes three interactional contexts that they identified to be varying in the demands placed on the cognitive control processes. Depending on the context, the cognitive processes adapt in order to fulfill the relevant demands. They also identified eight cognitive control processes involved in the three contexts, compared the relative demands of these processes in the three contexts, and identified some of the neural bases involved in these processes.

Firstly, the Adaptive Control hypothesis (Green & Abutalebi, 2013) differentiated between three distinct interactional contexts: (1) a *single language context* in which one of the bilingual's languages is used in one situation and the other is used in a different situation; (2) a *dual language context* where both languages are used in the same setting but typically when interacting with different speakers, which results in language switching between but not within sentences; and (3) a *dense code-switching context* in which a complex interweaving of both languages occur in a single sentence, with the replacement of words from one language into the sentence structure of the other.

Secondly, they highlighted eight cognitive control processes involved when a bilingual is in conversation. The speaker must first maintain the goal of speaking in one language and not the other (*Goal maintenance*). To do so requires one to control irrelevant interference. This entails two aspects: monitoring of conflicting information (*Conflict monitoring*) and suppression of such interference (*Interference suppression*). Also, in dual-language situations, being able to detect important cues (*Salient cue detection*), such as who is about

to speak in what language, is essential to having successful conversation. When switching languages, the speaker needs to inhibit the previously spoken language (*Selective response inhibition*, as well as *Task disengagement*) and allow the new language to the forefront (*Task engagement*). For speakers who code-switch frequently, a process of locating where one could adapt relevant parts of a language into another (*Opportunistic planning*) is also involved. Some neural structures were identified to be involved in the linguistic control process; a subsequent review in Abutalebi and Green (2016) presented experimental support for these neural bases. In dual language contexts, a network including the left prefrontal cortex, left and right inferior frontal cortices, parietal cortices, anterior cingulate cortex (ACC), presupplementary motor area, thalamus, and basal ganglia are heavily engaged. In dense code switching contexts, an additional pathway between the cerebellum and left prefrontal cortex is engaged. Specifically, Abutalebi and Green (2016) highlighted a few areas: the ACC as an area associated with conflict monitoring, resolution and language switching; parts of the left prefrontal cortex such as the left inferior frontal gyrus on controlling interference; the right inferior frontal cortex with response inhibition; the parietal cortices with short-term memory and language selection; as well as the thalamus and parts of the basal ganglia (left caudate and putamen) for language selection and production.

Linking the two, the authors proposed how the cognitive processes and their differences in the three interactional contexts would result in varying demands on each process for a bilingual, as compared to a monolingual speaker in a monolingual context. Specifically, it was suggested that the (1) single

language context would increase demands on only goal maintenance, conflict monitoring and interference suppression; (2) dual language context would increase demands in all processes except opportunistic planning; and (3) dense code-switching would increase demands only in opportunistic planning. Hence, dual language situations would be the most demanding, followed by single language and finally dense code-switching. Table 1 includes a summary of the differences. These differences also prompted the authors draw attention to the importance of taking into account language context when designing experimental tests, since it was important to ensure that the study design would allow for cognitive processes of interest to be adequately activated.

Table 1

Summary of the Adaptive Control hypothesis: Control Processes, the Associated Neural Areas, and Relative Demands of Each Context on the Processes

Control Processes	Associated Neural Areas	Interactional Contexts		
		Single language	Dual language	Dense code-switching
Goal maintenance	Network including left PFC/IFC, parietal cortices, ACC, pre-SMA, right IFC, thalamus, and basal ganglia	Increased	Increased	Equal
Conflict monitoring		Increased	Increased	Equal
Interference suppression		Increased	Increased	Equal
Salient cue detection		Equal	Increased	Equal
Selective response inhibition		Equal	Increased	Equal
Task disengagement		Equal	Increased	Equal
Task engagement	Cerebellar-left prefrontal connection	Equal	Increased	Equal
Opportunistic planning		Equal	Equal	Increased

Note. PFC = prefrontal cortex ;IFC = inferior frontal cortex; ACC = anterior cingulate cortex; pre-SMA = presupplementary motor area. (Adapted from Green & Abutalebi, 2013)

After identifying the different processes and varying demands on each process depending on the context, the authors rationalized that in order to interact successfully with minimal effort, the cognitive control processes are required to adapt so as to be successful across the different contexts, hence the “adaptive” component of the hypothesis. To illustrate, in a single language context, if a bilingual repeatedly switches into their other, non-relevant language, it would be highly disruptive to the conversation. Hence there is a demand to adapt the processes of goal maintenance, conflict monitoring and interference suppression, but less of cue detection, response inhibition, task disengagement, engagement and opportunistic planning, since there is no explicit exposure to or use of the other language. In a dual language context, the demands are more than in the single language context, and hence the adaptive response is also more complex. The speaker must maintain the goal of speaking in the language at hand, manage conflict and suppress interference of the other language, but also be able to switch languages in the event that they detect a need to (such as the entrance of a new conversant), which entails inhibiting the previous language, disengaging it and engaging the new one. Less demand will be required for opportunistic planning, since code-switching is unlikely to be useful in this context. Lastly, in the dense code-switching context, the demand is to adapt to the process of opportunistic planning in order to ensure successful code-switching, for reasons such as trying to fit in with the community of speakers. In such context when there is no need to clearly differentiate between the two languages, demands are reduced for the rest of the control processes.

Does Bilingual Experience Benefit General Cognitive Control?

Given the bilingual experience, it is suggested that the demands of engaging these cognitive circuitry in order to manage the two language systems will result in neural changes in the relevant regions; additionally, the more a particular circuitry is engaged, the more neural changes are expected to occur (Abutalebi & Rietbergen, 2014). These changes could be manifested in several ways. Neurally, changes would include increases in grey matter density reflecting greater structural capacity, increases in responsiveness of neurons, and/or increases in white matter connectivity indicating better connectivity in the network (Green & Abutalebi, 2013). Some studies have supported this; compared to monolinguals, bilinguals have increased grey matter in some of the regions involved in language control, with grey matter density correlated with L2 proficiency (Abutalebi et al., 2012; Della Rosa et al., 2013; Pliatsikas, Johnstone & Marinis, 2014).

Behaviorally, tests that measure the relevant cognitive processes, both in linguistic and non-linguistic domains, should show better performance (e.g. higher accuracy, faster reaction times, smaller switch costs etc.) due to the bilingual experience. Research in this area has increased extensively in the recent years (Bialystok, 2017). Specifically, many researchers have compared monolinguals and bilinguals – taking them as homogenous, separate groups – and compared their performance on an extensive list of executive function² tasks, to mixed findings.

² We define executive function (EF) as an umbrella term for cognitive control processes required for goal directed behaviour, which includes problem representation, planning of action, and behavioural control, in order to fulfill a task demand (Zelazo, Qu, & Müller, 2005). In the present thesis, it is considered a subset of cognitive control. EF is often distinguished into three components (Friedman et al., 2008): inhibitory control (the ability to inhibit prepotent responses), cognitive flexibility (flexibly switching between tasks or

Some studies have found a bilingual advantage on executive functioning tasks as compared to monolinguals (reviews in Adesope, Lavin, Thompson & Ungerleider, 2010; Barac, Bialystok, Castro, & Sanchez, 2014; Bialystok, 2017; Bialystok, Craik, & Luk, 2012; Hilchey & Klein, 2011). Specifically in children, there have been bilingual advantages found on an extensive list of tasks, including tests of inhibitory control such as the flanker task (Poarch & Bialystok, 2015), the Attention Network Task (ANT; Poarch & Van Hell, 2012; Yang, Yang, & Lust, 2011), and the Simon task (Martin-Rhee & Bialystok, 2008; Poarch & Van Hell, 2012); tests of cognitive flexibility such as the Dimensional Change Card Sorting task (DCCS; Bialystok, 1999; Carlson & Meltzoff, 2008; Kalashnikova & Mattock, 2014), and the ambiguous figures task (Wimmer & Marx, 2014); as well as tests of working memory (Morales, Calvo, & Bialystok, 2013). In order to address concerns regarding how monolinguals and bilinguals from different countries might fundamentally differ and hence overinflate bilingualism as a factor, some studies incorporated multiple monolingual or bilingual populations to account for this (Bialystok & Viswanathan, 2009; Yang, Yang, & Lust, 2011). For example, Yang, Yang and Lust (2011) compared Korean–English bilingual four-year-olds to three monolingual groups: English and Korean monolinguals in the U.S. and another Korean monolingual group in Korea. The purpose of the study was to distinguish the effects of the bilingual advantage from the effects of culture. It was found that the bilinguals performed most accurately and quickly among all the groups on the Attention Network Task (ANT). Although they did find a culture effect, in which Korean monolinguals from Korea performed slower but

mental sets), and updating working memory (monitoring incoming information relevant for task at hand and appropriately replacing irrelevant information).

more accurately than the monolingual groups from the U.S., the bilinguals outperformed all of them, showing that the bilingual advantage was greater than the culture effect.

However, there were difficulties in trying to theoretically account for all the differing aspects of executive function that seem to be advantageous in bilinguals and not monolinguals. No single theory, such as those regarding inhibition (Green, 1998), monitoring (Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009), working memory (Morales, Calvo, & Bialystok, 2013), or cognitive flexibility (Prior & Gollan, 2011) seemed to be able to fully explain and account for the diverse findings.

Additionally, there are some who remain unconvinced of the bilingual advantage, due to inconsistent findings (reviewed in Hilchey & Klein, 2011), small sample sizes and lack of convergent validity in executive functioning tasks (Paap & Greenberg, 2013; Paap & Sawi, 2014), as well as insufficient control over confounding variables such as socioeconomic status (Morton & Harper, 2009) and non-verbal intelligence (Rosselli, Ardila, Lalwani, & Velez-Urbe, 2015). A study conducted by Antón et al. (2014) recruited 180 bilingual children between 7-12 years old and 180 monolinguals matched on various demographic variables, and compared their performance on the Child-ANT. They did not find any significant differences on any of the ANT performance indices between bilinguals and monolinguals, even though general performance on the task was consistent with expectations that the incongruent condition would result in more inaccuracies and slower responses than the congruent condition. Hence, they concluded that the bilingual advantage in children is non-existent or highly elusive.

To consolidate the mixed findings to explain why different studies seem to identify advantages across different mechanisms in executive function (e.g. inhibition, cognitive flexibility, or working memory), Qu, Low, Zhang, Li, and Zelazo (2015) propose that the bilingual advantage is context-dependent. In a similar line to the Adaptive Control hypothesis (Green & Abutalebi, 2013), they suggest that bilinguals allocate cognitive resources towards their goal, thus the bilingual cognitive advantage can manifest itself in different ways depending on the task demands; bilingualism may facilitate performance even when the task does not require inhibition. In their study, bilinguals displayed advantages in areas where the task demands were highest; being faster at suppression when the task required more suppression than activation, and being faster at activation when suppression was not needed (Qu et al., 2015). The variability in bilingualism advantage presented in the literature could thus be an effect of differing contexts triggering different task demands.

Additionally, a new perspective was proposed by Bialystok (2015, 2017), of which the attention system is posited to be the mechanism underlying how bilingual experience might improve executive function. Bialystok (2015, 2017) put forward that, given that bilinguals seem to outperform monolinguals in cognitive tasks even at pre-verbal ages (found as young as 6 months of age, in Singh et al., 2015), the bilingual experience may cause a change in the way that attention is directed to the environment. Since young, bilinguals are exposed to the presence of two languages, which involve two differing sets of linguistic components and facial configurations. The differences in the systems create contrasts, which draws attention to result in greater processing than similarity. Hence, the need for increased attention results in both the

improvement of attention and the creation of complex representations of two languages in the bilingual's mind. Instead of the inhibition perspective of suppressing the non-target language, this theory suggests that upon joint activation of both languages, attention, together with a general selection mechanism, is recruited to select the relevant language and to avoid interference. Since attention control underlies all of the executive functioning tasks, this proposal does not endorse a particular component of executive function being the mechanism underlying the bilingual advantage, but would suggest a more generalized overall cognitive process that acts on both facilitation and inhibition. Hence, it could possibly explain the diverse findings in the literature on the bilingual advantage across different executive functioning mechanisms. More details about attention and how one's extent of bilingualism is expected to relate to it will be covered in a later section.

Also, some researchers have identified the lack of homogeneity within bilingual groups being examined in previous research as one of the reasons behind contradictory findings. Commentaries by Baum and Titone (2014) as well as Valian (2015) have suggested that the bilingualism is complex and more has to be done to identify the specific experiences that contribute to the mechanisms that possibly underlie the differences in cognitive processing between monolinguals and bilinguals. Baum and Titone (2014) also suggest that instead of using the monolingual-bilingual dichotomy, the field should adopt a "neuroplasticity" view towards bilingualism, reframing bilingualism as an experience that would, taking into account its individual variances between bilinguals, gradually affect cognitive control and subsequently performances in executive functioning.

For this reason, in the following section, we discuss recent research that has attempted to account for the extent of bilingualism, and its relation with cognitive control.

Bilingualism Balance and its Association With Cognitive Control

Bilingualism is not categorical; the experiences associated with being bilingual are complex and dynamic, making it difficult to quantify the extent of one's bilingualism (Luk & Bialstok, 2013). Although no objective criteria have been set up to measure the extent of bilingualism, there is some consensus that measuring the extent of bilingualism involves some combination of information on language proficiency and usage of both languages (Bialystok & Barac, 2012; Luk & Bialystok, 2013; Prior & Gollan, 2011). Unsurprisingly, studies have differed on the way they operationalize bilingualism and the extent of it. Here, we focus on bilingualism balance³ in proficiency, or the extent to which a bilingual has comparable proficiency in both of his languages (Weber, Johnson, Riccio, & Liew, 2016). In the present thesis, we use proficiency, measured by receptive and expressive vocabulary size, as measures analogous with amount of linguistic exposure and production respectively. Our focus on proficiency is driven by research suggesting that proficiency in bilingual children is well correlated with amount of linguistic exposure (Place & Hoff, 2015, Thordardottir, 2011) and use (Bedore et al., 2012). Although a distinction is sometimes made between bilingual proficiency and usage in adult bilinguals (Luk & Bialstok, 2013), for young children in the process of learning two languages, proficiency is highly associated with active bilingual usage; children

³ Some papers refer to the relative proficiency between the two languages as language dominance (Bedore et al., 2012; Gathercole & Thomas, 2009)

often respond in the language they are spoken to, and it is unlikely for children to have high proficiency in a language they do not use often. Proficiency is also expected to play a significant role in explaining the relationship between bilingualism balance and cognitive control (elaborated in the next section). We acknowledge that the individual's cognitive propensity towards language mastery does also contribute to one's proficiency. However, we treat such individual cognitive differences as a random effect across the population, and use other related measures (specifically intelligence, in the present thesis) as proxy measures to account for it in our analyses when necessary.

Comparable proficiency in both languages of a bilingual is primarily driven by proficiency in the weaker language, and how similar it is to the proficiency of the dominant language. Hence, a more-balanced bilingual would be defined as one with very similar proficiencies in both languages, while a less-balanced bilingual would be one with much better proficiency in the dominant language, and much lower proficiency in the weaker language.

Theoretically, how would bilingualism balance relate to cognitive control? Here we present two perspectives. The first perspective is in line with the view that inhibitory control is the key mechanism behind how a bilingual's proficiency in the weaker language is related to cognitive control. However, inhibitory control alone is insufficient to explain some of the findings in the previous studies that compare more and less-balanced bilinguals on different executive functioning tasks. Hence, we propose a second perspective. Based on the importance of context highlighted in the Adaptive Control hypothesis (Green & Abutalebi, 2013), together with Bialystok (2015, 2017)'s proposal on the role of attentional control, this perspective accounts for other non-inhibitory

processes involved in the management of two languages, as well as the differing contexts in which bilingualism may impact on cognitive control.

Previous perspective: Inhibition based. Bilingualism balance is driven strongly by proficiency of the weaker language; to become a balanced bilingual, one would need to improve the proficiency of the weaker language to a level comparable to that of the dominant language. When the weaker language is at a low proficiency, engaging it is an effortful task. This is because concepts and words are weaker in connection, and there may be uncontrolled interference from the dominant language that needs to be inhibited (Abutalebi & Green, 2007). Hence, over time, as one improves the proficiency of the weaker language, there is also increased engagement in these suppressions. This results in functional changes in parts of the brain that are also involved in cognitive control. Some neuroscience studies have examined how differences in proficiency of the weaker language is related to neural changes, with the finding that an increase in proficiency in the weaker language is related to an increase in grey matter density in the left inferior parietal lobule, which has also been found to be related to better cognitive control task performance (Mechelli et al., 2004; Della Rosa et al., 2013). There have also been behavioural studies that have found an inhibitory control advantage for more-balanced bilinguals over less-balanced bilinguals. Table 2 presents a summary of some of the research comparing bilingual balance and cognitive control in children; several studies have found significant differences for different bilingual proficiencies on inhibition tasks such as the Simon task (Tse & Altarriba, 2014) or the flanker task (Bialystok & Barac, 2012).

However, this inhibition perspective is insufficient in explaining all the findings in Table 2. There are studies that have found better performance of more-balanced bilinguals over less-balanced ones in other cognitive control areas such as cognitive flexibility (e.g. Vega & Fernandez, 2011). Hence, we propose this new attention-based perspective that also focuses on the importance of context (drawing insight from the Adaptive Control hypothesis), from which to understand differences between bilinguals of differing proficiencies and the effect on cognitive control.

Proposed perspective: Contextual-based Attention Control. One of the assumptions underlying the Adaptive Control hypothesis is that the bilingual speakers are equally and highly proficient in both their languages (Green & Abutalebi, 2013, p. 525), hence the cognitive adaptations are said to be stable, with no reference to proficiency. However, this is unlikely to be the case for most bilinguals; there is usually a more dominant language and a weaker language. We posit here that differences in proficiencies result in differences in cognitive adaptations proposed in the hypothesis, with more-balanced bilinguals who have greater proficiency in their weaker language having already attained a greater amount of cognitive adaptive control. This is due to them having already undergone the process functionally adapting their brains in relation their environmental linguistic contexts, hence leading to them having better cognitive task performances in the studies presented previously.

To illustrate, a less-balanced bilingual, by virtue of the lower proficiency in their weaker language, is unlikely to be exposed much (whether by choice or by circumstances) to their weaker language. It is likely that the less-balanced bilingual is spending most of their time with their dominant

language, whether in a purely single language context, or a mixed⁴ but mostly dominant language context. The more-balanced bilingual would then, in comparison to the less-balanced bilingual, spend more time in either single, weaker language contexts, or more equally-mixed language contexts. We will first consider the case of comparing differently balanced bilinguals in single language contexts.

Comparing across purely single language contexts, the less-balanced bilingual has less exposure to, and correspondingly lower proficiency, in their weaker language as compared to the more-balanced bilingual. With lowered proficiency, the less-balanced bilingual experiences more interference from their dominant language when accessing concepts in their weaker language (Abutalebi & Green, 2007). Hence, in line with Bialystok (2015, 2017)’s proposal, more attention is needed to monitor for and select the weaker language when the context demands it. With increased proficiency, less attentional control would be needed in the same context, as the increased proficiency is likely to result in more automatic processing of the language, hence requiring less conscious cognitive effort. The more-balanced bilingual would thus have undergone this process of increased proficiency and its resultant decrease in conscious effort of attention control when dealing with this language. Some support for this can be found in fMRI research looking at neural activity differences when less and more-balanced bilinguals listen to

⁴ We consider mixed languages context as including dual language context and other contexts where both languages are used towards the same speaker, in a conscious way. The Adaptive Control hypothesis also identifies a dense code-switching context. However, we do not consider it here, as the context is assumed to be one where both languages are in a co-operative (as opposed to competitive) relationship with each other (Green & Abutalebi, 2013). Hence, this context is likely to refer to code-switching that uses language change freely with less cognitive restrictions, and such context is less likely to result in cognitive “training” from linguistic experience.

their weaker language; less-balanced bilinguals engage brain areas associated with attention, working memory and monitoring, while more-balanced bilinguals engage areas associated with sensory and semantic processing (Archila-Suerte, Munson & Hernandez, 2015). Therefore, the more-balanced bilingual is expected to be better in cognitive control as compared to the less-balanced bilingual, since the former has gone through the process of improving the efficiency of their attentional control while the latter has yet to do so. This is in line with the previously described neuroimaging studies showing increased grey matter (e.g. Della Rosa et al., 2013) and decreased prefrontal activation (summarized in Abutalebi & Green, 2007) with increased proficiency in the weaker language.

Next, comparing across mixed language contexts, it is expected that the less-balanced bilingual is exposed to more of their dominant language even in the mixed languages context, as compared to the more-balanced bilingual, who is likely to have a relatively greater amount of their weaker language in the language mixture. Since more-balanced bilinguals are exposed to situations where they need to monitor for the presence and transition of two languages more often than less-balanced bilinguals, consistent with Bialystok (2015, 2017), the need for increased monitoring and other attentional control mechanisms would result in the improvement of attention over time. Assuming this contextual adaptation causes functional changes in the brain, the more-balanced bilinguals are expected to perform better on cognitive control tasks than the less-balanced ones.

Additionally, because our proposed perspective places emphasis on the different contexts in which bilingual interaction occurs, it suggests that by

increasing exposure towards the weaker language, whether in single or mixed language contexts, less-balanced bilinguals may show better attentional control due to the increased demands of the contexts. Because the context increases the attentional demand, the less-balanced bilingual is forced to engage more attention control in the interaction; subsequently, the effort may carry over to other successive tasks. Conversely, if a more-balanced bilingual is put into a single dominant language context, the decreased demand in the context (as compared to a mixed language one) may result in less cognitive effort engaged, and this reduction in necessary effort may also carry over to subsequent tasks. This is the premise upon which we designed Study 3 of the current thesis; more details will be presented in Chapter 5.

In the next section, we present studies that have been previously conducted to examine bilingualism balance and several aspects of cognitive control, with a particular focus on child studies. This is due to the age-related differences expected in the relationship between bilingualism and cognitive control (Bialystok, 2017).

Previous studies. Some studies have found better performance in cognitive control tasks for more-balanced bilinguals as compared to less-balanced bilinguals, although results vary depending on the task (Bialystok & Barac, 2012; Nicolay & Poncelet, 2015); Sorge, Toplak & Bialystok, 2017; Tse & Altarriba, 2014; Vega & Fernandez, 2011; Videsott et al., 2012). In the summary table (Table 2), all of the studies presented are conducted with child participants, with the exception of Yow & Li (2015), which was conducted with young adults but are from the same population as those in our study, hence it was included for reference. Due to the difficulty in measuring language

proficiency and, by extension, bilingual balance, studies have varied in their methods of measuring as well as comparing (categorically or continuously) between bilinguals in their study. Thus, the summary table also identifies the methods and types of comparisons used in the different studies.

We detail three previous research papers in particular that have influenced the studies in this thesis.

The study by Bialystok and Barac (2012) was one of the first to adopt a continuous variable approach to study the degree of bilingualism and its effect on cognitive control performance in children. The authors recruited bilingual English-Hebrew eight to nine year olds, who had spent varying amounts of time in immersion education and hence varied in the extent of bilingualism. They created a composite score of the extent of balance of bilingualism, by calculating second language receptive vocabulary scores divided by first language receptive vocabulary scores, to form a ratio. They found that, after controlling for age, non-verbal intelligence and first language receptive vocabulary, performance on a flanker task was predicted by the extent of balance of bilingualism and the amount of time spent in immersion education. They concluded that the extent of bilingualism was related to cognitive control task performance, with the more-balanced bilinguals performing better than the less-balanced ones.

Poarch and van Hell (2012) adopted a categorical approach to comparing bilingual balance, comparing groups of German monolinguals, second language learners of English, German-English bilinguals, and German-English-Other language trilinguals. Participants were between five to eight years old, and cognitive control was measured using the Simon task in Study 1

and Attention Network Test (ANT) in Study 2, both used to test inhibitory control. For the Simon task, results showed that in terms of the Simon effect (difference in performance between congruent and incongruent trials), monolinguals had significantly larger Simon effect compared to trilinguals, but no other pairs of group differences were significant. For the ANT, the most significant finding was that the second language learners exhibited a larger conflict effect (difference in performance between congruent and incongruent trials) than either the bilinguals or trilinguals. The conclusion was that because the second language learners were still in the process of acquiring their new language, the cognitive control benefits accredited to bilinguals were possibly not yet accrued.

The study by Thomas-Sunesson, Hakuta, and Bialystok (2016) compared how the degree of bilingualism related to the performance on cognitive control tasks in Hispanic children in the USA, given that these children were from a low socioeconomic background. Spanish-English bilinguals between eight to nine years old were measured on their receptive vocabulary in both languages to determine their extent of bilingualism balance, which was operationalized as the numerical difference between the two scores. They also completed a measure of conflict resolution (flanker task), a measure of response inhibition (stop-signal task), and a measure of working memory (frog matrices). Consistent with previous research comparing bilinguals and monolinguals on these tasks, there was no significant relationship found with the stop signal task, but extent of bilingualism was positively related to performance on the flanker and frog matrices task. The authors concluded that regardless of socioeconomic background, bilingualism seems to provide an

additive effect on cognitive control, with more-balanced proficiency in both languages relating to better cognitive control.

The studies summarized in Table 2 generally show a trend of more-balanced bilinguals (in some studies simply known as bilinguals) performing better on various cognitive control tasks than less-balanced bilinguals (or second language learners). Some studies have included monolinguals for comparison, but only one study (Nicolay & Poncelet, 2015) found a significant difference in cognitive control task performance between monolinguals and less-balanced bilinguals. The findings highlight the importance of taking into account the balance of the bilinguals when trying to compare performance on cognitive tasks, whether between monolinguals and bilinguals or only within bilinguals. Additionally, a few studies categorized their participants into two different groups representing two different extents of bilingualism balance (Poarch & van Hell, 2012; Prior, Goldwasser, Ravet-Hirsh, Schwarz, 2016; Vega & Fernandez, 2011), but usually split using the median or some arbitrary value, making comparisons across studies difficult. As with forcefully categorizing any continuous variable, variations in the data are lost, and the split point becomes inflated in importance as compared to every other value. Hence, it is important to treat bilingualism balance as a continuous variable, as the more recent studies have done (e.g. Sorge, Toplak, & Bialystok, 2017; Weber, Johnson, Riccio, & Liew, 2016). However, what is the best way to measure bilingualism balance on a continuum? We cover this in the next section.

Table 2

Summary of Previous Research on Bilingualism Balance and Cognitive Control

Paper	Age of Participants	Sample Size	Languages	Bilingual Balance: Categorical or Continuous?	Extent of Bilingualism Measured by?	Cognitive Control Tasks	Key Findings
Bialystok & Barac (2012)	8-11 year olds	Study 1: 100; Study 2: 80	English, Hebrew	Continuous (Immersion program)	PPVT ratio (L2/L1), years in immersion school	Metalinguistic task, flanker, color-shape switch	<ul style="list-style-type: none">• Metalinguistic tasks: Related to PPVT scores• Flanker: Related to balance and/or time in immersion school• Color-shape switch: No sig. results
Carlson & Meltzoff (2008)	6 year olds	50	Spanish, English, some Japanese	Categorical (BL, Immersion, ML)	Group categorization according to criteria	Advanced DCCS, Simon Says, Visually cued recall, Kansas Reflection/Impulsivity Scale, Comprehensive Test of Nonverbal Intelligence (C-TONI), ANT, Delay of Gratification, Statue, Gift delay with cover	<ul style="list-style-type: none">• Composite score of all tasks: BL better performance than immersion and ML• BL better than immersion on Visually cued recall• BL better than ML on Advanced DCCS• Items combined into a Conflict subscore (first 6 tests of previous column) showed BL better than both immersion and ML• No group differences for other 3 tasks combined into Delay subscore

Paper	Age of Participants	Sample Size	Languages	Bilingual Balance: Categorical or Continuous?	Extent of Bilingualism Measured by?	Cognitive Control Tasks	Key Findings
Crivello et al (2016)	Time 1: 24 month olds; Time 2: 31 month olds	92	English, French	Both - Categorical (BL vs. ML); Continuous (Compare within BL)	No. of translational equivalent vocabulary (Tested by MacArthur Communicative Development Inventory)	Conflict tasks (Reverse Categorization task & Shape Stroop task), Gift Delay, Response control, WM task (Multilocation task)	<ul style="list-style-type: none"> • Within bilingual sample, increase in translational equivalent vocab over time related to increased post conflict trial accuracy • No sig. results for gift delay and multilocation
De Cat, Gusnanto, Serratrice (2017)	5-6 year olds	174	English, various other languages	Both - Categorical (BL vs. ML); Continuous (Compare within BL)	Bilingualism Profile Index (survey created by authors)	Digit Span (Forward and Backward), DCCS card version, Simon task	<ul style="list-style-type: none"> • Digit span & DCCS: No sig. results • Simon task: Overall, BL performed better than ML (No Simon effect differences) • Amount of bilingualism experience positively related to Simon task performance
Nicolay & Poncelet (2015)	Time 1: 5 year olds; Time 2: 8 year olds	101	French, English	Categorical (ML vs. Immersion)	Both time points: EOWPVT (Expressive One-Word Picture Vocabulary Test), Receptive vocab with BPVT (British Picture Vocabulary Test)	Both time points: KITAP (Test for Attentional Performance in Children) - Alerting, Auditory Selective Attention, Divided Attention, Mental Flexibility	<ul style="list-style-type: none"> • Immersion group better on alerting, auditory attention, divided attention & flexibility than ML, despite being unbalanced BLs

Paper	Age of Participants	Sample Size	Languages	Bilingual Balance: Categorical or Continuous?	Extent of Bilingualism Measured by?	Cognitive Control Tasks	Key Findings
Poarch & Bialystok (2015)	8-11 year olds	203	English, various other languages	Categorical (ML, partially BL, BL, TL)	LBSQ survey	Modified Flanker task	<ul style="list-style-type: none"> • BL & TL faster than partial BL & ML at trials with conflict • No sig. difference between BL & TL, and partial BL and ML
Poarch & Van Hell (2012)	5-8 year olds	Study 1: 75, Study 2: 56	German, English, various other languages	Categorical (Study 1: ML, BL, TL, L2 learners; Study 2: L2 learners, BL, TL)	Test for Reception of Grammar	Simon task, ANT	<ul style="list-style-type: none"> • Simon task: TL smaller Simon effect than ML, BL marginally smaller than ML • ANT Conflict: BL & TL less conflict effect than L2 learners;
Prior, Goldwasser, Ravet-Hirsh, Schwarz (2016)	Study 1: 4-5 year olds; Study 2: 10 year olds	Study 1: 60; Study 2: 90	Russian, Hebrew	Categorical (Balanced BL, Unbalanced BL, ML) - Using median split of difference in vocabulary scores	All in both languages - Study 1: PPVT, Expressive vocab (MacArthur Communicative Development Inventory); Study 2: PPVT only	Study 1: Flanker, DCCS cards version Study 2: Flanker	<ul style="list-style-type: none"> • Study 1: No sig. results • Study 2: Balanced BL less conflict from flanker than ML, unbalanced BL perform in the middle but no sig. difference

Paper	Age of Participants	Sample Size	Languages	Bilingual Balance: Categorical or Continuous?	Extent of Bilingualism Measured by?	Cognitive Control Tasks	Key Findings
Sorge, Toplak, & Bialystok (2017)	8-11 year olds	208	English, various other languages	Both - Categorical (Grouped those reported to be almost ML vs more BL); Continuous (within those who were more BL)	31 survey items on language use at home	Strengths and Weaknesses of Attention-Deficit/Hyperactivity Disorder Symptoms and Normal Behavior Scale (SWAN), Stop signal, Flanker, Frog matrices (working memory)	<ul style="list-style-type: none"> Stop signal task performance was related to attention more than bilingualism Accuracy on flanker was related to both attention ability and bilingualism Performance on the frog matrices was related to bilingualism only
Thomas-Sunesson, Hakuta, & Bialystok (2016)	8-9 year olds	64	Spanish, English	Continuous (Difference in vocabulary scores)	PPVT (English), Test de Vocabulario en Imagenes Peabody (TVIP; Spanish)	Flanker, Stop-signal, Frog matrices	<ul style="list-style-type: none"> Bilingualism predicted variance on congruent and incongruent trial performance on flanker task, as well as on the frog task No findings for stop signal task
Tse & Altarriba (2014)	5-9 year olds	100	Cantonese, English	Continuous (Proficiency of L2 and the ratio of L2/L1 considered separately)	Vocabulary definition test (both languages)	Simon task, Simon switching task (Direction vs. Location trials), WM (Operation span)	<ul style="list-style-type: none"> Simon task: L2 proficiency related to goal maintenance & conflict resolution Controlling for age, L2/L1 ratio related to conflict resolution only Simon switching: No findings with L2 proficiency WM: Both L2 proficiency & age-controlled L2/L1 ratio related to task performance

Paper	Age of Participants	Sample Size	Languages	Bilingual Balance: Categorical or Continuous?	Extent of Bilingualism Measured by?	Cognitive Control Tasks	Key Findings
Vega & Fernandez (2011)	9-10 year olds	40	Spanish, English	Categorical (Group split by L1-L2 larger or smaller than 15)	English & Spanish Oral Vocabulary subtests of the Bilingual Verbal Ability Tests (BVAT)	Wisconsin Card Sorting Test (WCST), Stroop task	<ul style="list-style-type: none"> • Difference score between vocabulary tests were correlated with errors on the WCST (smaller difference, less errors) • More-balanced BL group had less errors on the WCST than less-balanced BL.
Videsott, Della Rosa, Wiater, Franceschini, & Abutaleb (2012)	10 year olds	118	Ladin, Italian, German, English	Both - Categorical (Derived from 1. Median split of total proficiency of all languages, or 2. Top and bottom quartile of L2+L3 scores); Continuous (Mean corrected total proficiency of all languages, or mean corrected L2+L3 scores)	Self-report, teachers evaluation based on school grades	ANT	<ul style="list-style-type: none"> • No sig. results with Stroop • High overall linguistic competence performed faster overall and showed smaller Alerting effect than low competence • High added linguistic proficiency (L2+L3) performed faster than low proficiency, also correlated with smaller Alerting effect

Paper	Age of Participants	Sample Size	Languages	Bilingual Balance: Categorical or Continuous?	Extent of Bilingualism Measured by?	Cognitive Control Tasks	Key Findings
Weber, Johnson, Riccio, & Liew (2016)	4-7 year olds	30	English, Spanish	Continuous (ratio of L1/L2)	PPVT, TVIP	Behavior Rating Inventory of Executive Function (BRIEF), Day-Night Stroop, Tower task, Selective attention task	<ul style="list-style-type: none"> Bilingualism balance correlated with caregiver task initiation ratings (higher balance = less difficulty in task initiation) No other sig. results on other tasks
*Yow & Li (2015)	18-25 year olds	72	English, Mandarin-Chinese	Continuous (Derived from survey)	Language use, Language proficiency, Age of acquisition (AoA)	Stroop, flanker, Number-letter switching, N-back	<ul style="list-style-type: none"> Stroop interference effect related to AoA and balanced usage Task switching mixing cost related to balanced proficiency and usage

Note. BL = Bilingual; ML = Monolingual; TL = Trilingual; L1 = First Language; L2 = Second Language; L3 = Third language; PPVT = Peabody Picture Vocabulary Test; DCCS = Dimensional Change Card Sort task; WM = Working Memory; ANT = Attention Network Test.
 * Participants were young adults (different target age), but are from the same community as those in the present thesis.

Issues in measurement. Due to a lack of consensus on how bilingual proficiency should be operationalized, there is also much debate on how bilingual balance should be determined. We briefly address some of the issues surrounding the difficulty in measurement of each of these variables and detail the reasons for the choice of methods used in the present thesis.

Measurement of bilingual proficiency. As seen in Table 2, studies have used parent/self report proficiency (Sorge, Toplak & Bialystok, 2017; Videsott et al., 2012), standardised proficiency tests in vocabulary or grammar (Bialystok & Barac, 2012; Poarch & Van Hell, 2012), or the amount of time spent in an immersion program (Nicolay & Poncelet, 2015) as proxy for the extent of one's bilingualism. This variance in methodology is due to the lack of consensus on any type of classification to account for language proficiency differences in bilinguals (Altarriba & Heredia, 2008), nor any agreement on what exactly should be used to determine proficiency in a language, due to the complexity of language systems in general (Treffers-Daller, 2011). For young children, self and parent reports can be difficult; depending on the age of the child and the amount of time a parent spends with the child, the accuracy of the reports may vary. Hence, some studies use standardized tests, often using vocabulary as a proxy to measure language proficiency. These tests aim to objectively capture an indication of the child's relative proficiency between the languages, by using tests that are comparable between the two languages. For our research, we adopt this method of using standardized vocabulary assessments as a proxy for language proficiency to determine the language balance of children within our bilingual sample.

Furthermore, two different vocabulary tests, receptive and expressive vocabulary, will be used in order to separately examine two different aspects of the language experience, language exposure and production, respectively. Studies using vocabulary assessments to measure bilingual proficiency generally include measures of receptive vocabulary such as the Peabody Picture Vocabulary Test (PPVT) to test for comprehension (e.g. Bialystok & Barac, 2012; Weber, Johnson, Riccio, & Liew, 2016). Some also include expressive vocabulary tests as a measure of communicative expression (e.g. Nicolay & Poncelet, 2015; Vega & Fernandez, 2011). However, these two aspects of vocabulary are either used to estimate language proficiency on their own, or are sometimes combined into a general score (Prior, Goldwasser, Ravet-Hirsh, Schwarz, 2016). In the present study, we examine the two separately. We consider receptive vocabulary a representation of an individual's level of language exposure, given that a high (or low) receptive vocabulary score necessitates that the individual has had substantial (or little) exposure to the language. We also consider expressive vocabulary a representation of an individual's level of language production ability, given that a high (or low) expressive vocabulary score is expected to reflect a high (or low) amount of speech produced by an individual in that language. These are assumptions that will be assessed directly in Study 1 of the present thesis. These two forms of vocabulary are separated because we believe that the two aspects of language experience (language exposure and production) as well as the level of bilingualism balance in both these aspects are differentially related to cognitive control. More details will be provided in the section describing the research aims of the present thesis.

Having acknowledged the importance of vocabulary assessments in bilingual language proficiency, in the following section, we evaluate previously used methods of operationalizing bilingual balance with such assessments and justify the method used in the present thesis.

Measurement of bilingual balance. Previous studies have calculated bilingualism balance as either simply the proficiency of the weaker language (Tse & Altarriba, 2014), the numerical difference between the proficiency scores of the two languages (Thomas-Sunesson, Hakuta, & Bialystok, 2016) or the ratio of the two scores (Bialystok & Barac, 2012; Weber, Johnson, Riccio, & Liew, 2016). We contend that some combination of both the difference and ratio score is ideal as an indicator of bilingualism balance. Firstly, the difference score refers to the pure numerical difference between the measured proficiencies of the two languages. However, the value derived does not provide us any information about proficiency of either of the two languages, and often, multicollinearity problems prevent the inclusion of one or both of the proficiency values when conducting analyses with this difference score. Given that the importance of the proficiency of the weaker language was highlighted in a number of previous studies (Della Rosa et al., 2013; Tse & Altarriba, 2014), the difference score seems to provide insufficient information about the true nature of the bilingual's language abilities. Yet, the value representing the proficiency of the weaker language alone is also not an adequate representation of bilingualism balance, since it is important to examine how the weaker language compares with the stronger one. There is neuroimaging evidence suggesting that when the proficiency of the weaker language is comparable to that of the stronger language, processing in the weaker language becomes more

automatic than controlled (summarized in Abutalebi & Green, 2007). Chee et al. (2001) found that frontal activations were higher for all bilingual participants' weaker language as compared to their dominant one, despite each half of the participants having contrasting language dominance in the same language pair; Tatsuno and Sakai (2005) found that when completing semantic tasks in the weaker language, bilinguals with higher proficiency in that language showed lower activity in the prefrontal cortex than bilinguals with lower proficiency. Thus, it is important to consider the proficiency of the weaker language in relation to the stronger one in order to adequately represent bilingualism balance. The ratio score used in previous studies takes into account this relative difference in languages, but has its shortcomings. One of the drawbacks of the ratio score is that it does not distinguish between equally high proficient balanced bilinguals and equally low proficient balanced bilinguals, since both of these individuals are balanced bilinguals and hence would have the same ratio score. There is some evidence to suggest that higher general linguistic competency may be related to better cognitive control (Videsott et al., 2012). Hence, in the present thesis, we propose to use a ratio score that marries the previous methods, quantified by calculating the difference in both languages scores divided by sum of both languages scores $[(\text{Language A} - \text{Language B})/(\text{Language A} + \text{Language B})]$. This ratio not only takes into account the difference in performance across languages (at the numerator), it also accounts for the child's general ability in language task performance (at the denominator). This ratio is similar to those used to calculate laterality in neuroimaging studies (e.g. Desmond et al., 1995). Additionally, we adopt two separate ratio values as proxy for bilingualism balance: the first score

is derived from the ratio of receptive vocabulary scores between the two languages, and the second score is from the ratio of expressive vocabulary scores between the two languages.

Furthermore, performance on vocabulary tasks often require reasoning skills, and some high proficient balanced bilinguals may perform better than the low proficient balanced bilinguals due to some underlying intelligence factor (beyond vocabulary knowledge) that may also impact any cognitive control task performance. In order to isolate the effects of bilingualism balance on cognitive control, it is important to account for these possible confounds. Thus, for the present thesis, when analyzing the relationship between bilingualism balance and cognitive control, non-verbal intelligence (reasoning skills) is considered as a control variable (as done in Bialystok & Barac, 2012), and bilingualism balance ratio is expected to relate to cognitive control task performance above and beyond these control variables.

In summary, based on the Adaptive Control hypothesis, bilingualism balance is expected to relate positively with cognitive control, with more-balanced bilinguals performing better on cognitive control tasks than less-balanced bilinguals. In the next section, we detail the specific component of cognitive control that is of interest in the present thesis: Attention.

Attention: A Key Component of Cognitive Control

“Attention serves as a basic set of mechanisms that underlie our awareness of the world and the voluntary regulation of our thoughts and feelings” (Posner & Rothbart, 2007; p. 6).

As encapsulated in the quote above, attention is a fundamental process underlying all conscious cognitive control. There is a constant demand on attentional capabilities when engaging in cognitive activities; to monitor for cues, focus on important aspects, and filter out irrelevant parts. For the present thesis, we adopt the model of attention proposed by Posner and Petersen (1990). We first introduce the attention network model and the Attention Network Test (ANT) designed to assess this network, highlight the importance of examining the attentional network in the relationship between bilingualism balance and cognitive control, then subsequently identify the aspects of the bilingualism experience that is expected to relate to the attention network.

The Attention Network Model

Following Posner and Petersen's (1990) model of attention, the attention network is theorized to involve three distinct components: alerting, orienting, and executive control. *Alerting* is defined as achieving and sustaining an alert mind; *Orienting* is the act of being selective when presented with information from sensory input; and executive control (known here on as *conflict*) refers to the ability to monitor and overcome distracting stimuli in order to carry out goal directed behaviour. These three components are traced to distinct neural anatomy and serve different functions.

The alerting system (also known as sustained attention) has been associated with activations in the frontal and parietal regions of the right hemisphere, as well as the thalamus (Fan, McCandliss, Sommer, Raz & Posner, 2002; Posner & Rothbart, 2007; Pozuelos, Paz-Alonso, Castillo, Fuentes, & Rueda, 2014). Variations in alertness is manipulated by presenting warning

signals before a target, and high levels of alertness are characterized by a maintenance of a state of readiness even when there is no warning presented.

The orienting system (also known as selective attention) activates areas of the superior parietal and temporal parietal junction (Fan et al., 2002; Posner & Rothbart, 2007; Pozuelos et al., 2014). Orienting is manipulated by presenting a warning cue at the position of the target, thus directing attention to the cued location. High levels of orienting are characterized by the ability to redirect attention to a new target location even when there is no warning cue. As highlighted by Posner and Petersen (1990), the orienting network is strongly associated with the visual system, including the ventral occipital lobe.

The conflict system (also known as executive attention) is associated with the anterior cingulate cortex (ACC), the ventral lateral prefrontal cortex, as well as the basal ganglia (Fan et al., 2002; Posner & Rothbart, 2007; Pozuelos et al., 2014). Tasks that manipulate conflict include the Stroop task and the flanker task, in which one component of the task needs to be attended to (e.g. colour of word in Stroop task; direction of central arrow in flanker task) while another (name of word in Stroop task; direction of surrounding arrows in flanker task) needs to be inhibited. High levels of conflict monitoring are characterized by the ability to perform similarly in the presence and absence of conflicting stimuli, demonstrating low interference by distractors.

The attention networks have been extensively studied in the neuropsychological literature, spanning across age groups and also in various populations with neuropsychological disorders (MacLeod et al., 2010). This three component approach to attention has allowed for studies to examine the heritability (Fan, Wu, Fossella, & Posner, 2001) and development (Rueda et al.,

2004) of attention, mainly using a test designed specially to assess the networks: the Attention Network Test (ANT). In the next section, we detail the test, as well as some studies conducted with the test that provided insight into the network independence and age-related developments of the networks of attention.

The Attention Network Test (ANT). In line with the attentional network model, Fan, McCandliss, Sommer, Raz and Posner (2002) developed the Attention Network Test (ANT), a speeded choice task that is a combination of the flanker and cued reaction time task (MacLeod et al., 2010). The original ANT, designed for adults, requires participants to determine whether a central target arrow is pointing left or right. These arrows can appear above or below a central fixation point. In some trials, flanker arrows are presented in the same or opposite direction from the central arrow. Before each arrow(s) is (are) presented, participants may see ‘cues’ as to the position of the arrows. In total, there are 12 conditions, with four cue conditions (no cue, central cue, double cue and spatial cue) and three flanker (congruent, incongruent and neutral) conditions. The three components of attention are calculated as separate attention network scores, using differences in performance (error rates and/or reaction times) when comparing across conditions. Specifically, the alerting score is derived from the difference in performance between the no cue and double cue conditions, the orienting score is derived from the difference in performance between the center cue and spatial cue conditions, and the conflict score is derived from the difference between congruent and incongruent conditions. For each of these scores, a smaller number indicates better performance.

Although the three networks contribute to the control of attention, they were originally said to be distinct in their functions (Posner & Petersen, 1990; Fan et al., 2002). In the original study introducing the ANT, Fan et al. (2002) reported no significant correlations between the three network scores representing the three attention networks. However, they did report an interaction effect between the cues and flankers, with no cue and spatial cue conditions reducing the conflict effect. Subsequent studies (summarised in MacLeod et al., 2010) also found similar interactions between cues and flankers, suggesting that the three attention networks (measured by the ANT) were not entirely independent. Fan, McCandliss, Fossella, Flombaum, and Posner (2005) identified that it was possible that the networks influenced each other in relation to other task demands, but argued that the lack of correlations between the scores and the generally distinct neural areas associated with the three networks provided support for the independence of the networks. More recently, Wang et al. (2014) suggested that the computing method for the three attention networks might also be a reason as to why there are inconsistent relationships found between the attention networks. They pointed out that in the original ANT calculations, each difference formula was averaged across several other conditions used to induce and measure other networks, hence the score is likely to be representative of the effect of more than one network. They proposed a new method of computing the three attention network scores by using specific cue-with-flanker conditions, contrasting against the original computations which averaged across multiple cues or flankers that were not of interest. They argued that using the specific cue-with-flanker conditions would make the resulting calculations purer than the original scores. They would also,

given the different permutations of attention networks inherent in the different cue by flanker conditions, be able to identify and calculate the effects of each network on each other. In their study done with young adults, they found that despite using their new calculations which were supposed to reduce inter-network relations, there were interactions found between the alerting and conflict networks, as well as the orienting and conflict networks. Taken together, the literature shows there is not yet a consensus on the independence of the three attention networks.

As for age-dependent development of the three networks, we focus on the development of the networks in young children, for the purposes of the present thesis. Rueda et al. (2004) adapted the ANT for children, by replacing the arrows with yellow fish with arrows at its belly. Animation and sound feedback upon response was also added to make it more like a game so that children could maintain interest. In the study, the authors examined developmental differences in the three attentional network scores by comparing six, seven, eight, nine and 10 year olds. They found that the network scores displayed different rates of development, with the alerting and orienting networks showing minimal change between six to 10 years of age, and the conflict network improving markedly from six to seven years of age, but remaining stable after that. In the discussion, they also alluded to tests they ran on four year-olds, who showed much larger conflict scores than the six year olds, suggesting that the conflict network begins developing before age six. Hence, it can be seen that during early childhood, the attentional networks develop rapidly. In young children, the attentional networks are also highly responsive to environmental input, and short-term training can improve

attentional control in preschoolers (Diamond, 2012; Rueda et al., 2005). For instance, Lim and Qu (2017) designed a 15 minute single-session mindfulness training for preschool children, and results showed that the mindfulness training influenced attentional scope of children in a Global-Local task. Those who were predominantly using global processing showed a decrease in such processing, and similarly those who were predominantly using local processing showed a decrease in such processing. This suggests that attention in preschoolers are highly plastic and can be changed in efficacy.

The Role of Attention in the Relation Between Bilingualism and Cognitive Control

In a review of the literature regarding bilingualism and executive functioning, Bialystok (2015) identified attention as being an essential part of all the tasks involved in the measurement of executive functioning. Similarly, attentional control mechanisms are involved in bilingual lexical access (Costa, Hernandez, & Sebastian-Galles, 2006). Hence, it is logical to link the experience of bilingualism with increased attentional control, both within theoretical boundaries and extending from previous research. In the summary table (Table 2) of the existing literature on bilingualism balance and executive functioning, although subsumed under the umbrella of executive function (and hence cognitive control), a number of studies have used the ANT (e.g. Carlson & Meltzoff, 2008; Poarch & van Hell, 2012; Videsott et al., 2012) or other measures of attention (Nicolay & Poncelet, 2015). One study, by Sorge, Toplak and Bialystok (2017), assessed eight to 11 year olds in their bilingualism balance, parent-reported attention levels and performance on three executive

functioning tasks and found that performance on a flanker task was related to both attention and bilingualism balance. Although attention in their study was reported and not measured, there are grounds to believe that bilingualism balance would relate to attentional control. Also, since the ANT is a variation of the flanker task, it would stand to reason that bilingualism balance would be related to performance on the ANT as well.

As previously described, Bialystok (2015, 2017) hypothesized that the bilingualism experience influences the attention system to adapt to the demands unique to the environment, and these adaptations subsequently appear in tests of cognitive performance. Since attention develops from a young age and is refined throughout childhood, it is able to develop together with lifelong bilingualism, which also begins at infancy.

In the present study, since we conceptualize the attention network as a component of general cognitive control, we are interested to examine how the bilingualism experience will relate to the attention network. Specifically, the components of alerting and conflict are expected to relate to the bilingualism experience. This will be detailed in the next section.

How is Bilingualism Expected to Relate to The Attention Network?

Comparing the Adaptive Control hypothesis (Abutalebi & Green, 2013), which details the cognitive aspects of bilingual language management, against the attention network model (Posner & Petersen, 1990), there are some similarities. Firstly, the alerting network seems to have some commonality with the salient cue detection step of the Adaptive Control hypothesis, since both involve being vigilant and prepared for any new stimuli. Additionally, the

conflict network seems to be involved in several of the steps in the Adaptive Control hypothesis, including conflict monitoring, interference suppression, and selective response inhibition. Furthermore, the neural areas identified to be involved in the Adaptive Control hypothesis overlap with the areas involved in the attention network: the right prefrontal, parietal cortex and thalamus for alerting, as well as the anterior cingulate cortex (ACC) and basal ganglia for conflict. Hence, we expect to see a positive relation between bilingualism balance and alerting and conflict scores of the ANT, with an increase in bilingualism balance associated with better alerting and conflict scores (smaller difference in performance between constituent cue/flanker conditions). For orienting, due to the strong involvement of the visual network, we are unable to find an association between the network and the steps of the Adaptive Control hypothesis, given that the hypothesis generally deals with speech. However, we acknowledge that there are some overlaps in the neural areas involved in orienting and the Adaptive Control hypothesis, such as the parietal cortices.

Previous studies have shown some support for the relationship between bilingualism balance and the different attention networks. Most commonly, results are found for the conflict network (e.g. Carlson & Meltzoff, 2008; Poarch & van Hell, 2012), where more-balanced bilinguals have smaller conflict scores than less-balanced bilinguals. For the alerting network, Videsott et al. (2012) found that those with higher proficiency in their weaker language displayed higher alertness than those with lower proficiency. For the orienting network, Poarch and van Hell (2012) reported finding that bilinguals perform better than second language learners, but the results mostly did not reach significance, hence their results must be interpreted with caution.

Interestingly, each of these studies have found different results with different attention networks using what is ostensibly the same ANT task, despite all comparing between varying levels of bilingual balance or weaker-language proficiency. One possibility is that the ANT itself is not a highly reliable measure; using RT as the indicator results in reliabilities of .36 for alerting, .41 for orienting, and .81 for conflict (Fan et al., 2001; MacLeod et al., 2010). Another possibility is that the measure of bilingualism balance used is different between studies and hence, each of the studies were measuring different aspects of the bilingualism experience. It is possible that different aspects of the bilingualism experience, such as the amount of language exposure or speech production in the two languages, relate separately to the different attention networks. Thus, we distinguish between two bilingual experiences, balance of language exposure and language production, and their distinct relationships with two of the components of the attention network. The details are presented in the next section describing the present research framework.

The Present Paper: Bilingualism Balance and Attention Control

After outlining the theoretical associations and previous studies linking bilingualism balance and the attention network, we are interested to examine how variations in bilingualism balance relates to differences in performance on the ANT. Additionally, we are also interested to understand the mechanism underlying bilingualism balance and attentional control; whether the our proposed contextual-based attention control perspective is viable as a mechanism to address this relation. There are three research aims in the present

thesis. Each research aim is driven by existing research gaps, and the three research aims will be addressed by three studies conducted in this thesis.

Research Aim 1: To Examine Whether Vocabulary Balance Scores Represent Actual Bilingual Language Experience

As previously mentioned in the section on issues with bilingualism measurement, there is no universally accepted operationalization of bilingualism proficiency or balance. Hence, there is also a lack of studies showing how the indices used to operationalize bilingualism balance taken from objective measures such as vocabulary tests in children actually correspond to parental reports of their child's language exposure and production. For our research, we use receptive vocabulary ratio to represent bilingual language exposure balance, and expressive vocabulary ratio to represent bilingual language production balance respectively. Study 1 directly addresses the question as to whether these scores are representative of the child's bilingual experience by comparing the vocabulary test scores and ratios with parental reported language exposure and production of each language. We expect that larger vocabulary ratio scores $[(\text{Language A} - \text{Language B})/(\text{Language A} + \text{Language B})]$, which represent more-balanced bilingualism, would correspond with higher levels of parental reported exposure and use of the weaker language, and lower levels of exposure and use of the dominant language. Hence, Study 1 provides the foundation upon which the bilingualism balance ratio will be justified for use in the subsequent study.

Research Aim 2: To Examine How Different Bilingual Balance Aspects Relate to Different Attention Networks

Based on both theoretical links and previously conducted literature, there has been evidence showing a positive relation between level of bilingualism balance and attention control. However, findings are not consistent across the different attention networks, and one possibility is that differing aspects of the bilingual experience relates differently to the attention networks. Here, to be comprehensive, we compare between more and less-balanced bilinguals in the domain of dual language contexts, since that is proposed to require the most cognitive control. We consider the seven cognitive processes highlighted in the Adaptive Control hypothesis that are used in dual language contexts, together with the three attention networks. Specifically, we identify two separate relations.

The first link we hypothesize is between bilingual balance of language exposure, operationalized in this study using receptive vocabulary ratio, and the alerting component of the ANT. We hypothesize that there is a positive correlation between receptive vocabulary ratio and alerting scores, indicating that those with more-balanced bilingual language exposure will be more alert. This is because those with more-balanced language exposure are more likely to experience varied language contexts in their surroundings as compared to the less-balanced bilinguals who are mostly in their dominant language. Even in mixed languages context, the less-balanced bilingual is expected to have a larger proportion of their context in their dominant language, while the more-balanced bilingual will have either equal or more proportion in the weaker language. Hence, more-balanced bilinguals are more likely to have greater

sustained attention or maintain a higher state of vigilance by default, due to their daily environmental demand to monitor for the presence and transition of both of their languages. They are then better able to detect and react to cues (a component of both Adaptive Control hypothesis and the alerting network) as compared to a less-balanced bilingual.

The second link we hypothesize is between bilingual balance of language production, operationalized by expressive vocabulary ratio, and the conflict network. We hypothesize that there is a positive correlation between expressive vocabulary ratio and conflict scores, meaning that those with more-balanced bilingual language production will be less likely to be distracted by conflicting information. This is due to the more-balanced bilinguals being more likely to express themselves in both languages, and from the Adaptive Control hypothesis, doing so requires monitoring for and suppression of the non-target language, as well as the inhibition of the previous language and activation of the new language in the event that a language switch is needed; all of which are processes previously highlighted to be associated with the conflict network. Less-balanced bilinguals are more likely to express themselves mainly in their dominant language, resulting in fewer occurrences of the cognitive processes identified above. Figure 1 shows a diagrammatic representation of the two hypotheses and the proposed processes behind them.

Figure 1. Overview of the hypothesized relationships in the present study.

Research Aim 3: To Examine the Mechanism Behind Bilingualism Balance and Attentional Control

Given that we find a positive relation between the level of bilingualism balance and attention control, the next step would be to identify the mechanism underlying this relation. In particular, we are interested to see if the contextual-based attention control perspective that we proposed can account for some of the relationship between bilingualism balance and attention control. To do this, we identify different language proportions that are expected to differ among bilinguals with differing balance levels. To recap, the less-balanced bilingual is likely to be spending more time in their dominant language, where demands on the language (and attentional control) processes are low. The more-balanced bilingual will spend comparatively more time in with their weaker language,

resulting in them needing to engage in more language control processes, and this also help to fine-tune the attentional control processes.

In order to examine the relevance of the different language context in this relation, instead of examining individual differences and development of bilingualism balance and attention across time, we instead use an experimental design to randomly assign participants to different language contexts in order to see if the contextual changes affect attentional control. Additionally, since each of these language contexts differ in frequency of occurrence between more and less-balanced bilinguals, inducing these language contexts also allow the induction of a particular language frame within the participants, regardless of their own level of bilingualism balance. Specifically, after being exposed to the single dominant language context (common in less-balanced bilinguals), the low demand in the context may result in reduced attentional control engaged, resulting in lower performance on the subsequent attention task. Also, after being exposed to the single weaker language context or the mixed language context (common in more-balanced bilinguals), the high demands of the context may result in increased attentional control engaged, leading to higher performance on the subsequent attention task. Two of the attention networks, the alerting and conflict networks, are expected to be involved. The specific hypotheses are listed in Study 3 in Chapter 5.

By isolating and inducing specific language contexts, it is possible to clearly examine the role of these language frames on attention control, giving an indication to the contexts that more and less-balanced bilinguals differ in that results in the different levels of ANT performance. The success of the context manipulation will also indicate the importance of context in

bilingualism balance research, as well as provide support for the contextual-based attention control perspective as underlying the cognitive processes behind how bilinguals manage two languages in the brain.

In view of the importance of language context in bilingualism research, the next section details the background of the population examined in the present thesis: Preschool children from Singapore.

Present Population: Preschoolers in Singapore

As previously mentioned, development of attention begins from a young age, and Rueda et al. (2004) found different developmental trajectories for each of the three attention networks, with some components developing minimally past age six. Recognizing this, we have chosen to study preschool children slightly younger than six years old (about five years old) to capture differences between children before development of the attention networks plateau. Preschool children have very plastic levels of attentional control (Petersen & Posner, 2012), with some previous studies showing that short-term training can improve attentional control in preschoolers (Diamond, 2012; Rueda et al., 2005). Hence, it is very likely that the bilingualism experience of these young children would have played a role in the development of their attentional control.

Preschool children are also an ideal target age group for examining the relationship between bilingualism and attentional control as they are still in the process of mastering their languages, hence attentional control is likely to be heavily involved in the language control processes. When mastery of a language has been attained, there is a reduction of activity in the prefrontal

cortex during the use of that language as the processes becomes more automatic and thus do not require much conscious control (Abutalebi & Green, 2007). Thus, the lack of mastery of their languages makes the preschool children ideal for examining the attentional control aspects behind bilingual language management.

In Singapore, English is the official language of administration. Young children in Singapore undergo mandatory bilingual education, with lessons primarily held in English, while also taking language classes in the language of their ethnicity (known as the mother-tongue). Because of this, the dominant language of most children is English. Due to the importance of English in education, some parents have opted to speak more English to their children at home, resulting in a reduction in the use of mother-tongue at home, hence a large variance in the proficiency of both languages can be found within children of the same age group, depending on their home language.

Our target population, the English-Mandarin bilinguals, are mostly of Chinese descent and are the largest ethnic group in Singapore (Department of Statistics Singapore, 2016). Most children are simultaneous bilinguals; both English and Mandarin are used in home contexts to communicate to the child, although to varying degrees depending on homes. Additionally, it is acceptable for young bilinguals to use of both of their languages depending on contexts; both of their languages are used separately in school albeit to different extents, and code switching between the two languages in casual conversation is widespread. Thus, the bilingual language environment in Singapore is more closely related to the dual language (and sometimes the dense code-switching)

context, than the single language context. For the purposes of our study, we deem our population as mainly dual language context bilinguals.

Variability in bilingualism balance proficiency between children in our population can be attributed to several factors. Firstly, there are differences in the amount of each language children are exposed to in the home environment, resulting in different proficiencies of each language. In general, there are three types of home environments: mostly English, mostly Chinese, or some mixture of two languages (including code switching). This factor of differing home language is deemed, in the present thesis, to be the largest contributor to varying levels of bilingualism balance in the population.

Secondly, there are differences in the amount of each language children are exposed to in the preschool environment, as a variation between schools. However, all preschools in Singapore function in dual language contexts; there are separate teachers who speak each of the two languages and code switching is less acceptable in school context. Additionally, on average, children are exposed to more English than Chinese, and this variation is not expected to be extremely large between schools since all preschools prepare their children for formal education, which has a fixed curriculum.

Thirdly, there are individual differences in the children's abilities to learn a language, which may be related to their general intelligence. In the present dissertation, non-verbal intelligence is measured as a proxy for such innate cognitive differences, in order to isolate and examine the relationship between bilingual language experience and attention control.

All these factors contribute to a large variance in the degree of bilingualism balance in Singaporean preschool children, and these make them ideal for our research purposes.

Summary

In summary, from young, the experience of being a bilingual is expected to affect general cognitive control, because the need for the brain to manage two languages reinforces the processes involved and extends to non-linguistic cognitive control. Previous research has shown that in children, there is a positive relation between bilingualism and cognitive control; this was initially examined by comparing between bilinguals and monolinguals, and subsequently refined to include the examination of different levels of bilingualism balance. Additionally, attention was identified as a key component of the relationship between bilingualism and cognitive control, hence, using this previous research as the backbone, we are interested to examine how bilingualism balance relates to attentional control in preschoolers, as well as what mechanism underlies this relation.

However, the lack of precisely defined boundaries for bilingualism proficiency and balance measurement has contributed to the field of mixed findings. The first study of the present thesis aims to examine the relevance of bilingual balance measured by vocabulary tests with parental reports of daily bilingual experience, with the findings providing support for the use of such vocabulary tests and balance scores in the subsequent studies. The second study examines the research question on how bilingualism balance relates to attentional control, with different aspects of the bilingualism experience

(balance of exposure or balance of production) relating separately to different attention networks. The third study uses an experimental design to understand the mechanism underlying the relation between bilingualism balance and attentional control, by manipulating language contexts in order to induce a particular language frame in the bilingual child participants. Together, the three studies will contribute to the mixed state of the literature a perspective that provides support for a type of bilingualism balance measurement, as well as a relation between bilingualism balance and attentional control that takes into account bilingualism contexts.

Study 1 was designed to examine the representativeness of vocabulary test ratio scores in estimating the language experiences of a bilingual child, by comparing test scores to parental reported linguistic experiences. In the next chapter, we will detail the rationale, methods, results, and discussion for this study.

CHAPTER 3

STUDY 1

Rationale of the present study

As mentioned in the previous chapter, there has not been a consensus on how bilingual language proficiency should be measured. In the present study, we propose to use vocabulary tests as objective measures to estimate the proficiency of each language in our bilingual sample. In the process, the relative difference in test scores across languages would also give us an indication of the individual's language dominance, whether they are English or Chinese dominant, and their bilingualism balance, or how comparable they are in their two languages.

Given the lack of consensus on how to quantify proficiency and bilingualism balance, there has also been a dearth of studies showing how vocabulary test scores used to represent bilingualism balance in children relate to the real-world situations of language exposure and production, as reported by parents. It is important to verify that these objective test scores, used in previous studies ostensibly to represent bilingualism balance, are actually an accurate representation of what the children experience in their daily lives. Hence, the aim of the present study is to examine the relations between the bilingualism balance ratio derived from vocabulary tests and parental reports of language exposure and production in the bilingual preschooler.

As explained previously, we have chosen to use the ratio of vocabulary scores between languages as the operationalization of bilingualism balance across the studies in this thesis. Ratios are separately calculated for receptive and expressive vocabulary to investigate the correlations with parent reported

language exposure and production respectively, before averaging the two vocabulary scores to see how the composite numbers correlate to a combined parental report score. Both the quality (proficiency of caretaker in each language) and quantity (amount of time child is spoken to and speaks in a language) of language exposure will be measured and compared separately, to assess whether the vocabulary scores and ratios are indicative of both aspects of language. We expect that smaller vocabulary ratio scores, which represent more-balanced bilingualism, would correspond with higher levels of parental reported exposure and use of the weaker language, and lower levels of exposure and use of the dominant language. Strong correlations between the variables would indicate that the ratios of vocabulary scores do reflect the actual proportion of bilingual language exposure and production of the child, justifying the use of these ratio scores in the further studies to represent these two aspects of language experience.

Methods

Participants

A total of 233 English-Mandarin Chinese bilingual children participated in this study. All children were attending Kindergarten-1 (second year of three years of pre-formal education in Singapore), and were recruited from several local childcare centers. All participants had either one or both parents who were ethnically Chinese, with the exception of two children who were from Japanese families. All parents reported that their children were exposed to English and Mandarin to varying degrees, across situations such as at home and in school. In addition, all children attended both English and Mandarin-Chinese classes in

school, with different teachers for each language. In Singapore, the primary language of instruction in schools is English, hence it is not uncommon for parents to choose to speak English (as opposed to their mother-tongue, Mandarin) at home as they may feel that it is beneficial to their child's academic achievement. Additionally, parents of 44 participants reported that their child was exposed to an additional third language at home, with 37 families reporting a dialect or variant of Chinese, two reporting Japanese, two Thai, two Bahasa Indonesian, and one German. Participants were excluded if their reported exposure to languages other than English and Mandarin at home was higher than 50%, which resulted in four participants being removed from the sample. Another 15 participants were removed due to incomplete information given on the survey regarding language exposure and production. The final sample was of 214 children, 103 males, Age range = 55-71 months, $M = 63.1$ months, $SD = 4.11$.

Recruitment was done through working with childcare centers. Childcare centers around Singapore were contacted and briefed regarding the nature of the study. Centers interested to participate were then given the consent forms and survey packets to hand out to parents. Only children whose parents consented to their participation were tested.

Measures

Parental surveys were given out on paper and collected before vocabulary testing began. All vocabulary test images were presented on laptop screens but scoring was done manually on paper.

Parental report questionnaire. The child's main caretaker or parent was given a paper survey, which included questions on child's age, gender, parents' education level, household income, and details on who the child spent the most time with on a daily basis. Additionally, the caretaker was asked to report details on their child's language exposure and production. Because there was no incentive given to the caretakers for completing the survey, and also because of the relative difficulty in getting caretakers to report exact quantities of language exposure in their child's life, we chose to use a simplified proportion measurement as opposed to a lengthy language questionnaire. The survey respondent provided, for each caretaker of the child (up to a maximum of five), the percentage of time English and Mandarin (and any other language if relevant) was spoken to and by the child, with each score adding up to 100 percent. For example, for Child X, the mother could report speaking English to the child 50% of the time, and Mandarin for the other 50% of the time, while reporting that the child speaks to the mother English 75% of the time, and Mandarin for the remaining 25% of the time. The respondent was also asked to provide the English and Chinese proficiency of each caretaker, on a scale of zero (Cannot speak, cannot understand) to four (Speaks very well, understands very well). A copy of the survey items is provided in Appendix A.

Peabody Picture Vocabulary Test-IV (PPVT; Dunn & Dunn, 2007).

The PPVT is designed to measure receptive vocabulary in English, and a Chinese adaptation of the test was used to assess Mandarin receptive vocabulary. This Chinese adaptation was made by first having a native Chinese speaker familiar with English to translate the terms used in the test from English to Chinese. Next, a second bilingual translated the terms back into

English in order to check for accuracy. Some of the Chinese terms were changed in order to be more culturally appropriate. The test contains two parallel forms, Form A and Form B, and each child was tested in one form per language, order counterbalanced.

Each item consisted of four numbered pictures, and children selected the picture that matched the word given by the experimenter. Items were arranged in increasing difficulty, in sets of 12 totalling to 19 sets. The basal item (start item of testing) was determined by the child's age, according to recommendations in the PPVT manual. Testing ceased when the child got eight or more items wrong in a set. Scores were tabulated by subtracting the number of mistakes made from the item number of last item administered. Testing and scoring were done separately for the two languages.

Expressive Vocabulary Test-2 (EVT; Williams, 2007). The EVT is designed to measure English expressive vocabulary, and a Chinese adaptation of the test was used to measure Mandarin expressive vocabulary. Similar to the PPVT, the Chinese adaptation went through double translation. For the EVT, the second translator was a local postgraduate student, hence she also checked for cultural appropriateness. For each item, children were shown a picture and asked to respond to the tester's question regarding the picture. Some questions involved identifying an item in the picture, while other questions required the child to provide a synonym when given the name of the item presented. This task was done in both English and Mandarin, with the order of languages counterbalanced.

Procedure

Before testing began, childcare centres were given a set of forms that parents had to complete and return. These included written consent procedures and the parental report questionnaire. Equivalent English and Chinese versions of the forms were created, and parents were given the forms in the language that teachers advised the parent would prefer.

For each child, the testing session was held in a quiet room in the child's childcare centre, and the children were tested individually. Experimenters (six in total including the PhD student in charge) were all fluent English-Mandarin Chinese bilinguals, and each child was accompanied by an experimenter throughout the entire testing session.

At the beginning of the session, experimenters asked the child for consent by asking if the child agreed to “play some games” with the experimenter. Once the child agreed, the testing began. The first task presented was the PPVT in one of two languages (English or Mandarin Chinese), the order of which was counterbalanced among participants. The PPVT was chosen as the first task as it does not require the child to speak if they are not comfortable, allowing the experimenter to spend more time building rapport with shy children. Next, the EVT was presented in the same language. Subsequently, the PPVT in the other language was presented, and the last task was the EVT in this language. This ensured that all participants only switched between languages once in the entire session. Each session lasted approximately 45 minutes. At the end of the session, children were given stationery or small toys as reward for participation.

Results

For all statistical tests, an alpha level of .05 was used.

Preliminary calculations

For the parental report questionnaire, when reporting the caretaker that the child spends the most time with (primary), 132 out of the 214 families reported it to be the child's mother (61.7%), with 29 (13.6%) families reporting it to be the father. The remaining families reported that their child spent most time with either their maternal (22 respondents; 10.3%) or paternal (21 respondents; 9.8%) grandmothers, domestic helpers (eight respondents; 3.7%) or other family members (two respondents; 1.0%). The primary caretaker was reported, on average, to spend slightly more time speaking English (50.54%) than Mandarin Chinese (46.59%) to their child, and that the child was more likely to speak English (55.79%) than Chinese (43.27%) to the caretaker. When asked to report their proficiency in English and Chinese (scale of zero to four), caretakers reported slightly higher proficiencies for Chinese (3.19) than English (2.82). A subset of participants ($n = 122$) were told to report the number of hours spent with the child on a typical weekend (non-school day). On average, the caretakers spent 13.7 hours with the child.

Only 194 (out of 214) respondents reported information on the caretaker their child spent the next (secondary) most amount of time with. 100 families reported it to be the child's father (51.5%), while 51 families reported it to be the child's mother (26.3%). 20 families reported it to be the family's domestic helper (10.3%), while the remaining reported paternal grandmothers (seven respondents; 3.6%) or grandfathers (six respondents; 3.1%), maternal grandmothers (four respondents; 2.1%) or grandfathers (four respondents;

2.1%), or other family members (two respondents; 1.0%). The secondary caretaker was reported, on average, to also spend more time speaking English (54.32%) than Chinese (42.34%) to the child, and that the child was more likely to speak English (59.69%) than Chinese (39.22%) to the caretaker. These secondary caretakers reported very similar proficiencies in English (2.89) and Chinese (2.89). A subset of these caretakers ($n = 109$) reported spending an average of 12.1 hours on a typical weekend with the child. All subsequent reported caregivers were deemed to be less influential on the child's language development (out of 81 respondents reporting on the third caretaker of the child, an average of only 7.5 hours was spent with the child on a typical weekend), hence their language exposure reports were not considered in subsequent analyses.

In order to combine the parental reported percentages of time spent on each language, for each participant, average scores was calculated for the amount of English and Chinese spoken to and by the child per caretaker (either one or two). Then, modeling after the ratio used to calculate bilingualism balance with the vocabulary scores, an *exposure* score and *production* score was calculated, using the following formulas:

Exposure

$$= \frac{\text{Average English spoken to child} - \text{Average Chinese spoken to child}}{\text{Average English spoken to child} + \text{Average Chinese spoken to child}}$$

Production

$$= \frac{\text{Average English spoken by child} - \text{Average Chinese spoken by child}}{\text{Average English spoken by child} + \text{Average Chinese spoken by child}}$$

Scores ranged from -1 to 1, with smaller numbers indicating more Chinese, larger numbers indicating more English, and values at/close to zero indicating equal time with both languages. Finally, a composite score of *parent*

reported language proportion quantity was calculated from both exposure and production by averaging the two values.

For vocabulary scores, the raw ratio for each type of vocabulary (receptive ratio using PPVT and expressive ratio using EVT) was calculated separately, using the following formulas:

$$PPVT \text{ raw ratio} = \frac{PPVT \text{ English} - PPVT \text{ Chinese}}{PPVT \text{ English} + PPVT \text{ Chinese}}$$

$$EVT \text{ raw ratio} = \frac{EVT \text{ English} - EVT \text{ Chinese}}{EVT \text{ English} + EVT \text{ Chinese}}$$

Scores also ranged from -1 to 1, with smaller numbers indicating better Chinese scores, larger numbers indicating better English scores, and values at/close to zero indicating equal performance in both languages. Similarly, a composite score was also calculated for *vocabulary test language balance* by averaging the two vocabulary ratio values. Out of the 214 children in the sample, 154 of them were clearly English dominant, with better scores on both English vocabulary tests than Chinese, while 14 of them were clearly Chinese dominant, with higher scores on both Chinese vocabulary tests than English. The remaining 46 participants were not clearly dominant in either language, with higher performance in one of the two languages in one of the two tests. However, these participants tended to score very close to zero in both their vocabulary test ratio scores, indicating balanced bilingualism.

Table 3 presents the means, standard deviations, skewness and kurtosis of the parental reported scores, the vocabulary test scores and the derived scores. Figure 2 presents Q-Q plots to show the distribution of exposure,

production, parental reported language proportion quantity, PPVT raw ratio, EVT raw ratio, and vocabulary test balance.

Table 3

Means, Standard Deviations, Skewness and Kurtosis values for parent reported language exposure and production, PPVT, EVT, and all derived scores

	<i>M (SD)</i>	<i>Min – Max (in current sample)</i>	<i>Skewness (SE = .17)</i>	<i>Kurtosis (SE = .33)</i>
Parent reported % of				
Ave. Eng to Child	51.75 (31.20)	0 – 100	-.12	-1.25
Ave. Chi to Child	44.91 (30.31)	0 – 100	.20	-1.20
Exposure	.06 (.63)	-1.00 – 1.00	-.18	-1.26
Ave. Eng by Child	57.41 (33.32)	0 – 100	-.30	-1.31
Ave. Chi by Child	41.58 (33.23)	0 – 100	.35	-1.27
Production	.16 (.67)	-1.00 – 1.00	-.33	-1.30
PR Language Balance	.11 (.64)	1.00	.25	-1.31
PPVT				
PPVT _{Eng}	80.80 (18.60)	32 – 132	.07	-.08
PPVT _{Chi}	60.72 (23.41)	12 – 142	.38	-.19
PPVT raw ratio	.16 (.23)	-0.48 – 0.77	-.04	-.18
EVT				
EVT _{Eng}	63.82 (16.51)	8 – 100	-.44	-.002
EVT _{Chi}	32.77 (14.76)	3 – 88	.71	1.38
EVT raw ratio	.33 (.26)	-0.74 – 0.91	-.53	1.24
Vocab Test Balance	.24 (.23)	-0.61 – 0.83	-.28	.55

Note. N = 214. Eng to child = Average English spoken to child; Chi to child = Average Chinese spoken to child; Exposure = (Ave. Eng to child – Ave. Chi to child)/(Ave. Eng to child + Ave. Chi to child); Production = (Ave. Eng by child – Ave. Chi by child)/(Ave. Eng by child + Ave. Chi by child); PR Language Balance = Parent reported average language balance, derived from average of Exposure and Production; PPVT ratio = (PPVT Eng – PPVT Chi)/(PPVT Eng + PPVT Chi); EVT ratio = (EVT Eng – EVT Chi)/(EVT Eng + EVT Chi); Vocab Test Balance = Vocabulary test scores average language balance, derived from average of PPVT and EVT ratio.

Figure 2. Q-Q plots of Exposure, Production, PR (Parental Reported) Language Balance, PPVT raw ratio, EVT raw ratio, & Vocabulary Test Balance

Demographic variables

There were no significant gender differences for all key variables (Mann-Whitney U tests, $ps > .10$). One-way ANOVA conducted to examine experimenter differences on all vocabulary tests also did not find significant differences (Kruskal-Wallis tests, $ps > .07$). There were no order effects on vocabulary test performance (Mann-Whitney U tests, $ps > .06$), indicating no systematic differences between those who did the tests in English first and those who started with Chinese.

Using Spearman correlations, age of participants at time of testing had significant but small correlations with parent reported levels of Chinese spoken by child ($r = -.14, p = .04$), parent reported production ratio ($r = .14, p = .04$), PPVT_{Eng} ($r = .22, p = .001$), PPVT raw ratio ($r = .15, p = .03$), EVT_{Eng} ($r = .27, p < .001$). This suggests that older children are more likely to have parents report that they use more English, and also have stronger English receptive and expressive vocabulary.

Correlations

We conducted separate analyses to examine the relationship between (1) the quality of language the child is exposed to, based on the rated proficiency of the primary and secondary caretakers identified in the survey, and the (2) proportion (quantity) of language exposure and production reported by parents.

Firstly, bivariate (Spearman) correlations were conducted between the reported proficiencies of primary and secondary caretakers in English and Chinese, the child's vocabulary scores and the derived ratios. Table 4 presents the correlations of interest.

Table 4
Correlations among parent reported language proficiency, PPVT, EVT, and derived ratios

	Primary Caretaker English Proficiency (<i>N</i> = 210)	Primary Caretaker Chinese Proficiency (<i>N</i> = 210)	Secondary Caretaker English Proficiency (<i>N</i> = 189)	Secondary Caretaker Chinese Proficiency (<i>N</i> = 189)
PPVT _{Eng}	.37***	-.13	.26***	-.15*
PPVT _{Chi}	-.28***	.29***	-.27***	.13
PPVT raw ratio	.42***	-.31***	.35***	-.19**
EVT _{Eng}	.41***	-.15*	.33***	-.17*
EVT _{Chi}	-.31***	.30***	-.19*	.17*
EVT raw ratio	.49***	-.30***	.32***	-.21**
Vocab Test Balance	.49***	-.32***	.36***	-.20**

Note. *N* is denoted at the top of each column. * $p < .05$, ** $p < .01$, *** $p < .001$.

PPVT ratio = (PPVT Eng – PPVT Chi)/(PPVT Eng + PPVT Chi); EVT ratio = (EVT Eng – EVT Chi)/(EVT Eng + EVT Chi); Vocab Test Balance = Vocabulary test scores average language balance, derived from average of PPVT and EVT ratio.

For the English proficiency of the primary caretaker, small but statistically significant positive correlations were found with the child's PPVT_{Eng} score ($r = .37, p < .001$) and EVT_{Eng} score ($r = .41, p < .001$), and negative correlations were found with PPVT_{Chi} score ($r = -.28, p < .001$) and the child's EVT_{Chi} score ($r = -.31, p < .001$). For the Chinese proficiency of the primary caretaker, there were significant positive correlations with PPVT_{Chi} score ($r = .29, p < .001$) and the child's EVT_{Chi} score ($r = .30, p < .001$), and a small negative relationship with the child's EVT_{Eng} score ($r = -.15, p = .03$).

PPVT raw ratio scores were positively correlated with primary caretaker's English proficiency ($r = .42, p < .001$) and negatively correlated with Chinese proficiency ($r = -.31, p < .001$), indicating that higher receptive vocabulary balance was related to the primary caretaker having better

proficiency in the English language, and less proficiency in the Chinese language. Similarly, EVT raw ratio scores were positively correlated with primary caretaker's English proficiency ($r = .49, p < .001$) and negatively correlated with Chinese proficiency ($r = -.30, p < .001$), indicating that higher expressive vocabulary balance was also related to the primary caretaker having better proficiency in English and less proficiency in Chinese. This is reasonable given that higher ratio scores indicate more dominance in English and lower ratio scores indicate more dominance in Chinese. Consistent with the component vocabulary ratios, Vocabulary Test Balance scores were also positively correlated with primary caretaker's English proficiency ($r = .49, p < .001$) and negatively correlated with Chinese proficiency ($r = -.32, p < .001$).

For the secondary caretaker, there were some statistically significant correlations in the same direction as those of the primary caretakers, but in comparison they were smaller in size, suggesting that the proficiency of the primary caretaker affected the child's receptive and expressive vocabulary slightly more than that of the secondary caretaker. Taken together, the correlations imply that the vocabulary scores and derived ratios did vary in relation to the quality of each language the child was exposed to, with higher language proficiency in the caretakers relating to higher vocabulary scores in the child.

Next, bivariate (Spearman) correlations were also conducted to examine the relations between the parent reported language exposure scores, the vocabulary test scores and all derived scores. Table 5 presents the correlations between these variables.

Table 5

Correlations among parent reported language exposure and production quantities, PPVT, EVT, and all derived scores

	Chi to child	Exposure	Eng from child	Chi from child	Product ion	PR Lang Balance	PPVT Eng	PPVT Chi	PPVT raw ratio	EVT _{Eng}	EVT _{Chi}	EVT raw ratio	Vocab Test Balance
Eng to child	-.95***	.98***	.89***	-.87***	.89***	.96***	.50***	-.46***	.63***	.56***	-.42***	.61***	.67***
Chi to child		-.98***	-.89***	.90***	-.90***	-.97***	-.48***	.44***	-.61***	-.55***	.41***	-.60***	-.65***
Exposure			.90***	-.90***	.90***	.98***	.50***	-.46***	.63***	.57***	-.42***	.61***	.67***
Eng from child				-.98***	.99***	.96***	.52***	-.51***	.69***	.56***	-.48***	.68***	.73***
Chi from child					-.99***	-.97***	-.51***	.51***	-.68***	-.56***	.46***	-.67***	-.72***
Production						.97***	.52***	-.52***	.69***	.57***	-.47***	.68***	.73***
PR Lang Balance							.53***	-.50***	.68***	.58***	-.46***	.66***	.71***
PPVT _{Eng}								-.06	.51***	.83***	-.20***	.57***	.57***
PPVT _{Chi}									-.87***	-.08	.66***	-.56***	-.76***
PPVT raw ratio										.45***	-.64***	.75***	.93***
EVT _{Eng}											-.11	.57***	.54***
EVT _{Chi}												-.84***	-.78***
EVT raw ratio													.93***

Note. N = 214 for all correlations. *** $p < .001$.

Eng to child = Average English spoken to child; Chi to child = Average Chinese spoken to child; Exposure = (Ave. Eng to child – Ave. Chi to child)/(Ave. Eng to child + Ave. Chi to child); Production = (Ave. Eng by child – Ave. Chi by child)/(Ave. Eng by child + Ave. Chi by child); PR Language Balance = Parent reported average language balance, derived from average of Exposure and Production; PPVT ratio = (PPVT Eng – PPVT Chi)/(PPVT Eng + PPVT Chi); EVT ratio = (EVT Eng – EVT Chi)/(EVT Eng + EVT Chi); Vocab Test Balance = Vocabulary test scores average language balance, derived from average of PPVT and EVT ratio.

Correlations between the parent reported percentages of each language spoken to/by the child with vocabulary tests were first examined. Moderate-sized correlations were found between parent reported English spoken to child and PPVT_{Eng} scores ($r = .50, p < .001$) and parent reported English spoken by child and EVT_{Eng} scores ($r = .56, p < .001$). Weaker but significant correlations were found between parent reported Chinese spoken to child and PPVT_{Chi} scores ($r = .44, p < .001$), and parent reported Chinese spoken by child and EVT_{Chi} scores ($r = .46, p < .001$). Next, the correlations between the parent reported overall exposure/production with vocabulary ratios were examined. Moderately strong correlations were found between parent reported overall exposure and PPVT raw ratio ($r = .63, p < .001$), indicating that increased exposure scores, which correspond to higher reported exposure to English as compared to Chinese, was related to higher PPVT raw ratio scores, which also indicate better receptive vocabulary in English as compared to Chinese. Similarly, moderately strong correlations were found for parent reported overall language production and EVT raw ratio ($r = .68, p < .001$), suggesting that increased production scores, which correspond to higher reported production of English as compared to Chinese, was related to higher EVT raw ratio scores, which indicate better expressive vocabulary in English as compared to Chinese. Finally, looking at the combined scores, parent reported language balance was strongly correlated with vocabulary test balance scores ($r = .71, p < .001$), implying that an increase in parent reported language proportion (more English in the child's life as compared to Chinese) also corresponded to an increase in the difference between English and Chinese vocabulary test scores, taking into account their total vocabulary scores.

Additionally, we also sought to identify the difference in language experiences that more-balanced bilinguals have as compared to less-balanced bilinguals, in terms of their parental reported amount of each language spoken to and by the child. Firstly, we examined correlations between PPVT and EVT raw ratios with parent reported English and Chinese quantities, reported in Table 5. Moderately strong positive correlations were found for parent reported English spoken to child ($r = .63, p < .001$) and by child ($r = .68, p < .001$), while moderately strong negative correlations were found for parent reported Chinese spoken to child ($r = -.61, p < .001$) and by child ($r = -.67, p < .001$). Since larger raw ratio scores corresponded to relatively better performance in English than Chinese, and most of the participants (154 out of 214) were English dominant, this meant that larger relative imbalance in vocabulary scores was correlated with increased English exposure and production of the child, as well as decreased Chinese exposure and production.

Subsequently, in order to examine balance along a uni-directional continuum, we extracted the clearly English dominant participants ($n = 154$), who had raw ratios ranging from 0 to 1, and ran correlations for them only. Scores closer to zero indicated more balance, while scores closer to 1 indicated more dominance in English. The remaining sample, with raw ratios that ranged from -1 to 0, was not analyzed because the Chinese dominant participants ($n = 14$) were too small a sample size to analyze on their own, and the dominant language of the remaining participants ($n = 46$) was unable to be ascertained.

For the English dominant participants, we correlated their parental reported amounts of dominant language (English) and weaker language (Chinese) with the raw ratios. Spearman's correlations showed that there was a

significant positive correlation between PPVT raw ratio with the amount of English language spoken to the child ($r = .52, p < .001$), and a significant negative correlation with the amount of Chinese language spoken to the child ($r = -.50, p < .001$). For EVT raw ratio, there was a significant positive correlation with the amount of English language spoken by the child ($r = .54, p < .001$), and a significant negative correlation with the amount of Chinese language spoken by the child ($r = -.53, p < .001$). These correlations suggest that less-balanced bilinguals (low raw ratios), as compared to more-balanced bilinguals (high raw ratios), were more likely to be exposed to and speak more of their dominant language English (positive correlations), and less of their weaker language Chinese (negative correlations), meaning that less-balanced bilinguals' language experiences were more skewed towards their dominant language.

Discussion

The results presented support for the use of the ratio of the English and Chinese vocabulary scores as a measure of bilingualism balance, to represent the relative exposure and production of the languages in the child's daily life. Small correlations were found for primary caretaker's language proficiency with child's vocabulary test scores, while moderate to strong correlations were found for parent reported exposure and production of the two languages with the vocabulary test scores and derived ratios. Specifically, parent reported language exposure scores correlated significantly with receptive vocabulary ratios, and parent reported language production scores correlated significantly with expressive vocabulary ratios. This implies that the vocabulary test scores

and, in particular, the ratios used to represent bilingualism balance, are indicative of the child's bilingual language experience, both in terms of quality and quantity. This study provides some evidence to support the use of vocabulary tests and relative ratios in objectively measuring the proportion of language production and exposure of a bilingual child, and adds to the existing literature by providing support to this avenue by which bilingualism balance can be quantified. Hence, in the subsequent studies, we will use the receptive vocabulary ratio as the operationalization of language exposure, and the expressive vocabulary ratio as the operationalization of language production.

The results also confirmed the difference in language experiences that more-balanced bilinguals have as compared to less-balanced bilinguals. In particular, less-balanced bilinguals have more linguistic experiences in their dominant language as compared to more-balanced bilinguals, and less-balanced bilinguals also have less linguistic experience in their weaker language compared to the more-balanced bilinguals. These findings provide some support for how bilinguals with different balance levels differ in their experience with the two languages, and this is line with one of the assumptions that underlie our proposed perspective on contextual-based attention control. Furthermore, the differences in language context experienced by more and less-balanced bilinguals is also one of the motivations of the design of Study 3, hence this study helps to strengthen the rationale by providing clear evidence regarding the difference in experience in each language depending on bilingualism balance.

One notable finding among this sample of children is that most of them are English dominant children. This is understandable given that most of formal

education in Singapore is in English, and parents may choose to speak more to their child in English before they enter formal education in order to help their child transit into school. However, because including the Chinese dominant participants did not change the direction of the results, we chose to include all participants regardless of language dominance. Other previous studies (e.g. Weber, Johnson, Riccio, & Liew, 2016) also grouped their bilinguals together and did not distinguish between children with dominance in different languages in the same language pair. Because we were interested to examine the amount of each language the child experiences in their daily life, as reported by their parents, we created an index that distinguished between English and Chinese dominant participants, with English dominant participants scoring positively on the ratio and Chinese dominant participants scoring negatively on the ratio, and balanced participants scoring in the middle, close to zero. However in our subsequent studies, because bilingualism balance and not specific language dominance is our variable of interest, we will modify the ratio formula to collapse across participants regardless of language dominance, comparing only across the function of how relatively similar or different their vocabulary scores across the two languages are. More details will be presented in Study 2.

One of the major limitations in this study is the lack of a normed vocabulary test in both English and Chinese for the present population. Although the PPVT in English is often used as a measure of receptive vocabulary (as seen in Table 2), the test was developed for use in the United States, with normed scores provided for their population. Due to the lack of an equivalent scale in the Singapore context, we adopted the PPVT to be used to test the English proficiency in our current sample, and used a translation as a

measure of Chinese proficiency. Raw scores were used, given the lack of locally developed norms. Moreover, given the differences in the order of which terms are learnt in different languages (Tardif et al., 2008), it is not ideal that we did not use a standardized Mandarin Chinese vocabulary test, especially considering that in our study, we compare the scores of the two languages against each other. Hence, caution has to be taken in interpreting the results. However, because our test samples consist of mainly English dominant bilinguals who use both languages in multiple contexts, we do not completely discount the value of the translated test, since it may be that some of the child participants were taught their Chinese vocabulary through English. Additionally, our significant moderate to strong correlations found in this study provide sufficient evidence to suggest that when comparing ranking across the sample, the tests are indeed indicative of the relative experience the children have against each other, according to their parents' reports of their linguistic experiences. Hence we believe that the translated tests were sufficient for the purposes of this study, and we will continue to use these tests in the next two studies in this paper. Nonetheless, it would be ideal to develop a standardized Mandarin Chinese vocabulary test in future studies, and to develop norms for both the English and Chinese test for the current population.

Due to limitations in resources, we were unable to use a more comprehensive language questionnaire with more items to capture more precise differences in language experience, such as context specific differences (e.g. languages used when watching television, reading to child etc.) We were also unable to get more detailed, quantitative information about the children's language exposure in school context, to support our assumption that schools are

dual language environments with a stronger emphasis on English than Mandarin. Hence, caution must be taken when interpreting the results. However, given the relative difficulty in getting caretakers to report exact hours in which children are exposed to each language (Thordardottir, Rothenberg, Rivard, & Naves, 2006), reporting percentages is a simplified alternative. Other possible alternatives to explore in future studies include using an ordinal scale of hours spent using each language with each caretaker, with each option corresponding to a few hours (e.g. 0-5 hours, 6-10 hours etc; as used in Thordardottir, 2011). This measure would also take into account the amount of time spent with each caretaker in different days across the week, a detail in which we were also unable to capture in our short measure. Nevertheless, the correspondence of the objective vocabulary measures and subsequently calculated ratios with the parent reported proportions demonstrated in this study justifies the use of vocabulary ratios as representation of bilingualism balance, and these objective measures will be used in the subsequent studies.

One possible criticism to the study is that if the bilingualism ratio scores are supposed to be highly representative of the child's language exposure and production, the correlation coefficients should be much larger. Vocabulary scores are measures of proficiency, which are related to exposure and production, but also include additional variances across individuals such as their non-verbal reasoning skills, which directly affect their performance on vocabulary tasks but have less bearing on their language experiences. Additionally, quality and quantity of linguistic input was considered separately in the analyses; it is evident that the vocabulary ratio score is a single measure that encapsulates both. To address the issue of individuals' non-verbal

reasoning skills affecting their performance on vocabulary tests and the attention task (the dependent variable for the subsequent studies), non-verbal intelligence will be measured and controlled for in the analyses.

Theoretically, the findings of this study provide support for the use of ratios calculated using the PPVT and EVT in representing bilingual balance in exposure and production in future studies. The ratios provide a representation of the relative difference in both languages in a bilingual in terms of exposure and production, hence allowing for these to be taken into account when comparing within groups of bilinguals. Thus, in the next study, we will use such vocabulary ratios to examine the relation between bilingualism balance and attentional control.

CHAPTER 4

STUDY 2

Rationale of the present study

As mentioned in the literature review, previous research has shown that the extent of one's bilingualism is related to advantages in cognitive control; relatively more-balanced bilinguals have been found to perform better on attentional control as compared to less-balanced ones (e.g. Poarch & van Hell, 2012; Sorge, Toplak & Bialystok, 2016). However, results are mostly inconsistent across different attention networks, with different aspects of the bilingualism experience addressed in different studies. Hence, building on previous research and the findings of Study 1, we aim to identify the relation between two aspects of bilingualism balance, quantified using receptive and expressive vocabulary ratios, and attentional control, measured by the Child-Attention Network Task (ANT).

We expect that when comparing between bilinguals, individuals who are more comparably proficient to both their languages (more-balanced) are better at controlling their attention when necessary, as compared to less-balanced bilinguals. Specifically, different components of attention are expected to be separately linked to the aspects of language exposure and language production in a bilingual, due to the differing mechanisms underlying attentional management in these different contexts.

For the purposes of the present study, we are interested to separate the comprehension and production aspects of language experience in order to examine the two pathways. This is done by choosing tasks that are said to tap on each skill: the receptive vocabulary task meant to measure language

exposure does not require language production; the expressive vocabulary task meant to measure language production only requires basic comprehension. According to this, two hypotheses were made.

As previously mentioned in the section on research questions in the present paper, the first hypothesis relates to language exposure. We have predicted that bilingual language exposure, operationalized by the ratio of receptive vocabularies, would be positively related to the alerting component of the attention network. This is because cue detection, a component of both the Adaptive Control hypothesis and the alerting network, is a skill developed by those with more-balanced language exposure in their linguistic environment. Since they are more likely to be exposed to more varied linguistic contexts, they are also more likely to have greater sustained attention or maintain a higher state of vigilance due to their daily experience in observing and partaking in multiple language contexts. With this, they are then able to perform better on cue detection as compared to the less-balanced bilinguals, who experience their dominant language to a larger extent and have less reason or opportunities to monitor their environment. Hence, we expect that higher receptive vocabulary ratios, which indicate better bilingualism balance, would be related to more alert performance on the ANT.

The second hypothesis relates to language production. We have predicted that bilingual language production, operationalized by the ratio of expressive vocabularies, would be positively related to the conflict network. Compared to less-balanced bilinguals, more-balanced bilinguals are more likely to express themselves in both languages. As previously reviewed, doing so requires monitoring of and suppression of the non-target language, as well as

the inhibition of the previous language and activation of the new language in the event that a language switch is needed. All of these are processes involved in both the Adaptive Control hypothesis as well as the conflict network. For less-balanced bilinguals, they express themselves mainly in their dominant language, hence they would engage the cognitive processes highlighted above less frequently, as compared to the more-balanced bilinguals. Thus, we expect that higher expressive vocabulary ratios would be related to better conflict management performance on the ANT.

No specific hypotheses are expected for the Orienting network. Figure 1 (in Chapter 2) shows a diagrammatic representation of the expected relationships.

For the purposes of examining variations of bilingualism balance with attentional control, the vocabulary ratios would be calculated similar to Study 1, with some slight modifications. Since specific language dominance is not of interest in this study, the formula was modified to better fit a uni-directional measure of bilingualism balance, collapsed across participants with different dominant languages. The formula calculates the absolute value of each participant's PPVT and EVT raw ratio separately, and in order to get a balance index (where larger values indicate more balance and more similar vocabularies across languages), the calculated value would be deducted from 1 (where 1 is the largest possible score). The final formulas are as follows:

$$\textbf{PPVT balance ratio} = 1 - |\textbf{PPVT raw ratio}|$$

$$\text{where PPVT raw ratio} = \frac{\text{PPVT English} - \text{PPVT Chinese}}{\text{PPVT English} + \text{PPVT Chinese}} \text{ (used in Study 1)}$$

$$\textbf{EVT balance ratio} = 1 - |\textbf{EVT raw ratio}|$$

$$\text{where EVT raw ratio} = \frac{\text{EVT English} - \text{EVT Chinese}}{\text{EVT English} + \text{EVT Chinese}} \text{ (used in Study 1)}$$

Values would range from 0 to 1, where scores closer to 1 indicate more balanced vocabulary scores, without considering language dominance. This ratio is meaningful because an increase in value will correspond to an increase in balance (more similar performance in vocabulary tests across languages).

Methods

Participants

128 English-Mandarin Chinese bilingual children attending Kindergarten-1 in Singapore were recruited from local childcare centers (60 males, Age range = 55-67 months, $M = 61.0$, $SD = 3.51$). Participants and their parents are a subset who participated in Study 1. All participants were ethnically Chinese. All parents reported that their children were exposed to both English and Mandarin at home, and all children attended both English and Chinese classes in school, with different teachers for each language. As previously mentioned, most lessons were conducted in English, with mandatory Chinese lessons daily in all preschools.

Measures

All computerized tests were presented on laptops running Windows 7 or 8 operating systems, with children's key presses registered on physical buttons below the touchpads of the laptop. Pictures for vocabulary tests were also presented on laptop screens, but responses were coded manually on paper.

Demographic questionnaires. Parents were given a background information questionnaire, which included questions on age, gender, parents' education level, and household income.

Peabody Picture Vocabulary Test-IV (PPVT; Dunn & Dunn, 2007) and Expressive Vocabulary Test-2 (EVT; Williams, 2007). The two vocabulary tests were administered separately, as per Study 1.

Child Attention Network Task – Shortened (ANT; Rueda et al., 2004). An adapted version of the ANT task for children (previously used in Lim & Qu, 2016) was used in this study. The present task was condensed with reference to the shortened adult ANT (Fan et al., 2005), and consisted of three cue (no cue, center cue and spatial cue) and two target conditions (congruent and incongruent), shown in Figure 3. The shortening was done in the interest of reducing testing time, and to minimize fatigue effects of the children given the number of tasks administered. Split half reliabilities reported in the original Child-ANT paper was .93 for overall accuracy and .94 for overall RTs. The stimuli were presented via E-Prime 2.0 software (Version 2.0, Psychology Software Tools, Pittsburgh, PA).

Figure 3. Sequence of each trial of the shortened child ANT, with illustrations on cue and target conditions.

The task was designed to resemble a computer game, and children were shown yellow fish on a blue background. The fish were either swimming rightward or leftward, and the children were instructed to press either the right or left button as quickly as they could, in order to feed the fish in the middle. They were instructed to place the index finger of each hand on the corresponding side of the buttons, and told to feed the fishes as fast as possible.

Every child completed all 6 conditions (3 cues X 2 flanker), presented in random order. In total, there were 84 trials; 12 for training and 3 blocks of 24 actual trials. There was sound feedback presented to the child, with a “Woohoo!” sound presented when the key press was correct, and a “Huh?” sound when the key press was incorrect or absent after 1700ms.

Participants were scored separately on their error rate and median⁵ reaction time (Rueda et al., 2004). Error rate was calculated as the proportion the participant failed to respond correctly or on time (1- Accuracy), while only correct trials were used in the computation of reaction time. Both scores are seen to be representative of individual performance: accuracy demonstrates the ability to complete the task demands, and reaction time represents speed, given the ability to complete the task.

Two different versions of the attentional network scores were calculated: the original scores from Fan et al. (2005) and the new calculation proposed by Wang et al. (2014). The inclusion of both calculations was to further examine the independence of the attention networks in relation to bilingualism balance. Wang et al. (2014) raised the concern that in the original ANT calculations, each difference formula was averaged across several other conditions used to measure other networks, hence the score may be representative of the effect of more than one network. They then proposed a new set of calculations to extract, as much as possible, individual network scores unaffected by other networks. They also transformed scores into a ratio for the purposes of accounting for the baseline performance.

Hence, for the original calculation, attentional network scores were calculated by subtracting between different conditions, using these formulas:

Alerting = No cue – Centre cue (averaged across flankers);

Orienting = Centre cue – Spatial cue (averaged across flankers);

and Conflict = Incongruent – Congruent (averaged across cues).

⁵ We used median RTs instead of mean RTs because children are not very consistent across trials, and the median RT score is less sensitive to outliers than the mean (Carlson & Moses, 2001). Median scores were also used in the original child ANT paper (Rueda et al., 2004). However, we also ran analyses with the mean RT scores and found results very similar to the ones presented here.

For the new calculations, a total of seven formulas were calculated for each of the three networks, as well as the combinations of their effects on each other. The seven formulas are listed below.

$$\text{Alerting} = \frac{\text{Center cue congruent} - \text{No cue congruent}}{\text{No cue congruent}}$$

$$\text{Orienting} = \frac{\text{Spatial cue congruent} - \text{Center cue congruent}}{\text{Center cue congruent}}$$

$$\text{Conflict} = \frac{\text{No cue incongruent} - \text{No cue congruent}}{\text{No cue congruent}}$$

Alerting with conflict effect

$$= \frac{\frac{\text{Center cue incongruent} - \text{No cue incongruent}}{\text{No cue incongruent}} - \text{Alerting}}{\text{Alerting}}$$

Orienting with conflict effect

$$= \frac{\frac{\text{Spatial cue incongruent} - \text{Center cue incongruent}}{\text{Center cue incongruent}} - \text{Orienting}}{\text{Orienting}}$$

Conflict with alerting effect

$$= \frac{\frac{\text{Center cue incongruent} - \text{Center cue congruent}}{\text{Center cue incongruent}} - \text{Conflict}}{\text{Conflict}}$$

Conflict with orienting effect

$$= \frac{\frac{\text{Spatial cue incongruent} - \text{Spatial cue congruent}}{\text{Spatial cue congruent}} - \frac{\text{Center cue incongruent} - \text{Center cue congruent}}{\text{Center cue congruent}}}{\frac{\text{Center cue incongruent} - \text{Center cue congruent}}{\text{Center cue congruent}}}$$

Kaufman Brief Intelligence Test-2 (KBIT). The Matrices subtest of the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 1990) was used as a measure of non-verbal intelligence. Non-verbal intelligence scores were collected to control for general non-linguistic abilities that may underlie

performance on both vocabulary and attention tasks. Children were shown a target stimulus with five to six picture options presented below, and were required to choose the picture that matched the target stimuli, as a test of their ability to identify links or relationships between the target and the answer. Raw scores on the KBIT were calculated by subtracting the number of errors made from the last item number administered. Standardized scores were derived from the KBIT manual.

Procedure

Before testing began, childcare centres were given a set of forms that parents had to complete and return. These included written consent procedures and the background information questionnaire. Equivalent English and Chinese versions of the forms were created, and parents were given the forms in the language that teachers advised the parent would prefer.

For each child, the testing session was held in a quiet room in the child's childcare centre, and the children were tested individually. Each child was tested in two separate sessions, and both sessions were conducted at least a day apart. This was so that the child would not be fatigued over the course of testing. Experimenters (four in total including the PhD student in charge) were all fluent English-Mandarin bilinguals, and each child was accompanied by an experimenter throughout the entire testing session.

The first test presented was the PPVT in one of two languages (English or Mandarin), the order of which was counterbalanced among participants. Next, the EVT was presented, with the order of languages presented first (English or Mandarin) counterbalanced as well. For the second session, the PPVT was

again the first task, this time in the language that was not previously tested, followed by the KBIT, and ANT. To reduce likelihood of fatigue, children were allowed to take breaks between tasks, and between blocks of the ANT. Instructions for all other tasks, except the PPVT and EVT which had prescribed language for instructions, were presented in either language that the child expressed to be more comfortable conversing in, usually English. At the end of the session, children were given stationery or small toys as reward for participation.

Results

For all statistical tests, an alpha level of .05 was used.

Preliminary analyses

Participants who scored less than 20% accuracy on any of the six conditions of ANT were removed from analyses. It was deemed that the low accuracy meant that the participants did not understand the demands of the task. Additionally, reaction time (RT) scores are also less meaningful when accuracy is low, hence this criteria was put in place to ensure that all data points used were accurate representations of individual ability. This resulted in the removal of six participants. One participant was removed as the participant scored below 2 *SD* from the mean (of 100) on the standardized KBIT score, indicating that the child likely had difficulties understanding the task or may be atypical in development, given that standardized scores measure against a normed population. This participant also had the longest overall median reaction time of the remaining sample on the ANT, further supporting our decision to remove this participant. The final sample used in all subsequent analyses was 121 (59

males, Age range = 55-67 months, $M = 61.07$, $SD = 3.52$), which was 94.53% of the total participants recruited). Out of this sample, 99 children demonstrated English dominance, 11 showed dominance in Chinese, and the remaining 11 did not consistently perform better in one language across the two vocabulary tests. Compared to those included, excluded participants showed significantly lower EVT scores in English (-13.84 , $t(126) = -2.37$, $p = .02$), lower overall accuracy ($-.43$, $t(126) = -11.34$, $p < .001$) and larger overall RT (257.82 , $t(126) = 6.49$, $p < .001$) on the ANT.

There were no systematic order effects present, as participants did not differ in their performance on any of the vocabulary tests in relation to the order in which the tests were taken ($ps > .19$). There were also no significant differences in participant performance attributed to which experimenter administered the tests ($ps > .10$).

Demographic variables

We ran independent samples t-tests to check for gender differences, and did not find any significant differences between males and females on any of the vocabulary tests or ANT performance scores ($ps > .22$). Age of participants at first time of testing also did not significantly correlate with any of the performance scores on ANT, possibly due to the relatively narrow age range of the sample. The role of socioeconomic status (SES) was also considered. Parents of children were surveyed on their monthly family income, reported on an ordinal scale from 1 to 6, one being the lowest ($M = 4.15$, $SD = 1.53$, $n = 117$). Correlations between income and all ANT scores were run, and significant correlations were only found with ANT overall RT. Higher income ($r = -.26$, $p = .005$) was related to better overall performance (smaller RTs),

suggesting that more affluent children may have been more familiar with computerized tasks, resulting in faster responses across all conditions. Given that SES has been found to be a key variable in the relationship between bilingualism and cognitive control (Hartanto, Toh, & Yang, 2018), income was entered as a covariate in subsequent analyses.

Language measures

Table 6 shows the means and standard deviations for all language measures and the KBIT scores. As previously described, balance in each type of vocabulary (receptive and expressive) were calculated separately, using a ratio of 1 minus the absolute value of the difference in vocabulary scores of both languages divided by the sum of vocabulary scores of both languages, where scores ranged between 0 and 1 and a score of 1 indicated perfect balance between the two languages.

Table 6
Mean, Standard Deviation, Skewness and Kurtosis values for PPVT, EVT and KBIT scores

	<i>M (SD)</i>	<i>Min – Max (in current sample)</i>	<i>Skewness (SE = .22)</i>	<i>Kurtosis (SE = .44)</i>
PPVT				
PPVT _{English}	78.87 (18.72)	31 – 127	.05	-.21
PPVT _{Chinese}	61.66 (20.54)	15 – 117	.10	-.61
PPVT ratio	.81 (.15)	.26 – 1.00	-.79	-.52
EVT				
EVT _{English}	60.31 (15.24)	22 – 98	-.04	-.57
EVT _{Chinese}	31.90 (11.13)	6 – 66	.01	.50
EVT ratio	.68 (.19)	.14 – .99	-.39	-.10
KBIT (standardized scores)	107.22 (12.05)	79 – 138	-.05	-.37

Note. $N = 121$. PPVT ratio = $1 - |(PPVT \text{ English} - PPVT \text{ Chinese}) / -(PPVT \text{ English} + PPVT \text{ Chinese})|$; EVT ratio = $1 - |(EVT \text{ English} - EVT \text{ Chinese}) / -(EVT \text{ English} + EVT \text{ Chinese})|$

Preliminary ANT Analyses

Before calculating attentional network scores (Alerting, Orienting, Conflict), analyses were conducted on ANT raw scores, split by Cue X Flanker conditions. Table 7 presents the means and standard deviations of accuracy and median RT for each cue and flanker condition in the ANT, and the corresponding skewness and kurtosis indices. All distributions were deemed approximately normal (skewness & kurtosis between -1 and 1).

Table 7
Means, Standard Deviations, Skewness and Kurtosis of Accuracy and RT for Each Cue and Flanker Condition in ANT

Flanker Type	Cue Type								
	No cue	Centre cue	Spatial cue						
(1) Accuracy				<i>Skewness (SE = .22)</i>			<i>Kurtosis (SE = .44)</i>		
Congruent	.86 (.12)	.88 (.11)	.90 (.09)	-.98	-1.04	-.97	.64	.99	.86
Incongruent	.73 (.18)	.80 (.15)	.79 (.16)	-.75	-.80	-.96	.40	.73	.76
(2) Median RT (ms)									
Congruent	994.81 (118.03)	938.46 (129.47)	941.06 (123.47)	.42	.57	.35	.14	.29	.01
Incongruent	1070.03 (144.11)	1038.95 (146.44)	1041.70 (142.03)	.53	.53	.07	-.30	-.32	-.36

Note. $N = 121$. SDs presented in parentheses. RT scores are in milliseconds.

Separate 3 (Cue: no cue, center cue and spatial cue) X 2 (Type of flankers: congruent and incongruent) ANOVAs were conducted to examine variance of children's performance across conditions, on error rate and reaction time respectively.

For accuracy, main effects of both cue type ($F(2,240) = 21.21, p < .001, \eta_p^2 = .15$) and flanker type ($F(1,120) = 84.01, p < .001, \eta_p^2 = .41$) emerged, with a significant interaction effect found ($F(2,240) = 4.92, p = .008, \eta_p^2 = .04$).

Closer inspection revealed that incongruent flankers resulted in lower accuracy than congruent flankers ($-.11, p < .001$). The no cue condition showed significantly lower accuracy as compared to both center ($-0.04, p < .001$) and spatial cue ($-0.06, p < .001$; both Bonferoni corrected) conditions, and the difference was especially pronounced in the no cue-incongruent flanker condition.

For RT, main effects of both cue type ($F(2,240)=19.83, p < .001 \eta_{p2} = .14$) and flanker type ($F(1,120)=172.76, p < .001 \eta_{p2} = .59$) emerged, but no interaction effect was found ($F(2,240)=1.73, p = .18 \eta_{p2} = .01$). There was again a significant difference in flanker performance across cue types, with congruent flankers resulting in faster RTs than incongruent flankers ($-92.11, p < .001$). Across flankers, the no cue condition resulted in significantly larger RTs compared to the center ($-43.72, p < .001$) and spatial ($-41.04, p < .001$; both Bonferroni corrected) cue conditions, which were not significantly different from each other.

Attentional network scores were calculated separately for both error rate and RT, for both original and new calculations. For all network scores for the original ANT, smaller scores represent better performance. For the new ANT network scores, the formula differs slightly from the original ANT formula for the alerting and orienting network; the order of cues in the formula is swapped (e.g. original alerting score is center cue deducted from no cue, new alerting score is no cue deducted from center cue). Hence, for the new alerting and orienting accuracy scores, smaller scores represent better performance; for RT, larger scores represent better performance. For the new conflict accuracy scores, larger scores represent better performance; for RT, smaller scores represent better performance.

Table 8 includes means and standard deviations of overall accuracy, overall RT, and network scores calculated for both error rates and RT using the original method (Old alerting, Old orienting, Old conflict), as well as accuracy⁶

⁶ Accuracy (portion of correct items) instead of error rates (portion of wrong items) were used because some participants could have zero error, which would have made the denominator zero in some cases, resulting in invalid values. For the original ANT scores, differences in error rates were used.

and RT for the new method (New alerting, New orienting, New conflict). For the remaining four new scores (Alerting with conflict effect, Orienting with conflict effect, Conflict with alerting effect, Conflict with orienting effect), only RTs were used to calculate them (as done in Wang et al., 2014), because differences in accuracy data could have resulted in zero values, which would have resulted in invalid denominations. However, because the scores are derived from individual cue and flanker conditions, inconsistencies in the children's response timings resulted in a large range of values for each of these variables. In order to ensure meaningful analyses, participants with scores more than 3 SD from the mean were removed, resulting in a removal of between 12 to 18 participants depending on the variable; remaining sample sizes are listed in the table below. Distributions were approximately normal (skewness & kurtosis between -1 and 1) for most variables.

Table 8
Means, Standard Deviations, Skewness and Kurtosis of Accuracy, Error Rate (ER) and RT for attention network scores (Original and New Methods of Calculation)

	<i>M (SD)</i>	<i>Min – Max (in current sample)</i>	<i>Skewness (SE = .22 unless otherwise specified)</i>	<i>Kurtosis (SE = .44 unless otherwise specified)</i>
Overall Accuracy	.83 (.09)	.49 – .99	-.88	.93
Overall RT	989.97 (101.57)	775.00- 1289.00	.33	-.04
<i>Original calculations</i>				
Old alerting ER	.04 (.10)	-.29 – .29	-.04	.59
Old orienting ER	.01 (.09)	-.21 – .21	.01	-.61
Old conflict ER	.11 (.13)	-.17 – .58	.69	.80
Old alerting RT	44.34 (86.20)	-134.00 – 396.00	.73	1.08
Old orienting RT	-1.36 (86.22)	-.281.25 – 352.25	.42	1.10
Old conflict RT	92.44 (84.08)	-.111.50 – 364.00	.34	.20
<i>New calculations</i>				
New alerting acc	.03 (.18)	-.40 – .50	.49	.59
New orienting acc	.04 (.13)	-.19 – .37	.44	-.05
New conflict acc	-.15 (.22)	-.75 – .50	-.37	.80
New alerting RT	-.06 (.10)	-.29 – .27	.26	.14
New orienting RT	-.01 (.12)	-.29 – .37	.42	.23
New conflict RT	-.08 (.13)	-.22 – .44	.18	.15
Alerting with conflict effect RT (N = 103)	-.97 (1.45)	-4.96 – 3.00	-.33 (SE = .24)	1.13 (SE = .47)
Orienting with conflict effect RT (N = 109)	-.57 (1.67)	-4.12 – 4.98	.93 (SE = .23)	1.80 (SE = .46)
Conflict with alerting effect RT (N = 108)	-.48 (1.74)	-5.30 – 4.36	-.34 (SE = .23)	1.05 (SE = .46)
Conflict with orienting effect RT (N = 104)	-.43 (1.27)	-4.13 – 2.86	-.10 (SE = .24)	1.04 (SE = .47)

Note. $N = 121$ unless otherwise specified. RT scores are in milliseconds. The accuracy for original ANT uses difference scores of error rates (ER) while the accuracy for New ANT uses proportion of correct items (acc).

To check for the presence of the attentional networks, scores needed for calculation were examined for significant differences.

Analyses were first done for the original ANT calculations, using paired samples t-tests to confirm differences in constituent conditions for each score (as done in Rueda et al., 2004). For alerting scores, there were significantly different error rates ($t(120) = 4.67, p < .001$) and RTs ($t(120) = 4.66, p < .001$) between no cue and center cue trials, with no cue trials having a higher error rate and RT than center cue scores, showing the presence of the alerting effect. For orienting, however, there was no significant difference between center cue scores and spatial cue scores, for both error rate ($t(120) = 1.34, p = .168$) and RT ($t(120) = -.17, p = .86$), showing no evidence of an orienting effect. For conflict scores, the error rates ($t(120) = -9.09, p < .001$) and RT ($t(120) = -12.09, p < .001$) between incongruent and congruent trials were significantly different, with incongruent scores having a higher error rate and RT than congruent scores, showing a significant conflict effect.

For the new ANT calculations, one sample t-tests were done to determine if the scores were significantly different from zero (as done in Wang, 2014). Scores for alerting accuracy ($t(120) = 2.07, p = .04$), orienting accuracy ($t(120) = 3.13, p = .002$), conflict accuracy ($t(120) = -7.62, p < .001$), alerting RT ($t(120) = -6.03, p < .001$), conflict RT ($t(120) = 6.97, p < .001$), alerting with conflict effect ($t(102) = -6.77, p < .001$), orienting with conflict effect ($t(108) = -3.57, p = .001$), conflict with alerting effect ($t(107) = -2.86, p = .005$),

and conflict with orienting effect ($t(103) = -3.46, p = .001$) were significantly different from zero, showing the respective effects; only orienting RT ($t(120) = .96, p = .34$) was not, showing no orienting effect when calculated with RT.

Correlations

Partial correlations, controlling for income, were conducted to examine the relationships between age, the different language scores, KBIT and ANT. The sample size for all analyses was reduced to 117, due to the four missing data points on income information. The correlation table has been split into three tables for ease of viewing. Table 9a presents the correlations between age, PPVT, EVT, KBIT, and overall ANT scores (accuracy and RT), Table 9b presents the correlations between all the ANT network scores (original and new), and Table 9c presents the correlations between the language variables and the ANT scores.

Table 9a

Correlations among age, PPVT, EVT, KBIT, ANT overall accuracy (Acc) and reaction times (RT), controlling for income

	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Age	.30**	.02	.02	.28**	.01	-.08	.07	.02	.00
2. PPVT _{Eng}		.07	-.08	.78**	-.16	-.41**	.34**	.12	-.05
3. PPVT _{Chi}			.69**	.04	.59**	.46**	.22*	.23*	-.13
4. PPVT ratio				-.05	.44**	.49**	.10	.17	-.08
5. EVT _{Eng}					-.05	-.45**	.33**	.19*	-.08
6. EVT _{Chi}						.84**	.04	.23*	-.21*
7. EVT ratio							-.09	.11	-.14
8. KBIT								.17*	-.03
9. ANT Overall Acc									-.39**
10. ANT Overall RT									

$N = 117$. * $p < .05$, ** $p < .01$. Income was added as a control variable.

Table 9b
Correlations among ANT network scores accuracy (Acc), error rates (ER,) and reaction times (RT), both original (old) and new calculations, controlling for income

	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
1. ANT old alerting ER	-.40**	.09	.10	-.12	.01	.65**	-.27**	-.18*	-.11	-.02	-.04	.16	.04	.03	.01
2. ANT old orienting ER		-.04	-.01	.20*	.05	-.23*	.50**	-.001	-.01	-.12	-.10	-.26*	-.05	.03	.04
3. ANT old conflict ER			.12	-.05	.37**	.01	.06	-.79**	-.17	.12	.16	-.02	-.03	.11	-.07
4. ANT old alerting RT				-.25**	.08	.04	.002	-.14	-.67**	.18*	.05	.34**	.04	.03	.01
5. ANT old orienting RT					.03	-.04	.03	.02	.29**	-.69**	.01	-.13	-.03	-.16	.06
6. ANT old conflict RT						-.13	.06	-.35**	-.19*	.20*	.49**	.07	-.09	.40**	.19
7. ANT new alerting acc							-.51**	.31**	.08	-.12	-.11	.02	-.03	-.01	-.13
8. ANT new orienting acc								-.15	-.10	.01	.01	-.08	.11	.11	.15
9. ANT new conflict acc									.23*	-.09	-.13	-.08	.03	-.06	-.04
10. ANT new alerting RT										-.46**	.31**	-.17	.03	-.03	-.13
11. ANT new orienting RT											.19*	.12*	.001	.25	-.20*
12. ANT new conflict RT												.21*	.01	.24*	-.09
13. ANT alerting w conflict RT (N = 103)													.13	.16	.03
14. ANT orienting w conflict RT (N = 109)														.06	.32**
15. ANT conflict w alerting RT (N = 108)															.01
16. ANT conflict w orienting RT (N=104)															

N = 117 unless otherwise specified. * $p < .05$, ** $p < .01$. The accuracy for original ANT uses difference scores of error rates (ER) while the accuracy for New ANT uses proportion of correct items (acc).

Table 9c

Correlations between age, PPVT, EVT, KBIT, ANT accuracy (Acc), error rates (ER), reaction times (RT), against ANT network scores, controlling for income

	Age	PPVT _{Eng}	PPVT _{Chi}	PPVT ratio	EVT _{Eng}	EVT _{Chi}	EVT ratio	KBIT	ANT Overall Acc	ANT Overall RT
ANT old alerting ER	-.02	-.05	-.14	-.13	.03	-.10	-.08	-.01	-.22*	-.01
ANT old orienting ER	.03	.01	-.03	.06	-.10	-.12	-.002	-.09	.03	-.04
ANT old conflict ER	.04	-.07	-.22*	-.16	-.17	-.27**	-.20*	-.19*	-.51**	.13
ANT old alerting RT	.04	-.03	-.19*	-.23*	-.11	-.19*	-.09	-.07	-.13	-.07
ANT old orienting RT	.13	.04	.13	.14	.08	.11	.04	-.11	.04	-.03
ANT old conflict RT	.14	.02	-.05	-.04	.02	-.12	-.12	.03	-.09	.26**
ANT new alerting acc	-.12	.11	-.07	-.12	.11	-.08	-.11	.05	-.13	.04
ANT new orienting acc	-.02	-.21*	.001	.09	-.14	-.04	.03	-.09	-.21*	.06
ANT new conflict acc	-.12	.15	.21*	.10	.20*	.24*	.14	.21*	.42**	-.09
ANT new alerting RT	-.10	.08	.18	.18	.19*	.13	-.01	.08	.09	.07
ANT new orienting RT	-.01	-.05	-.10	-.13	-.07	-.07	.01	-.01	.06	.03
ANT new conflict RT	.01	.03	-.08	-.07	.12	-.11	-.17	-.01	.04	.03
ANT alerting w conflict RT (<i>N</i> = 103)	-.04	.09	-.10	-.03	.17	-.03	-.05	.01	.05	.03
ANT orienting w conflict RT (<i>N</i> = 109)	-.16	.03	-.06	-.01	-.01	-.07	-.07	.09	-.18	.12
ANT conflict w alerting RT (<i>N</i> = 108)	-.02	-.22*	-.03	.001	-.19	-.07	.05	-.08	.01	.22*
ANT conflict w orienting RT (<i>N</i> = 104)	.01	.08	-.10	.04	.07	-.15	-.12	.10	.07	.04

N = 117 unless otherwise specified. **p* < .05, ***p* < .01. The accuracy for original ANT uses difference scores of error rates (ER) while the accuracy for New ANT uses proportion of correct items (acc).

There were some notable correlations. Firstly, for the original ANT calculations, positive correlations were found between error rate and RT for orienting ($r = .20, p = .03$) and conflict ($r = .37, p < .01$) scores, although no such relationship was found for alerting. For the new calculations, there were no significant correlations between accuracy and RT for the three networks.

Secondly, between the receptive vocabulary tasks and original ANT scores, PPVT_{Chinese} and PPVT ratio were found to correlate negatively with alerting RT ($r = -.19, p = .04$; $r = -.23, p = .01$), suggesting that more balanced PPVT scores were related to faster RT in that domain. Additionally, PPVT_{Chinese} was correlated with conflict error rate scores ($r = -.22, p = .02$). For expressive vocabulary, EVT_{Chinese} and EVT ratio were found to correlate with conflict error rate scores ($r = -.27, p < .01$; $r = -.20, p = .03$), suggesting that more balanced EVT scores were related to smaller conflict effects in terms of accuracy.

For the new ANT calculations, PPVT_{Chinese} was found to correlate with conflict accuracy ($r = .21, p = .03$), a finding consistent with the original ANT scores. There was no significant correlation with PPVT ratio, although the correlation between PPVT ratio and alerting RT was close to significance ($r = .18, p = .06$). For expressive vocabulary, EVT_{English} was correlated with alerting RT scores ($r = .19, p = .04$), with higher English vocabulary relating to better alertness. EVT_{English} and EVT_{Chinese} were also found to correlate with conflict accuracy scores ($r = .20, p = .04$; $r = .24, p = .01$), suggesting that better expressive vocabulary scores across languages also related to better conflict management. For the combined network scores, only PPVT_{English} was significantly correlated with the conflict with alerting effect RT score ($r = -.22, p = .03$). Better receptive vocabulary in English was associated with smaller

differences in conflict effect between no cue and center cue conditions, signifying more consistent conflict management regardless of presence or absence of (center) cue.

Regressions

To examine the hypotheses in detail, two hierarchical regression models were analyzed to determine the relations between the language tasks and ANT performance. These models were adapted from analyses in Bialystok and Barac (2012). The dependent variables were the ANT attentional network scores; analyses were conducted separately for old and new calculations, in both accuracy and RT. For the first model, the independent variables entered were receptive vocabulary related. The first variables entered in Step 1 were control variables, including income and KBIT scores, in Step 2, the PPVT ratio scores were entered. The second model focused on using expressive vocabulary as predictors, and this included first entering income and KBIT scores in Step 1, and EVT ratio scores in Step 2.

Results for the original ANT calculations are presented first. VIF values were all below 4, indicating the absence of multicollinearity problems.

Table 10 includes the regression results for the first model with receptive vocabulary. Most of the regressions were not significant except for one. PPVT ratio ($\beta = -.23$, $p = .02$, $B = -134.25$, 95% CI [-243.01, -25.48]) was a significant predictor of the alerting RT score, $F(3,113) = 2.43$, $p = .05$, $R^2 = .06$, $\Delta F = 5.98$, $p = .02$. PPVT ratio predicted about 5% of the variance present in the alerting RT scores, above and beyond the other variables in the model.

Table 11 includes the regression results for the second model with expressive vocabulary. For this model, again only one aspect of the attention network showed significant results, this time in a different domain. KBIT scores ($\beta = -.21, p = .02, B = -.002, 95\% \text{ CI } [-.004, .00]$) and EVT ratio scores ($\beta = -.23, p = .02, B = -.16, 95\% \text{ CI } [-.29, -.03]$) were significant predictors of conflict error rate scores, $F(3, 113) = 3.48, p = .02, R^2 = .09, \Delta F = 5.83, p = .02$. Expressive vocabulary ratio was a significant predictor of performance on the conflict error rate scores, and contributed to about 5% of the variance present, above and beyond the other predictors.

In order to examine the independence of the two relations, regressions were run with both PPVT and EVT ratios as predictors, on alerting RT and conflict error rate scores separately. Income and KBIT were added into the model as control variables. Table 12 includes the results for both regressions. Despite putting both ratios in the same model, the results were consistent with those previously identified. PPVT ratio ($\beta = -.24, p = .03, B = -140.01, 95\% \text{ CI } [-90.53, 108.74]$) was the only significant predictor of the alerting RT score, $F(4, 112) = 1.81, p = .13, R^2 = .06, \Delta F = 2.98, p = .05$, although the overall model was not significant. Separately, EVT ratio ($\beta = -.21, p = .06, B = -.14, 95\% \text{ CI } [-.29, -.01]$) became a marginally significant predictor of conflict accuracy scores, $F(4, 112) = 2.63, p = .04, R^2 = .09, \Delta F = 2.97, p = .05$. Hence, the different vocabulary ratios and their relation with each ANT network seem to be distinct.

Next, to better understand the mechanism underlying these significant regression results, we ran regressions on each of the separate conditions contributing to the relevant attention networks. For Model 1 (receptive

vocabulary), given that the alerting network is composed of the no cue and center cue conditions, separate regressions were run on the mean RTs of each of these two conditions. There were marginally significant results only in the no cue condition. PPVT ratio ($\beta = -.17, p = .07, B = -.126.89, 95\% \text{ CI } [-.262.49, 8.71]$) marginally predicted alerting RTs, $F(3, 113) = 2.60, p = .06, R^2 = .07, \Delta F = 3.44, p = .07$, but results were overall not significant. This implies that the previously found relationship between PPVT ratio and alerting effect is not driven by any single cue condition, but instead it is the difference in performance across no and center cues that was related to receptive vocabulary balance.

For Model 2 (expressive vocabulary), given that the conflict network is composed of the congruent and incongruent flanker conditions, separate regressions were run for error rates of these two conditions. Table 13 shows the results of both regressions. There were significant results only in the incongruent flanker error rate. EVT ratio ($\beta = -.20, p = .04, B = -.15, 95\% \text{ CI } [-.28, -.01]$) significantly predicted error rates, $F(3, 113) = 4.00, p < .01, R^2 = .10, \Delta F = 4.54, p = .04$. This implies that the incongruent condition of the ANT is likely to be influencing the finding between EVT ratio and the conflict network of ANT, with more-balanced bilinguals having fewer errors with the incongruent flankers.

Table 10
Original ANT Error Rates (ER) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 1 (Receptive Vocabulary)

Variable Entered	Alerting (ER)					Orienting (ER)					Conflict (ER)							
	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2
Step 1						.001						.01						.04
Income	-.002	.01	-.03	-.35	1.00		-.001	.01	-.02	-.18	1.00		-.003	.01	-.03	-.36	1.00	
K-BIT	.00	.001	-.02	-.16	1.00		-.001	.001	-.10	-1.01	1.00		-.002	.001	-.19	-2.05	1.00	
Step 2						.02						.01						.02
Income	-.004	.01	-.06	-.66	1.06		.00	.01	.001	.10	1.06		-.01	.01	-.07	-.70	1.06	
K-BIT	.00	.001	-.002	-.02	1.01		-.001	.001	-.10	-1.08	1.01		-.002	.001	-.17	-1.89	1.01	
PPVT ratio	-.09	.07	-.13	-1.38	1.07		.04	.06	.08	.78	1.07		-.13	.08	-.14	-1.52	1.07	
Total R ²						.02						.02						.06
Step 1						.01						.01						.00
Income	4.37	5.25	.08	.83	1.00		-.27	5.24	-.01	-.05	1.00		-.251	5.14	-.05	-.49	1.00	
K-BIT	-.53	.67	-.07	-.79	1.00		-.81	.67	-.11	-1.22	1.00		.23	.65	.03	.35	1.00	
Step 2						.05*						.02						.00
Income	1.37	5.28	.02	.26	1.06		1.75	5.35	.03	.20	1.06		-.312	5.30	-.06	-.59	1.06	
K-BIT	-.36	.66	-.05	-.55	1.01		-.92	.67	-.13	-1.39	1.01		.26	.66	.04	.40	1.01	
PPVT ratio	-134.25	54.90	-.23	-2.45*	1.07		90.28	55.64	.16	1.62	1.07		-27.65	55.10	-.05	-.50	1.07	
Total R ²						.06						.04						.01

Note. * $p < .05$

Note. * $p < .05$

Table 11
Original ANT Error Rates (ER) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 2 (Expressive Vocabulary)

Variable Entered	Alerting (ER)					Orienting (ER)					Conflict (ER)							
	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2
Step 1						.001						.01						.04
Income	-.002	.01	-.03	-.35	1.00		-.001	.01	-.02	-.18	1.00		-.003	.10	-.03	-.36	1.00	
K-BIT	.00	.001	-.02	-.16	1.00		-.001	.001	-.09	-1.01	1.00		-.002	.001	-.19	-2.05	1.00	
Step 2						.01						.00						.05*
Income	-.004	.01	-.06	-.60	1.10		-.001	.01	-.02	-.20	1.10		-.01	.01	-.10	-1.08	1.10	
K-BIT	.00	.001	-.02	-.25	1.01		-.001	.001	-.10	-1.01	1.01		-.002	.001	-.21	-2.30	1.01	
EVT ratio	-.05	.05	-.09	-.90	1.11		-.01	.05	-.01	-.11	1.11		-.16	.07	-.23	-2.41*	1.11	
Total R ²						.01						.01						.09
Variable Entered	Alerting (RT)					Orienting (RT)					Conflict (RT)							
	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2
Step 1						.01						.01						.003
Income	4.37	5.25	.08	.83	1.00		-.27	5.24	-.01	-.05	1.00		-2.51	5.14	-.05	-.49	1.00	
K-BIT	-.53	.67	-.07	-.79	1.00		-.81	.67	-.11	-1.22	1.00		.23	.65	.03	.35	1.00	
Step 2						.01						.001						.01
Income	2.64	5.50	.05	.48	1.10		.31	5.52	.01	.06	1.10		-4.50	5.38	-.08	-.84	1.10	
K-BIT	-.59	.67	-.08	-.88	1.01		-.79	.67	-.11	-1.17	1.01		.15	.66	.02	.24	1.01	
EVT ratio	-46.19	44.28	-.10	-1.04	1.11		15.38	44.43	.03	.35	1.11		-53.19	43.28	-.12	-1.23	1.11	
Total R ²						.02						.01						.01
Note. * $p < .05$.																		

Note. * $p < .05$.

Table 12
Original ANT Alerting Reaction Time (RT) and Conflict Error Rates (ER) Hierarchical Regression Analyses Using Combined Model (Receptive & Expressive Vocabulary)

Variable Entered	Alerting (RT)					Conflict (ER)						
	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2
Step 1						.04						.01
Income	4.37	5.25	.08	.83	1.00		-.003	.01	-.03	-.36	1.00	
K-BIT	-.53	.67	-.07	-.79	1.00		-.002	.001	-.19	-2.05*	1.00	
Step 2						.05						.05
Income	1.59	5.43	.03	.29	1.11		-.01	.01	-.11	-1.10	1.11	
K-BIT	-.34	.67	-.05	-.51	1.04		-.002	.001	-.20	-2.20*	1.04	
PPVT ratio	-140.01	63.66	-.24	-2.20*	1.42		-.04	.10	-.04	-.39	1.42	
EVT ratio	9.10	50.29	.02	.18	1.48		-.14	.08	-.21	-1.89	1.48	
Total R ²						.13						.06

Note. * $p < .05$.

Table 13
Original ANT Conflict Error Rate (ER) Hierarchical Regression Analyses By Flanker, Using Model 2 (Expressive Vocabulary)

Variable Entered	Congruent (Acc)					Incongruent (Acc)				
	B	SE B	β	t	ΔR^2	B	SE B	β	t	ΔR^2
Step 1					.03					.06*
Income	-.01	.01	-.15	-1.60		-.01	.01	-.12	-1.33	
K-BIT	.00	.001	-.05	-.48		-.002	.001	-.21	-2.26*	
Step 2					.001					.04*
Income	-.01	.01	-.14	-1.43		-.02	.01	-.08	-1.93	
K-BIT	.000	.001	-.04	-.45		-.003	.001	-.22	-2.48*	
EVT ratio	.01	.05	.03	.30		-.15	.07	-.20	-2.13*	
Total R ²					.03					.10

Note. * $p < .05$.

Next, results for the new ANT calculations are presented. VIF values were all below 4, indicating the absence of multicollinearity problems.

Table 14 includes the regression results for the first model with receptive vocabulary, for the accuracy and RT of the three network scores. The results for the inter-network relations showed no significant models nor predictors, hence they are not presented. PPVT ratio did not emerge as a significant predictor in any of the results, although with alerting RT, PPVT ratio was nearing significance, $\beta = -.18, p = .07, B = .12, 95\% \text{ CI } [-.01, .25], F(3,113) = 1.98, p = .12, R^2 = .05, \Delta F = 3.39, p = .07$, which is consistent with the results in the original ANT scores.

Table 15 presents the regression results for the second model with expressive vocabulary, for the accuracy and RT of the three network scores. Again, there were no significant models for the inter-network scores. EVT ratio was not a significant predictor for any of the ANT scores, although there it was nearing significance as a predictor for conflict RT, $\beta = -.18, p = .06, B = -.12, 95\% \text{ CI } [-.25, .01], F(3,113) = 2.71, p = .05, R^2 = .07, \Delta F = 3.49, p = .06$.

Finally, both vocabulary ratios were entered as predictors into the same model, to predict the two scores previously seen to have marginal significance; alerting RT and conflict RT. Table 16 presents the results. For alerting RT, although the overall model was not significant, PPVT ratio emerged as a significant predictor, $\beta = .24, p = .03, B = .17, 95\% \text{ CI } [.01, .32], F(4,111) = 1.81, p = .13, R^2 = .06, \Delta F = 2.33, p = .10$. For conflict RT, neither the model nor any of the predictors emerged significant.

In summary, for the original ANT scores, PPVT_{Chinese} and PPVT ratio were significantly related to alerting RT, while EVT_{Chinese} and EVT ratio were

significantly related to conflict accuracy. For the new ANT scores, EVT_{English} and EVT_{Chinese} were related to conflict accuracy. However, results in general were inconsistent across analysis methods. Additionally, EVT_{Chinese} was also related to alerting RT, while $PPVT_{\text{Chinese}}$ was also related to conflict accuracy. Differences in results across different calculations will be addressed in the next section.

Table 14
New ANT Accuracy (Acc) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 1 (Receptive Vocabulary)

Variable Entered	Alerting (Acc)					Orienting (Acc)					Conflict (Acc)						
	B	SE B	β	<i>t</i>	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2
Step 1					.004						.02						.05
Income	.01	.01	.04	.44	1.00	-.01	.01	-.12	-1.26	1.00		.01	.02	.06	.58	1.00	
K-BIT	.001	.001	.05	.53	1.00	-.001	.001	-.09	-.95	1.00		.004	.002	.21	2.26	1.00	
Step 2					.02						.01						.01
Income	.001	.01	.01	.11	1.06	-.01	.01	-.10	-.99	1.06		.01	.01	.07	.77	1.06	
K-BIT	.001	.001	.06	.67	1.01	-.001	.001	-.10	-1.05	1.01		.004	.002	.20	2.15	1.01	
PPVT ratio	-.16	.11	-.13	-1.32	1.07	.09	.09	.10	1.03	1.07		.13	.14	.09	.91	1.07	
Total R ²					.02						.03						.05
Step 1					.02						.001						.04
Income	-.01	.01	-.13	-1.38	1.00	-.002	.01	-.03	-.26	1.00		-.02	.01	-.20	-2.12	1.00	
K-BIT	.001	.001	.08	.85	1.00	.00	.001	-.01	-.12	1.00		.00	.001	-.01	-.08	1.00	
Step 2					.03						.02						.004
Income	-.01	.01	-.09	-.93	1.06	-.004	.01	-.05	-.56	1.06		-.02	.01	-.21	-2.22	1.06	
K-BIT	.001	.001	.06	.67	1.01	.00	.001	.002	.02	1.01		.00	.001	-.001	-.01	1.01	
PPVT ratio	.12	.07	.18	1.84	1.07	-.11	.08	-.13	-1.36	1.07		-.06	.08	-.07	-.69	1.07	
Total R ²					.05						.02						.04

Table 15
New ANT Accuracy (Acc) and Reaction Time (RT) Hierarchical Regression Analyses Using Model 2 (Expressive Vocabulary)

Variable Entered	Alerting (Acc)					Orienting (Acc)					Conflict (Acc)							
	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2
Step 1						.004						.02						.05
Income	.01	.01	.04	.44	1.00		-.01	.01	-.12	-1.26	1.00		.01	.01	.05	.58	1.00	
K-BIT	.001	.001	.05	.52	1.00		-.001	.001	-.09	-.95	1.00		.004	.002	.21	2.26*	1.00	
Step 2						.01						.001						.03
Income	.001	.01	.01	.07	1.10		-.01	.01	-.11	-1.11	1.10		.02	.01	.10	1.09	1.10	
K-BIT	.001	.001	.04	.42	1.01		-.001	.001	-.09	-.92	1.01		.004	.002	.22	2.43*	1.01	
EVT ratio	-.10	.09	-.11	-1.13	1.11		.02	.07	.03	.27	1.11		.20	.11	.17	1.74	1.11	
Total R ²						.02						.02						.08
Step 1						.02						.001						.04
Income	-.01	.01	-.13	-1.38	1.00		-.002	.01	-.03	-.26	1.00		-.02	.01	-.20	-2.12	1.02	
K-BIT	.001	.001	.08	.85	1.00		.00	.001	-.01	-.12	1.00		.00	.001	-.01	-.08	1.02	
Step 2						.00						.00						.03
Income	-.01	.01	-.13	-1.33	1.10		-.002	.01	-.02	-.23	1.10		-.02	.01	-.25	-2.61*	1.39	
K-BIT	.001	.001	.08	.84	1.01		.00	.001	-.01	-.12	1.01		.00	.001	-.02	-.25	1.24	
EVT ratio	-.003	.05	-.01	-.05	1.11		.003	.06	.004	.04	1.11		-.12	.06	-.18	-1.87	1.67	
Total R ²						.02						.001						.07

Note. * $p < .05$.

Note. * $p < .05$.

Table 16
New ANT Alerting Reaction Time (RT) and Conflict RT Hierarchical Regression Analyses Using Combined Model (Receptive & Expressive Vocabulary)

Variable Entered	Alerting (RT)					Conflict (RT)						
	B	SE B	β	<i>t</i>	VIF	ΔR^2	B	SE B	β	<i>t</i>	VIF	ΔR^2
Step 1						.02						.04
Income	-.01	.01	-.13	-1.38	1.00		-.02	.01	-.20	-2.12	1.00	
K-BIT	.001	.001	.08	.85	1.00		.00	.001	-.01	-.08	1.00	
Step 2						.04						.03
Income	-.01	.01	-.11	-1.15	1.11		-.02	.01	-.25	-2.57	1.11	
K-BIT	.00	.001	.05	.48	1.04		.00	.001	-.03	-.29	1.04	
PPVT ratio	.17	.08	.24	2.16*	1.42		.03	.09	.04	.28	1.42	
EVT ratio	-.07	.07	-.13	-1.13	1.48		-.13	.07	-.19	-1.75	1.48	
Total R ²						.06						.07

Note. * $p < .05$.

Discussion

We investigated the relationship between bilingual balance and attentional control by comparing bilingual preschoolers with differing extents of language exposure and production. Using the Child-ANT, which separates attention into three networks, as well as two different sets of calculations to understand inter-network relations, various relationships were found between balance of bilingual language exposure and production with different aspects of attentional control. For the original ANT calculation method, higher language exposure balance, operationalized by receptive vocabulary ratio, was associated with faster alerting reaction times. This relationship was evidenced by correlations between PPVT ratio and ANT alerting RT, and supported in the regression analysis where PPVT ratio remained associated with alerting RT even after controlling for other key variables. There was also some support that language production balance, operationalized by expressive vocabulary ratio, was related to higher accuracy in conflict monitoring. There was a significant correlation found between EVT ratio and ANT conflict error rates; and in regressions controlling for key variables, EVT ratio emerged as a significant predictor in conflict error rates.

Additionally, across calculation methods for the ANT, there were inconsistencies in the findings. The new ANT calculation method revealed only correlations between the vocabulary scores themselves with the ANT network scores, but not the vocabulary ratios, and none of the regression models showed significance. The more consistent finding across both the original and new calculation methods was the correlation between PPVT and EVT scores in

Chinese with conflict accuracy; increased expressive vocabulary scores were associated with smaller conflict effect.

These findings support the overarching hypothesis that more-balanced bilinguals, as compared to less-balanced ones, are more able to manage their attentional capabilities and employ the suitable mechanism according to demands. However, the two separate relationships previously hypothesized (receptive vocabulary with alerting and expressive vocabulary with conflict) are likely not entirely accurate; the two relationships are not so well defined in the findings, as receptive vocabulary was also related with conflict, and expressive vocabulary was also associated with alerting when the different calculation methods were employed.

In terms of specific attentional networks, our hypotheses highlighted separate relations for language exposure and language production, and the differences in the two networks were intended to demonstrate how different aspects of language management may be inherently distinct. For language exposure, balance bilingual language exposure was suggested to have some positive impact on the achieving and maintenance of the alertness of the individual, and this is related to the individual's cue detection ability. For language production, the extent of balance in bilingual language production was expected to be related to performance in overcoming conflicting irrelevant information. However, although there was evidence in the direction of the hypotheses, there were findings for both types of vocabulary on both the alerting and conflict network. There were also different results depending on which version of the network calculations were used. Our conjecture is that firstly, the differences in scores between the original and new ANT calculations

are in part driven by the differences in the conditions used to calculate the results. For alerting RT, the original calculations involve using the average of both congruent and incongruent flanker scores, while the new calculations only involve the congruent flankers. For conflict accuracy, the original calculations involve using the average of all three cues, while the new calculation involve only using the no cue condition. Given that the different calculations used different conditions of the ANT, and performance outcome of the task was designed to differ as a consequence of condition, it is not surprising that the scores are not the same. Additionally, for the new calculations, the number of trials of which the accuracy and RT results were taken from is smaller than that of the original calculations (12 as compared to the original 24 or 36). Since children are not very consistent, having different number of trials from which to gauge a child's performance may result in a substantial difference in scores. The paper by Wang et al. (2014) studied young adults in their paper to support the use of the new calculations, and their participants had much higher accuracies (above 0.94 for all conditions) and smaller variances in their results. Hence, it is likely that more research would be needed in order to accurately apply the use of this calculation to the child population.

Secondly, another factor contributing to the mixed bag of findings is the likely inter-network interferences inherent in the design of the ANT. In general, the calculations would not result in inter-network interferences if the different cues affected each flanker similarly, and vice versa; this would be indicated by the lack of significance when analyzing cue by flanker interactions for accuracy and RT. However, in our current sample, there was an interaction effect found for accuracy, with the no cue-incongruent condition having significantly lower

accuracy than other cue and flanker combinations, suggesting that the alerting and conflict effect may have affected the performance in that condition concurrently. Hence, despite our efforts to isolate the two networks, some overlap was inherent within the design of the task. This would explain the differences in performance scores when using different calculations (which focus on different conditions), and also be a possible reason why both types of vocabulary, receptive and expressive, were found to be related to both alerting and conflict network scores.

Thirdly, there were also correlations found between the two types of vocabulary in each language, suggesting that performances on the vocabulary tasks were related. Thus, the difficulty in isolating the two types of vocabulary and two attention networks likely contributed to the mixed findings between the vocabulary scores, alerting and conflict networks. More extensive investigation into these relations in the future is warranted, to examine their relative dependence or independence. Nonetheless, the findings still support the overall hypothesis that higher vocabulary balance is related to better attentional control.

For the two different relations found in the study, it is noteworthy that results for conflict were found in association with accuracy/error rate while results for alerting were found in association with reaction time. We speculate one possible reason why this is so is due to the difficulty of each condition. Across all cue types, the incongruent condition was more difficult for our sample; errors were higher than the congruent condition and reaction times (for correct trials) were slower as well. Since reaction time is less meaningful when accuracy is not high, this could be a reason why significant results were seen for error rates in conflict scores but not reaction time. On the contrary, because

accuracy is higher for the no cue and center cue conditions, significant results were seen for reaction times and not error rates in alerting scores. This would perhaps account for why each network score ended up with a different performance indicator.

Another important finding in this study was how the vocabulary scores in the two languages were found to be correlates of alerting and conflict scores more consistently than the ratio score. This is noteworthy given that we reasoned that the relation between the proficiencies of the two languages would be a better indicator than simply the proficiency of the weaker language, but our current results suggest this might not be the case. Correlations between the dominant language proficiency and attention network task performance are likely an effect of the individual's inclination towards language mastery, or other general language related cognitive development. However, correlations with the weaker language vocabulary in our sample were found to be related to the attention network scores, sometimes to a greater extent (larger correlation coefficients) than the ratio scores. Given that ratio scores are strongly related to the vocabulary scores of the weaker language, it is likely that the proficiency of the weaker language itself plays a significant role in the relation to attention control. This suggests that the amount of exposure and production of a child in their weaker language is itself a significant predictor of alerting and conflict monitoring. This is a point that will be revisited in Study 3: the results also seem to suggest an important role of weaker language exposure in helping to improve attention control.

The main findings are in line with recent research on variability of bilingualism proficiency and balance on cognitive control, of which a number

of current literature focus on executive functioning. As mentioned in the literature review, this research developed from the initial idea of a general bilingual advantage in executive functioning over monolinguals, but due to mixed findings in the field, increased focus was put on the within-group variability of bilinguals, namely their language experience, and how this would relate to executive control. Studies that have taken into account bilingual balance and proficiency of their participants have found better performance in attentional control tasks for more-balanced bilinguals as compared to less-balanced bilinguals (e.g. Sorge, Toplak & Bialystok, 2016; Poarch & van Hell, 2012; Videsott et al., 2012). In this thesis, we have also adopted this within-group bilinguals comparison and found a relationship comparable to those previous studies. It is important to note that in the present study, there was no monolingual comparison group, hence it would not be sufficient to conclude that we found support for the bilingualism advantage over monolinguals. However, there is reason to believe that the results are indicative of the trend. A prior study comparing bilingual and monolingual adults found a bilingualism advantage on the ANT that extended only to conflict and alerting dimensions (Costa, Hernández, & Sebastián-Gallés, 2006), findings that are in line with ours. Hence, it is important that future studies intending to compare bilinguals and monolinguals on executive functioning should also take into account bilingualism proficiency and balance of their bilingual participants, while taking monolinguals as an extreme end on this balance spectrum. More information on the bilinguals' relative dual language exposure and production could be the answer to the debate on why bilinguals seem to have advantages in some studies but not others.

One of the drawbacks of this study was that the children did not seem to exhibit a clear orienting effect. It may be that the children only noticed a difference between the presence and absence of a cue, but was not aware of where the cue was on the screen. They were not explicitly instructed regarding the cues, which may be the reason why there were no significant differences between the center cue and spatial cue conditions.

Given the importance of attention development, especially in young children, the results suggest that bilingual experience may heighten attentional control. As evidenced by the findings, increase in balance of bilingual experiences correlate with better attentional control abilities. Hence, the next line of research is to examine the mechanisms behind why more-balanced bilinguals perform better than less-balanced bilinguals on the ANT. So far, the studies presented in this thesis have been correlational; it is not possible to identify whether better language balance improves attentional control causally. Hence, an experimental study is needed to further examine this issue.

CHAPTER 5

STUDY 3

Rationale of the present study

In Study 2, it was found that more-balanced bilinguals, compared to less-balanced ones, were better able to control their attention to better achieve and sustain an alert mind, and were also more apt at overcoming distracting stimuli to complete their goal. This therefore begs the question, how do more-balanced bilinguals differ from less-balanced ones? In the current study, we will focus on two main differences.

Firstly, for more-balanced bilinguals, the amount of time spent with the weaker language is larger than the less-balanced bilinguals. This was shown in the results from Study 1; higher vocabulary balance was associated with an increase in weaker language experience and a decrease in dominant language experience. As previously illustrated in our proposed contextual-based attention control perspective, the need to deal with the weaker language requires a high amount of attention when proficiency is low, in order to successfully monitor for and select the weaker language. As proficiency increases, less conscious attentional control is needed. Hence, assuming their exposure has been in similar language proportions while growing up, the more-balanced bilinguals would have undergone the process of training their attention control through the consistent exposure and use of their weaker language. The less-balanced bilinguals would have had less of such experience, and would thus be comparatively less competent in attention control. Hence, for less-balanced bilinguals, increasing the exposure of their weaker language is likely to allow them to further fine-tune their cue detection and conflict monitoring skills due

to the context increasing the need for them to identify and select the relevant language to engage in.

Secondly, another possible difference between more and less-balanced bilinguals resides in language switching. By virtue of the less dominant-skewed exposure to both languages, more-balanced bilinguals are more likely to experience language switching than less-balanced bilinguals. For less-balanced bilinguals, there is a lower likelihood of having to switch between languages, given that they are primarily surrounded by their dominant language, and have little to no incentive to switch to their weaker language. This is especially the case in the Singapore context, where most Chinese people do not limit their use of a certain language to a certain situation, since most of the population is Mandarin bilingual, albeit to differing extents. According to the Adaptive Control hypothesis, when bilinguals switch between languages, on top of identifying the language to be used, it is necessary to inhibit the previously spoken language, disengage the task of speaking said language, and allow the new language to the forefront to engage it. This sequence of events requires aspects of attentional control such as conflict monitoring, activation and suppression. Previous research has also suggested that such language switching relates to task switching performance in young adults, with Spanish-English bilinguals who regularly switch between languages exhibiting smaller switch costs on the colour-shape sorting task than Mandarin-English bilinguals in their sample who seldom language-switch, as well as English monolinguals (Prior & Gollan, 2011). Thus, it is plausible that, on top of having to detect the relevant language to be used, the language-switching experience in more-balanced

bilinguals also allows them more rehearsal in attentional control, hence resulting in them having better attentional control than less-balanced bilinguals.

It is important to note that we acknowledge that more-balanced bilinguals need not be frequent language switchers; it is possible that some balanced bilinguals use their two languages in completely different contexts, hence they do not engage in frequent language switching. Since proficiency is a consequence of usage, and usage in children is often directly related to exposure, this would mean that the more-balanced bilingual would need to be exposed to both language to a similar extent, in different settings. In our sample population this is less common than in other countries where there is one dominant societal language and often a separate home language for bilinguals; in Singapore, most situations can be considered mixed language contexts. On top of that, the children in our sample population undergo bilingual education; school serves as a mandatory dual language environment for all young bilinguals in Singapore. Hence, for our population, language switching is likely to be positively related to bilingualism balance.

Additionally, we deem the amount of time being exposed to mixed language contexts and the actual amount of language switching occurring to be separate. In a mixed language context, the context itself demands certain cognitive processes, such as cue detection in the event that a new language arises. However, it is possible to be in that high monitoring context with or without actually switching languages; when there is an expectation that you might have to switch but your conversational partner does not, therefore you also do not. This is thus the reason why we have chosen to separately consider each language context (dominant and weaker languages) independent from

language switching. This separation of the factors also allows us to examine the difference, if any, in relations between these phenomena.

As previously mentioned in Chapter 2, we suggested that even in the short term, by increasing exposure towards the weaker language, the less-balanced bilinguals could benefit cognitively from the increased demands of the contexts. When the context increases the attentional demand, the less-balanced bilingual is forced to engage more effort in the interaction; consequently, the effort may carry over to other successive tasks. Conversely, if a more-balanced bilingual is put into a dominant language context, the decreased demand of the context (as compared to a mixed language one) would result in less attentional effort engaged, and this reduction in necessary effort would also carry over to subsequent tasks.

Accordingly, Study 3 was designed to experimentally induce language experiences that would mirror everyday occurrences of the more and less-balanced bilinguals, to evoke a particular language frame within the individual participants. Prior to completing the ANT, children were randomly assigned to one of three conditions: (1) mostly using dominant language (DOM); (2) mostly using weaker language (WEAK); and (3) constant language switching (SWITCH) conditions. In all three conditions, children completed a language frame manipulation task; a picture identification task in which they heard picture names in the relevant language(s) and were required to identify and select the correct picture on the screen given two options. The study was designed with a specific focus on language exposure, with auditory cues in different languages as the primary manipulation. This is because in language learning, comprehension precedes production, hence as a first step, it is

important to understand how exposure to a particular language frame would influence the children's performance on the subsequent attentional task.

Each of the three conditions was designed to emulate particular bilingual language experiences, some occurring more in more-balanced bilinguals while others more evident in less-balanced bilinguals. We chose to induce such bilingual language experiences so as to isolate and identify specific relationships between each language experience and the related attentional networks, something we would not be able to do using observational or correlational methods. All three conditions were dual language in nature, but the extent to which each language was engaged was varied. The DOM condition was designed to evoke a dual language but less-balanced bilingual language frame, with the language experience skewed largely towards using the dominant language. The WEAK and SWITCH conditions were designed to evoke two different dual language experiences that more-balanced bilinguals would undergo, the former being more exposure to their comparatively weaker language, hence increasing the need for attention control to monitor and select the relevant language, while the latter being constant switching between the two languages, resulting in additional demands on detection, as well as activation and suppression of both language frames.

We identify two hypotheses. Firstly, comparing between the three conditions, we hypothesize that for the alerting network, performance on the WEAK and SWITCH conditions will be better than those in the DOM condition, with no significant difference between the former two. As previously mentioned, an increase in contextual demands may lead to an increase in effort needed to manage the context, which would extend to subsequent tasks. In the

WEAK and SWITCH conditions, cue detection, an aspect involved in monitoring for the relevant language to be used, is necessary, and this is related to alerting. For children in the DOM condition, reduced monitoring demands should then result in lower performance in this network.

Secondly, for the conflict network, performance for the SWITCH condition is hypothesized to be better than that in the DOM condition. This is because conflict involves overcoming distractions in order to complete the relevant goal, and this includes suppression of extraneous stimuli, which under language switching refers to the previous language. Thus, because suppression of the previous language (SWITCH condition) is required, performance in this condition is expected to be better than that of DOM condition which does not involve any suppression. It is also possible that the WEAK condition will result in better performance than the DOM condition on the conflict network, because to complete the task in the weaker language also requires suppression of the dominant language. However, it is unclear if these two types of suppression are similar or different in magnitude, hence it would be interesting to see how these two different suppression types would fare in comparison to each other.

One of the assumptions inherent in the design of the study is that the children would, by default, engage in their dominant language when presented with images that they have to identify. This is important because only when they engage their dominant language does presenting them with their weaker language result in conflict that they have to overcome. As a pilot test, we presented some of the participants the stimuli images with no auditory cues, and asked the participants to tell us at the end of the task what language they were using in their head to identify the items. We expect that most participants would

report naming the items in their dominant language, which was determined by vocabulary test. The results of the pilot test are presented in the results section, prior to the main study results.

Methods

Participants

For both the pilot and main study, 105 English-Mandarin Chinese bilingual children attending Kindergarten-1 in Singapore were recruited from local childcare centers (52 males, Age range = 58-71 months, $M = 65.5$, $SD = 3.54$). All parents reported that their children were exposed to both English and Mandarin at home, and all children attended both English and Chinese classes in school, with different teachers for each language.

Measures

Similar to Study 2, all computerized tests were presented on laptops running Windows 7 or 8 operating systems, with children's key presses registered on physical buttons below touchpads on the laptop. Pictures for vocabulary tests were also presented on laptop screens.

Demographic questionnaires. Parents were given a background information questionnaire, which included questions on age, gender, parents' education level, and household income.

Peabody Picture Vocabulary Test-IV (PPVT; Dunn & Dunn, 2007).

The receptive vocabulary tests were administered separately for each language, as per Studies 1 and 2.

Kaufman Brief Intelligence Test-2 (KBIT; Kaufman & Kaufman, 1990). This measure of non-verbal intelligence was administered to control for group differences in non-verbal reasoning skills between conditions, if any.

Child Attention Network Task – Shortened (ANT; Rueda et al., 2004). The ANT used was the same as that in Study 2. Again, participants were scored separately on their error rate and median reaction time (Rueda et al., 2004). Only correct trials were used in the computation of reaction time.

Picture Identification Task. The picture identification task was designed for the purposes of the present study, to evoke particular language frames that corresponded to language experiences that more or less-balanced bilinguals would experience. Three different versions of the picture identification task were created: an English version, a Mandarin version and a mixed language version. For all three versions, there were 105 trials in total, split into five practice trials, three blocks of 32 trials each, and four trials of manipulation check.

Across all three language versions, the instructions given and practice trials were the same. Children were told that this was a game in which they had to listen to the words presented through headphones and identify which of the two pictures on the screen was the item being named. They had to select the correct picture by clicking the button on the touchpad of the laptop that corresponded with the location of the picture (right side button for the right picture and vice versa). Computers were set to recognize clicks on each side separately, and accuracy and RT of the trials were recorded. They were also explicitly instructed that the task involved both languages, and that sometimes there would be language switches. To illustrate this, in the five practice trials,

the first two were items in English, the next two were in Mandarin, and the final item was in English again.

Target item pictures presented to the children were the same across conditions, and only varied in language (depending on the condition) and order of presentation, which was randomized. Items were single syllable (in English), single word (in Mandarin) nouns or verbs, ranging from animal names, toys, parts of the body to facial expressions. Items and pictures were selected from the first three blocks of the PPVT, the EVT, and also included other items that children in the population were deemed to be familiar with, across both English and Mandarin. According to the PPVT, items from the first three blocks were supposed to be items that were learnt before age five, which is approximately the age of the participants in this study. Hence, participants were unlikely to be unfamiliar with the target items. The items were intentionally chosen to be easy and for the task to be manageable, since the purpose was to elicit the language frame and not to tire the participants cognitively. Distractor items were words that either rhymed with or sounded similar to target items in English, or fell in the same item category as the target (e.g. hand and foot). There were 24 different target items and 27 different distractors, out of which 16 pairs were chosen and presented per block twice, resulting in 32 items. A detailed list of items is presented in Appendix B. In the pure English and Mandarin conditions, the same target items were presented twice. Hence in the single language conditions, all 96 items were in the same language, and order of items was fully randomized within blocks.

For the mixed language condition, target item pictures were presented once in each language. There were an equal number of items in each language

(48 each). Items were grouped into fixed sets of eight, with a total of four sets per block, and the order of the four sets was randomized instead of randomizing by trial. This allowed us to fix the number of English to Mandarin (and vice versa) switches across participants to keep it consistent for all; true randomization by trial would likely not allow for such consistency. Within each set of eight, the first and last items were always in English, while the items in the middle had varying number of English-to-Mandarin and Mandarin-to-English switches (range of between two to six).

For each trial, a black fixation cross on a white background was first presented on the screen for 500ms, followed by a blank screen for 1000ms, during which the audio clip naming the target stimuli was played. This was followed by the presentation of both the target and distractor picture items side by side, one on each side of the screen. The child was then tasked to select the named item by pressing the button that corresponded to the side that the image was on. There was no limit to the amount of time that could be spent on this screen. After the child had made his/her selection, the blank screen was again presented, this time for 500ms, before the next trial began. The position of the correct item on the screen (left or right side) was preset, but equally distributed among items. Audio clips played to the children were pre-recorded by the PhD student in charge, and the same person recorded both languages. Children were allowed brief periods of rest between blocks of testing, if they desired.

After the test trials, participants immediately went through four trials of manipulation check. The manipulation check was to ensure that the single language test conditions had successfully put the participants in a single language frame, especially those who were doing the task in their dominant

language. The four target items were the same across all conditions, presented in the same order, and were novel items that were previously not tested. Auditory clips were presented in the language that was different from the primary task; for the pure English condition, the items were presented in Mandarin, and for the pure Mandarin condition, the items were presented in English. For the mixed language condition, the first two items were in Mandarin (switched from the last test trial which was always English) while the last two were in English.

An additional non-auditory version of the picture identification task was created for the pilot test participants. In this condition, the child was told that he/she would be looking at some pictures, and to pay attention to the pictures being presented. For each trial, after the fixation cross was presented for 500ms, a blank screen was presented for 1000ms, followed by the target item picture. The target items, same as those in the other conditions of the task, were presented in the middle of the screen one by one, each remaining on the screen for 1500ms. Finally, a blank screen was presented for 500ms. Trials were also in three blocks of 32 each, with an additional four items at the end, which were the target items used in the manipulation check in the other conditions. Children were not explicitly instructed to identify the pictures, although some of them did so spontaneously. In between blocks, children were briefly asked questions about the pictures they saw (e.g. “What animals were there?” or “Which was your favorite picture?”) but the answer to the questions were not recorded as they were not deemed to be important beyond ensuring that the child was indeed paying attention to the images.

Procedure

The pre-testing procedure was similar to Study 2, with parents having to give consent and complete the demographics form before testing.

Children were tested individually, in a quiet room in the child's childcare centre. Each child was tested in two separate sessions, and both sessions were conducted at least a day apart. No child underwent two sessions in a day. This was so that the child would not be fatigued over the course of testing.

Experimenters (three in total including the PhD student in charge) were all fluent English-Mandarin bilinguals, and each child was accompanied by an experimenter throughout the entire testing session.

For the pilot test, participants were first tested on the PPVT in both languages (English and Mandarin), with the order counterbalanced. This was to identify the child's language dominance. For the second session, the child completed the non-auditory version of the picture identification task. Lastly, the child was asked on their perceived difficulty of the picture identification task they had done. Instructions for tasks other than PPVT were presented in the language that the child expressed to be more comfortable conversing in, usually English.

For the main study, prior to testing, conditions were randomly assigned to participant numbers, and participant numbers were assigned to children approximately according to their time of return of consent form, such that those whose parents returned the form earlier and were tested earlier had smaller participant numbers. However, conditions were not assigned in any particular order, hence the assignment was kept as random as possible. For mainly single language conditions (DOM and WEAK), participants were assigned a language

to be tested in, and language dominance was determined after testing was over. This meant that each child had an equal chance of being assigned to complete the English or Mandarin task, and only after testing was completed was it determined if the child belonged in the DOM or WEAK condition.

In the first session, the child was tested on the PPVT in both languages (English and Mandarin), with the order counterbalanced. For the second session, the child was first taught how to play the ANT, and given one block of twelve trials as practice. Then, the child completed the picture identification task according to their assigned condition, before immediately moving on to the ANT test trials. This was so as to minimize the delay between the picture identification task and the ANT, to allow for the language framing effects to carry over. Lastly, the child completed the KBIT, and as part of the debrief, was asked on their perceived difficulty of the picture identification task they had done. Instructions for all other tasks, except the PPVT which had prescribed language for instructions, were presented in the language that the child expressed to be more comfortable conversing in, usually English. At the end of the session, all children were given stationery or small toys as reward for participation.

Results

For all statistical tests, an alpha level of .05 was used.

Pilot test results

The pilot test involved 25 of the participants recruited for the study. Out of the 25, 22 showed higher scores in PPVT_{English}, while three had higher scores in PPVT_{Chinese}. When asked about which language they used to identify the

pictures presented to them in the non-auditory picture identification task, 19 of the 22 English dominant children reported using English, and two of the Mandarin dominant children reported using Mandarin. Three of the English dominant children reported using Mandarin as that was their preferred language, and one Chinese dominant child reported using English. Hence, a majority (80%) of the children reported identifying the pictures in their dominant language. This finding allows us to assume that in most cases, children are likely to identify pictures in their dominant language, hence presenting a label in a different language is likely to be cognitively demanding to them.

As a side analysis, on a difficulty scale of one to three (one being the easiest), the mean difficulty score reported for the task was 1.36. This showed that the items were fairly easy to identify and hence the task was not likely to be cognitively draining.

Preliminary analyses

The final sample on which subsequent analyses were conducted was 71 (37 males, Age range = 58-71 months, $M = 65.72$, $SD = 3.70$). Out of the remaining 80 participants recruited (excluding the pilot study participants), two participants did not finish testing due to personal reasons, four participants did not understand the ANT task and performed poorly, two participants had very low accuracy for individual conditions in the ANT (about 20% accuracy), and one participant's data was not saved due to a computer error. Out of these excluded participants, three were assigned to DOM condition, five were assigned to WEAK condition and one was assigned to SWITCH condition. Participants who were excluded were not significantly lower in their

performance on the PPVT in either language or on KBIT ($p > .12$). They were significantly lower on overall ANT accuracy ($t(76) = -8.84, p < .001$) as compared to those included.

There were no gender differences across any of the tests ($ps > .12$), nor any differences attributed to the order of which PPVT language was presented first ($ps > .18$). Due to a disproportionate number of participants being tested by different experimenters (71.7% of the participants were tested by the PhD student in charge), there were differences in overall accuracy ($F(2,75) = 4.25, p = .02$) of ANT when comparing between experimenters. However, within conditions, there was an approximately even number of participants tested by the other two experimenters (approximately three in each condition), so experimenter differences were not expected to affect the manipulation nor the results.

Demographics analyses (across conditions)

Children's language dominance was determined by their relative performance on the PPVT. The DOM and SWITCH conditions consisted of mostly English dominant children, with eight children in each condition identified as Mandarin dominant. For the WEAK condition, six of the children were Mandarin dominant; the rest were English dominant. Since assignment was random and language dominance was not important in this study, all participants regardless of language dominance were included.

To ensure that the random assignment reduced systematic errors, analyses were conducted to determine if there were any differences between the groups in terms of gender makeup, family income, average age, receptive

vocabulary scores, ratios, and non-verbal intelligence. Table 17 shows a summary of the values for each condition.

Table 17

Summary/Mean and Standard Deviations of Demographics by Condition

	DOM condition (<i>n</i> = 25)	WEAK condition (<i>n</i> = 21)	SWITCH condition (<i>n</i> = 25)	Overall (<i>n</i> = 71)
Gender	16 F (64%), 9 M (36%)	8 F (38%), 13 M (62%)	10 F (40%), 15 M (60%)	34 F (48%), 37 M (52%)
Income	4.71 (1.49) (<i>n</i> = 34)	4.60 (1.31) (<i>n</i> = 20)	4.73 (1.42) (<i>n</i> = 22)	4.68 (1.39) (<i>n</i> = 66)
Age	66.04 (3.57)	66.29 (3.73)	64.92 (3.81)	65.72 (3.70)
PPVT _{Dom}	89.48 (16.62)	85.95 (16.75)	93.12 (16.21)	89.72 (16.53)
PPVT _{Weak}	52.04 (19.60)	54.95 (19.88)	56.92 (20.35)	54.62 (19.77)
PPVT ratio	.17 (.30)	.19 (.24)	.17 (.27)	.18 (.27)
KBIT	103.16 (15.69)	105.33 (11.97)	109.36 (14.09)	106.00 (14.16)
Reported Difficulty	1.42 (.58) (<i>n</i> = 24)	1.62 (.67) (<i>n</i> = 21)	1.58 (.65) (<i>n</i> = 24)	1.54 (.63) (<i>n</i> = 69)

Note. Age in months. *SDs* presented in parentheses. DOM = mainly dominant language condition; WEAK = mainly weaker language condition; SWITCH = switching between both languages condition; PPVT_{Dom} = PPVT score in the dominant language; PPVT_{Weak} = PPVT score in the weaker language.

For gender, chi-square analysis showed no significant relationship between gender and experimental condition, $\chi(2) = 4.03, p = .13$. Separate one-way ANOVAs conducted for reported income ($F(2,63) = .05, p = .95; n = 66$ due to missing data), age ($F(2,68) = .92, p = .41$), PPVT_H ($F(2,68) = 1.08, p = .35$), PPVT_L ($F(2,68) = .38, p = .69$), PPVT ratio ($F(2,68) = .04, p = .96$) and KBIT scores ($F(2,68) = 1.24, p = .30$) were not significant, confirming that across the experimental conditions, none of the variables were systematically different.

Additionally, a one-way ANOVA was also conducted to compare the reported difficulty levels of the different picture identification tasks used in the different conditions. Each child reported on a scale of 1-3, one being easy, two being normal and three being hard, how they perceived the difficulty of the task to be. Data was missing for two participants, but for the remaining, there were no significant differences in the reported difficulty of the task across the conditions ($F(2,66) = .67, p = .52$).

Picture identification task performance

To ensure that the picture identification task was completed correctly and to determine if it was successful in putting the participants in the appropriate language frame, analyses were done on the performance of the picture identification task. Table 18 presents the means and standard deviations of each performance variable of interest across the multiple conditions (DOM, WEAK and SWITCH conditions).

Table 18
Means and Standard Deviations of Accuracy and RT for Picture Identification Task

	DOM condition (<i>n</i> = 25)	WEAK condition (<i>n</i> = 21)	SWITCH condition (<i>n</i> = 25)	Overall (<i>n</i> = 71)
Test trials Accuracy	.92 (.10) _a	.94 (.09) _a	.97 (.03) _a	.95 (.08)
Test trials RT (ms)	1039.79 (237.98) _a	977.19 (156.39) _a	987.40 (135.68) _a	1002.30 (182.02)
Manipulation trials Accuracy	.79 (.24) _a	.94 (.13) _b	.97 (.08) _b	.90 (.18)
Manipulation trials RT (ms)	2426.83 (1773.77) _a	1439.14 (727.52) _b	1276.20 (411.95) _b	1719.59 (1237.07)

Note. SDs presented in parentheses. DOM = mainly dominant language condition; WEAK = mainly weaker language condition; SWITCH = switching between both languages condition. Within rows, means that do not share subscripts differ significantly at $p < .05$, after Bonferroni adjustment.

The overall accuracies of the tasks were high across conditions, with the poorest person performing at 67% accuracy, indicating that the task was relatively easy for the children. Comparing across the conditions, there was no significant difference in overall accuracy ($F(2,69) = 2.40, p = .10$). There was also no significant difference across conditions in the median RT across trials ($F(2,69) = .79, p = .46$).

For the manipulation check trials, there was a significant difference found across conditions, in accuracy ($F(2,69) = 7.74, p < .001$) and RT ($F(2,69) = 7.15, p = .002$). For accuracy, post hoc analyses with Bonferroni correction revealed a significant difference between the DOM and WEAK conditions, with participants in the DOM condition having lower accuracy on the manipulation check trials than those in the WEAK condition ($-0.15, p = .01$). There was also a difference found between DOM and SWITCH condition, with the participants in the DOM condition having lower accuracy compared to those in the SWITCH condition ($-0.18, p = .001$). For RT, post hoc analyses with Bonferroni correction revealed significant differences between the participants in the DOM condition with both WEAK and SWITCH conditions. Those in the DOM condition took much longer to complete the trials than those in either the WEAK ($-987.69 \text{ ms}, p = .02$) or SWITCH ($-1150.63 \text{ ms}, p = .002$) conditions. Given that, in the DOM condition, the manipulation check trials were set to be in a different language than the test trials, the lowered accuracy and slower RTs suggest that the DOM condition did indeed induce the dominant language frame in the participants, making it difficult for them to switch to another language. However, the WEAK condition was not able to keep the participants in the language frame of the weaker language, as they successfully switched

languages and completed the manipulation trials in their dominant language without trouble.

Preliminary ANT analyses (All participants)

Before calculating attentional network scores (Alerting, Orienting, Conflict), analyses were conducted on ANT raw scores, split by cue X flanker conditions. Table 19 presents the means, standard deviations, skewness and kurtosis of accuracy and median RT for each cue and flanker condition in the ANT.

Table 19

Means, Standard Deviations, Skewness and Kurtosis of accuracy and median RT for each cue and flanker condition in ANT

Flanker Type	Cue Type								
	No cue	Centre cue	Spatial cue						
<i>(1) Accuracy</i>				<i>Skewness (SE = .29)</i>			<i>Kurtosis (SE = .56)</i>		
Congruent	.90 (.09)	.89 (.12)	.91 (.11)	-1.11	-2.11	-1.39	1.28	6.68	1.52
Incongruent	.80 (.17)	.81 (.16)	.81 (.17)	-1.15	-1.06	-1.06	.62	1.05	.73
<i>(2) Median RT (ms)</i>									
Congruent	973.00 (141.39)	904.14 (126.72)	940.53 (119.29)	.92	.67	.29	3.15	.12	-.34
Incongruent	1045.54 (145.03)	1005.64 (141.69)	1010.56 (140.70)	.21	.45	-.25	.57	-.41	.43

Note. $N = 71$. *SDs* presented in parentheses. RT scores are in milliseconds.

Separate 3 (Cue: no cue, center cue and spatial cue) X 2 (Type of flankers: congruent and incongruent) ANOVAs were conducted to examine variance of children's performance across cues and flankers, on error rate and reaction time respectively.

For accuracy, a main effect of flanker was found ($F(1,70) = 53.51, p < .001, \eta_p^2 = .43$), but no main effect of cue ($F(2,140) = .21, p = .81, \eta_p^2 = .003$)

nor an interaction effect ($F(2,140) = .84, p = .44 \eta_{p2} = .01$) was found.

Incongruent flankers resulted in lower accuracy across all cue conditions as compared to congruent flankers.

For RT, main effects of both cue ($F(2,140) = 14.65, p < .001 \eta_{p2} = .17$) and flanker ($F(1,70) = 74.53, p < .001 \eta_{p2} = .52$) emerged, but no interaction effect was found ($F(2,140) = 1.35, p = .26 \eta_{p2} = .02$). Across both flankers, the center cue and spatial cue conditions resulted in similar reaction times, and both conditions were significantly faster than the no cue condition, which had higher RTs. There was again a significant difference in flanker performance across all cue types, with incongruent flankers resulting in higher RTs than congruent flankers.

Paired samples t-tests were used to assess for the presence of the three attentional network scores by examining the differences between the scores used for calculations. For conflict scores, the error rates ($t(70) = 7.33, p < .001$) and RT ($t(70) = -8.89, p < .001$) between incongruent and congruent trials were significantly different, with incongruent scores having a higher error rate and RT than congruent scores, showing a significant conflict effect. For alerting scores, there was a significant difference when comparing the RT of no and center cue trials ($t(70) = -4.02, p < .001$), with no cue trials having higher RT than center cue scores. However, there was no significant difference when comparing error rates ($t(70) = .05, p = .96$), showing the presence of the alerting effect only in RT. For orienting, there was no significant difference between center cue scores and spatial cue scores, for both error rate ($t(70) = -.50, p = .62$) and RT ($t(70) = -1.04, p = .30$), showing no evidence of an orienting effect.

ANT performance across conditions

To identify differences in performance on the ANT across the language frame conditions, we conducted a 3 X 3 X 2 ANOVA, with a between-subjects factor of *language frame* (DOM, WEAK, SWITCH), and two within-subjects factors of *cue* (no, center, spatial) and *flanker* (congruent, incongruent), separately for accuracy and RT. Table 20 presents the means and standard deviations in each condition, Figure 4 shows a graphical representation of the results for accuracy, and Figure 5 shows the graph for RT.

Table 20
Means and Standard Deviations of ANT Cues and Flankers by Language Frame Condition

			DOM condition (<i>n</i> = 25)	WEAK condition (<i>n</i> = 21)	SWITCH condition (<i>n</i> = 25)
Accuracy	Congruent	No	.85 (.11)	.93 (.07)	.93 (.07)
		Center	.85 (.17)	.91 (.07)	.91 (.09)
		Spatial	.85 (.13)	.93 (.07)	.94 (.08)
	Incongruent	No	.73 (.20)	.86 (.09)	.81 (.18)
		Center	.74 (.17)	.88 (.10)	.83 (.18)
		Spatial	.72 (.19)	.86 (.11)	.84 (.18)
RT (ms)	Congruent	No	1014.82 (164.92)	929.36 (130.62)	967.84 (115.66)
		Center	941.10 (166.21)	871.10 (111.71)	894.96 (79.64)
		Spatial	955.82 (131.58)	866.99 (112.32)	884.78 (96.42)
	Incongruent	No	1050.92 (137.00)	977.64 (129.60)	1097.20 (147.42)
		Center	1025.86 (159.89)	989.76 (125.64)	998.76 (138.36)
		Spatial	1041.86 (165.35)	964.27 (125.47)	1018.14 (119.29)

Note. SDs presented in parentheses. DOM = mainly dominant language condition; WEAK = mainly weaker language condition; SWITCH = switching between both languages condition.

Figure 4. ANT accuracy performance by cue and flanker across conditions. DOM = mainly dominant language condition; WEAK = mainly weaker language condition; SWITCH = switching between both languages condition. Error bars denote SD.

Figure 5. ANT RT performance by cue and flanker across conditions. DOM = mainly dominant language condition; WEAK = mainly weaker language condition; SWITCH = switching between both languages condition. Error bars denote SD.

For accuracy, the main effect of flanker was statistically significant across all cues and language frame conditions, $F(1,68) = 52.46, p < .001, \eta_p^2 = .44$. Accuracy was lower in the incongruent flanker condition as compared to the congruent flanker condition ($-.09, p < .001$). There was also a main effect of language frame across cues and flankers, $F(2,68) = 8.28, p = .001, \eta_p^2 = .20$. Post hoc tests with Bonferroni correction showed statistically significant differences between DOM and WEAK conditions ($-.11, p = .001$) and DOM and SWITCH conditions ($-.09, p = .005$), with WEAK and SWITCH conditions having higher accuracy than DOM. There were no significant main effects of cue ($F(2,136) = .20, p = .82, \eta_p^2 = .003$), nor any combination of interaction effects found (cue X language frame [$F(4,136) = .32, p = .86, \eta_p^2 = .01$], flanker X language frame [$F(2,68) = 2.05, p = .14, \eta_p^2 = .06$], cue X flanker [$F(2,136) = .83, p = .44, \eta_p^2 = .01$], cue X flanker X language frame [$F(4,136) = .06, p = .99, \eta_p^2 = .002$]).

For RT, the main effect of flanker was statistically significant, $F(1,68) = 76.23, p < .001, \eta_p^2 = .53$, with congruent trials resulting in faster reaction times than incongruent trials ($-.93.08, p < .001$). There was also a main effect of cue, $F(2,136) = 14.15, p < .001, \eta_p^2 = .17$, and a main effect of language frame, $F(2,68) = 2.98, p = .05, \eta_p^2 = .08$. Analyses with Bonferroni correction showed that across flankers and language frames, performance in the no cue condition was significantly slower (higher RT) than that of the center cue ($52.71, p < .001$) or spatial cues ($50.99, p < .001$). The main effect of language frame showed, after correction, that participants in the DOM condition performed significantly slower than those in the WEAK condition ($71.88, p = .05$), but no other pairs were found to be significantly different. No other combinations of

interactions were significant (cue X language frame [$F(4,136) = 1.67, p = .16, \eta_p^2 = .05$], flanker X language frame [$F(2,68) = 2.26, p = .11, \eta_p^2 = .06$], cue X flanker [$F(2,136) = 1.46, p = .24, \eta_p^2 = .02$], cue X flanker X language frame [$F(4,136) = .88, p = .48, \eta_p^2 = .03$]).

To examine if language ability or bilingualism balance could have interacted with the language frame to produce the results on the ANT performance, correlations were run for the PPVT scores in both languages and PPVT ratio on the ANT scores, separately for each of the three conditions. Out of all the combinations, there were only two significant correlations, both in the WEAK condition. $PPVT_{Dom}$ was correlated with accuracy in the no cue condition ($r = .45, p = .04$) with higher vocabulary scores associated with higher accuracy, and PPVT ratio was correlated with old conflict RT ($r = -.44, p = .05$) with higher vocabulary balance associated with smaller conflict effect. All other correlations were not significant ($ps > .07$).

To test our hypotheses, separate one-way ANCOVAs were conducted for each of the three ANT network scores using both the original and new calculation methods⁷ (old alerting, old orienting, old conflict, new alerting, new orienting, new conflict), for both error rates and RT, in order to examine differences in ANT network scores across language frame conditions. PPVT ratio was entered into the analyses as a covariate, in order to examine and control for any effects of individual bilingualism balance on the ANT performance. Of all the 12 dependent variables, there was only one significant finding. There was a significant group difference across language frames on

⁷ There were additionally four inter-network calculations included in the new calculation method, but there were no significant findings for any of those variables, hence they were dropped from the analyses.

new conflict RTs ($F(2,67) = 3.40, p = .04, \eta_{p2} = .09$), with SWITCH participants exhibiting a bigger conflict effect than DOM participants, a result that was in the opposite direction from our hypothesis. For the original ANT calculations, there were no significant findings for either error rates in alerting ($F(2,67) = .03, p = .98, \eta_{p2} = .001$), orienting ($F(2,67) = .36, p = .70, \eta_{p2} = .01$), conflict ($F(2,67) = 1.92, p = .15, \eta_{p2} = .05$), or the RTs (alerting [$F(2,67) = 2.66, p = .08, \eta_{p2} = .07$], orienting [$F(2,67) = 2.13, p = .13, \eta_{p2} = .06$], conflict [$F(2,67) = 1.72, p = .19, \eta_{p2} = .05$]). For the new calculations, there were no significant findings for accuracy for alerting ($F(2,67) = .01, p = .99, \eta_{p2} = .00$), orienting ($F(2,67) = .06, p = .95, \eta_{p2} = .002$), conflict ($F(2,67) = 1.19, p = .31, \eta_{p2} = .03$), nor the RTs for alerting ($F(2,67) = .11, p = .90, \eta_{p2} = .003$) and orienting ($F(2,67) = .81, p = .45, \eta_{p2} = .02$). Between-group differences were approaching significance for old alerting RTs, but post hoc paired comparisons with Bonferroni correction did not reveal any statistically significant differences. PPVT ratio was not a significant covariate in any of the analyses.

Given that small group sizes in the current sample could have resulted in the lack of power needed to find significant differences in the network scores, we then examined the differences across language frame conditions on the individual components that form the network scores in the ANT. Additionally, we also conducted analyses examining language frame differences on overall accuracy and RT, to see if language frame manipulation resulted in overall differences in task performance, which may not be evident in the attentional networks, given that the network scores are tabulated by subtractions. Table 21 presents the means and standard deviations for each of the ANT network scores and its components across language frame conditions.

Table 21
*Means and Standard Deviations of ANT Network Scores and Components by
 Language Frame Condition*

		DOM condition (<i>n</i> = 25)	WEAK condition (<i>n</i> = 21)	SWITCH condition (<i>n</i> = 25)
Error rate/ Accuracy	Old Alerting	.00 (.12) _a	-.003 (.08) _a	.004 (.09) _a
	New Alerting	.001 (.22) _a	-.02 (.12) _a	-.01 (.10) _a
		No cue (both flankers)	.79 (.14) _a	.90 (.06) _b
		Center cue (both flankers)	.79 (.15) _a	.87 (.11) _b
	Old Orienting	-.01 (.13) _a	.01 (.07) _a	.02 (.11) _a
	New Orienting	.04 (.25) _a	.03 (.10) _a	.04 (.14) _a
		Spatial cue (both flankers)	.79 (.14) _a	.90 (.06) _b
	Old Conflict	.12 (.10) _a	.06 (.06) _a	.10 (.14) _a
	New Conflict	-.15 (.20) _a	-.07 (.13) _a	-.13 (.18) _a
		Congruent flanker (all cues)	.85 (.11) _a	.92 (.04) _b
		Incongruent flanker (all cues)	.73 (.15) _a	.83 (.16) _b
	Overall Accuracy	.79 (.12) _a	.90 (.04) _b	.88 (.09) _b
RT (ms)	Old Alerting	41.12 (84.51) _a	13.88 (68.33) _a	73.98 (113.15) _a
	New Alerting	-.07 (.13) _a	-.06 (.11) _a	-.07 (.12) _a
		No cue (both flankers)	1025.10 (132.25) _a	950.12 (120.61) _a
		Center cue (both flankers)	983.98 (140.29) _a	936.24 (113.05) _a
	Old Orienting	-11.75 (88.40) _a	35.04 (59.74) _a	8.99 (76.41) _a
	New Orienting	.03 (.15) _a	-.001 (.10) _a	-.01 (.10) _a
		Spatial cue (both flankers)	995.73 (116.97) _a	901.20 (108.73) _b
	Old Conflict	84.24 (96.62) _a	79.50 (71.04) _a	124.06 (99.15) _a
	New Conflict	.05 (.14) _a	.06 (.11) _{ab}	.14 (.15) _b
		Congruent flanker (all cues)	967.50 (121.70) _a	886.19 (108.20) _a
		Incongruent flanker (all cues)	1051.74 (127.88) _a	965.69 (119.91) _a
	Overall RT	996.78 (116.67) _a	919.98 (111.81) _b	957.06 (105.41) _{ab}

Note. *SDs* presented in parentheses. DOM = mainly dominant language condition; WEAK = mainly weaker language condition; SWITCH = switching between both languages condition. Within rows, means that do not share subscripts differ significantly at $p < .05$, after Bonferroni adjustment, with PPVT ratio as covariate.

For alerting, between-group differences in accuracy and RT for the no and center cue conditions were considered. For accuracy, the no cue condition showed significant between-group differences, $F(2,67) = 5.44$, $p = .01$, $\eta_p^2 = .14$, with those in the WEAK ($-.10$, $p = .01$) and SWITCH ($-.08$, $p = .05$) conditions having statistically significantly higher accuracy than those in the DOM condition, after Bonferroni correction. The center cue condition also showed significant between-group differences, $F(2,67) = 6.44$, $p = .003$, $\eta_p^2 = .16$, with those in the WEAK ($-.10$, $p = .02$) and SWITCH ($-.08$, $p = .05$) conditions having statistically significantly higher accuracy than those in the DOM condition, after Bonferroni correction. Figure 6 shows a graphical representation of the results. For RT, neither no cue ($F(2,67) = 2.63$, $p = .08$, $\eta_p^2 = .07$) nor center cue ($F(2,67) = 1.24$, $p = .30$, $\eta_p^2 = .04$) showed significant group differences. Specifically in the SWITCH condition, looking at mean values, the scores for old alerting RT seemed to be larger and had more variance than the other language frame conditions, which although not statistically significant, was in the opposite direction from hypothesized. This was due to fast performance on the center cue trials but slow performance on the no cue trials. Speculation as to why this might be the case will be addressed in the discussion.

Figure 6. Differences in ANT no and center cue accuracy across conditions. Brackets indicate significant differences. $*p < .05$, $**p < .01$. Error bars denote SD.

For Orienting, between-group differences in accuracy and RT for the spatial cue conditions were considered. For spatial cue accuracy, there were significant between-group differences, $F(2,67) = 7.87$, $p = .001$, $\eta_p^2 = .19$. Those in the DOM condition had statistically significantly lower accuracy than those in the WEAK condition ($-.12$, $p = .003$), and those in the SWITCH condition ($-.11$, $p = .004$; after Bonferroni correction). For spatial cue RT, there was a statistically significant difference, $F(2,67) = 4.82$, $p = .01$, $\eta_p^2 = .13$. Those in the DOM condition were significantly slower (higher RTs) than those in the WEAK condition (-93.65 , $p = .01$). A graphical representation is provided in Figure 7.

Figure 7. Differences in ANT spatial cue accuracy and RT across conditions. Brackets indicate significant differences. $*p < .05$, $**p < .01$. Error bars denote SD.

For conflict, between-group differences in accuracy and RT for the congruent and incongruent flanker conditions were considered. For accuracy, in the congruent flanker condition, there was a significant between-group difference found, $F(2,67) = 7.70$, $p = .001$, $\eta_p^2 = .19$, with those in the WEAK ($-.07$, $p = .01$) and SWITCH ($-.08$, $p = .002$) conditions having higher accuracy than the DOM condition. In the incongruent flanker condition, results were in the same direction. A statistically significant between-groups difference was found for incongruent flanker accuracy, $F(2,67) = 6.44$, $p = .003$, $\eta_p^2 = .16$, with those in the WEAK ($-.14$, $p = .003$) and SWITCH ($-.10$, $p = .03$) conditions performing more accurately than those in the DOM condition. A graphical representation is presented in Figure 8. For RT, neither the congruent ($F(2,67) = 2.60$, $p = .07$, $\eta_p^2 = .07$) nor incongruent ($F(2,67) = 2.94$, $p = .08$, $\eta_p^2 = .02$) flanker conditions had significant between-group differences.

Figure 8. Differences in ANT congruent and incongruent flanker accuracy across conditions. Brackets indicate significant differences. $*p < .05$, $**p < .01$. Error bars denote SD.

For overall accuracy, a statistically significant between-groups difference was found, $F(2,67) = 8.17$, $p = .001$, $\eta_p^2 = .20$, with those in the WEAK (-0.07 , $p = .007$) and SWITCH (-0.07 , $p = .01$) conditions performing more accurately than those in the DOM condition. For overall RT, there were also significant group differences ($F(2,67) = 3.17$, $p = .05$, $\eta_p^2 = .09$). Those in the DOM condition had significantly larger RTs than those in the WEAK condition (-77.05 , $p = .04$). A graphical representation is presented in Figure 9. An overall group difference in accuracy and RT across conditions possibly indicates a difference in overall demand of the different language frame conditions that may not have extended to specific attention networks. This will be discussed in further detail below.

Figure 9. Differences in ANT overall accuracy and RT across conditions. Brackets indicate significant differences. $*p < .05$, $**p < .01$. Error bars denote SD.

Discussion

In order to isolate the language experiences that contribute to the difference in performance on the ANT between the more and less-balanced bilinguals, we conducted an experimental study to manipulate different language frames among the bilingual children, and measured the subsequent performance on the ANT. Three language frames were identified: (1) mostly using dominant language (DOM condition), (2) mostly using weaker language (WEAK condition), and (3) constant language switching (SWITCH condition). The DOM condition was intended to reflect the less-balanced bilinguals' experience, while the WEAK and SWITCH conditions were designed to invoke different aspects of the more-balanced bilinguals' language experience. Results showed that in general, those in the WEAK and SWITCH conditions had significantly higher accuracy across the ANT as compared to those in DOM condition. Specifically, across all cue and flanker conditions, as well as overall accuracy, those in the WEAK and SWITCH condition were significantly more accurate than those in the DOM condition. For RTs, those in the DOM

condition were slower overall, and with spatial cues, as compared to those in the WEAK condition only.

Though we hypothesised that WEAK and/or SWITCH conditions would perform better in alerting and conflict networks than DOM, we did not find any significant group differences in the network scores except for one. Conflict RT calculated using the new method (difference between congruent and incongruent RTs with no cue only) resulted in a significantly larger conflict effect in the SWITCH condition than the DOM condition. Some possible reasons for these unforeseen findings will be considered below.

Our first hypothesis was regarding the the alerting network. We hypothesized that performance in this network in the WEAK and SWITCH conditions would be better than that in the DOM condition. Unfortunately we did not find any between-group differences across the language frame conditions in the alerting error rates nor RTs, hence this hypothesis was not supported. However, some indication of this trend was shown by significant group differences across language frame conditions on no cue and center cue accuracy, which are both components of alerting. In line with the direction of the hypothesis, WEAK and SWITCH conditions performed significantly better than DOM condition. Notably, participants in the SWITCH condition did not perform as expected; they had large RT scores for one of the conditions which contribute to the alerting network (in the old calculations): no cue-incongruent. Examining the two cue conditions that make up the alerting network, those in the SWITCH condition had relatively low RTs for center cues, performing as quickly as those in the WEAK condition, and this was faster than those in the DOM condition. However, once the cues were removed, those in the SWITCH

condition had much larger RTs than those in both the WEAK and DOM condition. This suggests that the language switching frame made participants aware of the presence of the center cue; they were able to use it to react very quickly to complete their task. However, this awareness did not extend to when there was no cue; one possibility is that the cue was such a salient source of aid that the participants were looking out for it, and hence when there was none, performance suffered. Because alerting is defined as not only attaining the state of alertness but also maintaining this state, the language switching manipulation in this study only managed to do the former but not the latter, hence the hypothesis could not be supported. Instead, it is possible that completing the manipulation task in the weaker language seems to allow for both attaining and maintaining alertness. Evidence of this include the slightly smaller new alerting score calculated from those in the WEAK condition (only using congruent flankers). One probable reason for this is that some aspect of continuously engaging in the weaker language allows for constantly “heightened” sense of alertness, due to the increased attentional control needed to engage in this unfamiliar frame. As compared to this, language switching might require slightly different aspects of attention control such as cue detection but not constant sustaining. Thus, it suggests that perhaps one of the differences in putting an individual in a mainly non-dominant language frame versus a constantly switching between languages one is the maintenance of the state of alertness.

Our second hypothesis was on the conflict network; that the SWITCH and possibly the WEAK conditions would have a smaller conflict effect than DOM condition. Unfortunately, this hypothesis was also not supported,

although the direction of the mean error rates in conflict across language frame conditions was consistent with the hypothesis, with the WEAK condition having smaller conflict error rates compared to the DOM and even the SWITCH condition. However, one surprising finding was that there was a significantly larger conflict effect on RTs (new calculation that only included the no cue trials) for the SWITCH participants as compared to the DOM participants. As previously mentioned, those in the SWITCH condition had unusually high RTs in the no cue-incongruent trials, hence this would have driven the observed results. We speculate that it is possibly due to the fact that the no cue-incongruent condition is the most cognitively demanding out of all the cue and flanker combinations, and it taps on both alerting and conflict networks. Participants in the SWITCH condition would have continuously engaged both networks for the mixed language picture identification task, and it is perhaps a fatigue effect that resulted in slower RTs in that condition. Those in the DOM condition completed the picture identification task mostly in their dominant language, hence it is unlikely to have as great a demand on both their attention networks. It is worth noting that as support for this reasoning, although RTs were long, accuracy of the SWITCH participants was still higher than those in the DOM condition, and error rates of conflict scores (both old and new) were comparable in both conditions. Hence, the large conflict RT effect observed in the SWITCH condition is likely to be confounded with factors not previously expected.

The most encompassing result found in this study is the relatively higher overall accuracy and lower overall RTs for the WEAK and SWITCH conditions as compared to the DOM condition. We designed the DOM condition to

emulate the less-balanced linguistic environment of more dominant language exposure, while the WEAK and SWITCH conditions were meant to be modelled after the more-balanced linguistic environment, with more exposure to the weaker language and/or language switching. This result reflects the finding in Study 2, as well as in previous research, on how greater bilingualism balance is related to better attention control. Given that the DOM condition picture naming task was likely the easiest of the three conditions, it could not have been fatigue that affected the participants performance on the subsequent ANT. Additionally, we checked for systematic errors and controlled for participants' own levels of bilingualism balance in our analyses, and the results were still significant. Manipulation checks also revealed that those in the DOM condition found it difficult to switch to their weaker language, indicating that they were successfully "within" the dominant language frame. This was likely the reason why they exhibited lower accuracies and higher RTs on the ANT overall as compared to the other language frames, since working within this dominant language frame is less likely to require heightened attentional control as compared to working within a weaker language or a mixture of languages.

Comparing between Study 2 and the present study (Study 3), there are a few differences in ANT performance. Firstly, given the significant relation between receptive vocabulary balance and alerting in Study 2, it was expected that in Study 3, for the conditions designed to emulate language frames of the more-balanced bilingual (WEAK and SWITCH conditions), there would be better alerting performance than that in the conditions designed to emulate language frames of the less-balanced bilingual (DOM condition). However, this result was not found. One possible reason is that the short term language frame

manipulation was not comparable to the long term experience an individual would have had to become a more or less-balanced bilingual. Future studies of similar design should increase the duration of the language frame manipulation to multiple training sessions to examine the effect of consistently highlighting a particular language frame and whether it results in longer term effects on the attentional networks.

Secondly, there was a difference in the presence of the different ANT network across studies. In Study 2 there was an alerting effect for both error rate and RT, but in Study 3, there was only evidence of an alerting effect in RTs. As for the orienting network, there was no evidence of the presence of the orienting effect in both studies, although there are some indicators from the spatial cue differences in accuracy in Study 3 that the participants did notice the differences in cue. As previously reviewed, the results on alerting and orienting network seem to not be high on reliability. However, the conflict effect was very clear and consistently present across studies, showing that the flankers did make a significant difference to both accuracy and RT performance. Even with the new ANT calculations, we were unable to truly separate the three attentional networks; across both studies, some of the participants struggled with the no cue-incongruent condition, which included both alerting and conflict networks, hence the effect of both could not be partialled out separately.

Returning to the present study, we presented a novel way to invoke particular language frames that bilinguals of differing balance levels experience in their everyday lives, in order to examine how these language experiences could possibly affect attentional control. Using a picture identification task

which tapped on the participants' receptive vocabulary, we were able to induce within the participants different language frames: mostly single language frames in either their dominant or weaker language, as well as a frame for constant language switching. Given that the dominant language manipulation was intended to reflect the language experiences of a less-balanced bilingual, the results suggest that the lack of variety in language experiences contributes to an overall lower attentional control. Conversely, when the bilingual is exposed to their weaker language or a mixture of languages, both situations likely to occur to a more-balanced bilingual, they are more likely to have better attentional control. Trends in the findings also suggest that engaging in the weaker language seems to sustain alertness more than constantly switching between languages, and engaging in the weaker language may allow for better management of conflicting distractions than only engaging in the dominant language.

To our knowledge, the present study is the first to experimentally manipulate language frames in order to examine the relationship between bilingual language experience and attentional control. Hence, extending from previous research which was mainly correlational and/or longitudinal, our study presents some evidence that not only does the degree of bilingualism affect attentional control, there are specific language contexts tied to that degree of bilingualism that are likely to be the cause of the differences in attentional control. However, it is important to take into account some factors in the present study when generalizing the findings. Firstly, our sample size of about 20 participants in each condition is not ideal; a larger sample size would ensure more power and thus more certainty in the results concluded. Secondly, every

bilingual language population in the world is unique; the uniqueness of language exposure and production in each community contributes, however unwittingly, to the results of any research involving bilinguals. In our population, language switching is common and not seen as taboo or unusual. Even at a young age, the children are not unfamiliar with the concept of switching or mixing between languages. Hence, this could have affected the specific results of our study; the language switching condition was not found to aid the sustaining of alertness in our population, but in another community where language switching is uncommon, it could be possible that it would have allowed for the sustaining of alertness to similar levels as those in the weaker language frame. Hence, more research using this paradigm should be conducted, in different populations with different bilingual language experiences, so that taken together, we can pinpoint the specific language experiences that would affect attentional control.

Further research can also be conducted by including additional manipulation conditions to examine how expressive language production would affect attentional control, on top of the current conditions that address more of receptive language experience. Given that in Study 2, we found relationships between expressive vocabulary balance with alerting and conflict, it would be interesting to see if the inclusion of a picture naming task or a conversation task (more expressive) in the different language frames would also affect attentional control, and how it would differ from the results of the present study. We hypothesize that the results will be in a similar direction, and might show a stronger effect; language production and expression requires more attentional control than comprehension.

In summary, using experimental manipulations, this study presented evidence that the advantage that more-balanced bilinguals have over less-balanced bilinguals in attentional control is due to their experiences in particular language contexts; due to the constant exposure to the dominant language that less-balanced bilinguals experience, they are likely to have decreased monitoring needs, while more-balanced bilinguals who are exposed to their weaker language and/or language switching have better attentional control abilities.

CHAPTER 6

GENERAL DISCUSSION

Summary of Results

In the present thesis, we set out to examine the relation between bilingualism balance and attentional control in the preschool population. Building on previous research showing a positive relation between bilingualism balance and cognitive control, we identified gaps in the research, including the lack of a definitive operationalization of bilingualism balance. Hence, in Study 1, we investigated the representativeness of receptive and expressive vocabulary tests and ratios as measurements of bilingualism balance on a child's daily language experience. We found moderate to strong correlations for parent reported exposure and production of the two languages with receptive and expressive vocabulary scores respectively. Additionally, for vocabulary balance ratios, there were moderately strong correlations showing that an increase in balance ratio corresponded to an increase in weaker language experience and a decrease in dominant language experience. The results provided support for the use of the vocabulary ratios as a measurement of bilingual balance for the subsequent studies, and also confirmed a fundamental theoretical assumption regarding how language contexts differ in more and less-balanced bilinguals. Building upon this, Study 2 used the receptive and expressive vocabulary ratios and examined the relation between these two aspects of bilingualism balance with attentional control. Language exposure balance, operationalized by receptive vocabulary ratio, and language production balance, operationalized by expressive vocabulary ratio, were found to relate to the alerting and conflict networks of the ANT. Together, the findings supported

the overarching view that more-balanced bilinguals, as compared to less-balanced ones, are more able to manage their attentional capabilities according to demands. Specifically focusing on receptive ability, Study 3 was designed to examine whether differing exposure to different language contexts, which is inherent in different levels of bilingualism balance, can affect changes in attentional control. We experimentally induced three language frames for participants to undergo before completing the attention task: one mainly using the dominant language, one mainly using the weaker language, and one involving constant language switching. The first condition was designed to emulate linguistic experience of the less-balanced bilingual, while the second and third conditions were designed to emulate different aspects of the linguistic experience of a more-balanced bilingual. Results showed that overall accuracy of participants in the dominant language condition was significantly lower than those in the weaker language and language switching conditions on the measure of attentional control. There were no significant group differences with regards to the specific attention networks except for a greater conflict RT effect on the participants who had to switch between languages as compared to those in their dominant language, which we attributed to a possible fatigue effect; language switching is likely to tap on the conflict network more than simply comprehending in the dominant language, hence participants who were switching between languages were slower (but not any less accurate) due to being slightly more fatigued. Collectively, the results suggest that the language context in which a bilingual is exposed to affects attentional control, likely due to the differing cognitive demands in each language frame, which then carries over to the attentional control task. In language frames with low cognitive

demands (dominant language frame), attentional control is less engaged than in language frames with higher cognitive demands (weaker language or language switching frames).

Taken together, the three studies present a coherent picture about the relation between bilingualism balance and attentional control in the preschool population. Bilingualism balance is positively related to attentional control, with the bilingualism experience being associated with two of the three attentional networks. Different levels of bilingualism balance also correspond to different frequencies of particular language contexts. When children are put through these different language frames, differing attentional demands relating to the language frames result in differing performance on the attentional control task. As such, it is likely that the variation in frequencies of the different language contexts is what contributes to the formation of children's bilingualism balance levels, which then affects their attentional control.

Key Research Findings

We highlight three major research findings that correspond to our research aims, and discuss the theoretical relevance and contribution of these findings to the field in general.

Vocabulary Ratio Scores as Representations of Bilingualism Balance

In the literature, bilingualism proficiency, and by extension bilingualism balance, has been operationalized in various ways. There is no commonly accepted way to quantify bilingualism balance, in part due to the complexity involved in measuring language proficiency. We chose to use a ratio of

vocabulary scores; quantified by the difference in both languages scores divided by sum of both languages score. Additionally, we identified two aspects of vocabulary, receptive and expressive vocabulary, to represent two different aspects of the bilingualism experience, language exposure and production, respectively. To justify the use of these ratios, we compared the vocabulary scores and ratios with parent reported language exposure and production percentages of each language, and moderately strong correlations supported the use of these scores.

Theoretically, the findings of this study provide support for the use of the receptive and expressive vocabulary ratios in representing bilingualism balance in exposure and production. A previous study by Gollan et al. (2012) comparing objective and self-reported measures of bilingualism balance and dominance in adults found that there was high agreement found between self-reported language dominance (which language is dominant), self-reported language proficiency and the objective measures of language proficiency such as naming tasks, but objective measures of language proficiency serve better to show the extent to which the individual is a balanced bilingual. The correlations reported in their study between self-reported language proficiency balance and objective tests language proficiency balance ranged $r = .197 - .586$, values that are comparable to the correlations found in our present study comparing vocabulary tests and parental reported language exposure and production. Thus, our results do present support for the use of these vocabulary ratios as the measure of bilingualism balance in our studies. There are other ways of operationalizing bilingualism balance, such as using a difference score between the two languages (e.g. Thomas-Sunesson, Hakuta, & Bialystok, 2016) or

simply the score of the weaker language (e.g. Tse & Altarriba, 2014), all of which would likely also capture some of the variances inherent in bilingualism balance.

In our study, by showing that the vocabulary ratios are indicative of an individual's real life bilingual language exposure and production in children, we suggest that these vocabulary ratios can also be considered as a measure of bilingualism balance in future studies.

The Relations Between Bilingualism Balance Exposure and Production With Alerting and Conflict Attention Network

In the present thesis, we distinguished between two aspects of the bilingualism balance, exposure and production, represented by receptive and expressive vocabulary respectively. We also adopted the model of attention proposed by Posner and Petersen (1990), which identifies three networks of attention: Alerting, Orienting, and Conflict. Proposing a contextual-based attention control mechanism based on the Adaptive Control hypothesis (Green & Abutalebi, 2013) and the role of attention highlighted by Bialystok (2015, 2017), we linked bilingualism balance together with the attentional networks and proposed two relations. Firstly, bilingualism balance exposure was proposed to be positively related to the alerting network, where bilinguals who are exposed more equivalently to their two languages have higher alertness. Secondly, bilingualism balance production was proposed to be positively related to the conflict network, where bilinguals who express more equivalently in their two languages are more accurate in managing conflicting distractions. Although we did find results consistent with our expected directions, we did not find two separate relationships between exposure and production, and alerting

and conflict. Instead, both language experiences were correlated with both attention networks. These results are consistent with some of the previous findings in the literature, in which different studies have found relationships between bilingualism balance and different attention networks. In some studies, more-balanced bilinguals were previously found to have smaller conflict scores than less-balanced bilinguals (Carlson & Meltzoff, 2008; Poarch & van Hell, 2012) while other studies found that those who had higher proficiency in their weaker language displayed higher alertness than those with lower proficiency (Videsott et al., 2012). Although we tried to separately consider different aspects of the bilingual language experience, given the extensive cognitive demands involved in the entire bilingual experience, it stands to reason that different attentional control networks would overlap when dealing with different aspects of managing the two languages. Additionally, language exposure and production are closely related; production is, more often than not, a direct consequence of exposure. Hence, the findings of the present thesis contribute to the field greater understanding of the components of the bilingual language experience that constitute the general relationship between bilingualism balance and attentional control.

Examining the Mechanism Behind Bilingualism Balance and Attentional Control: The Importance of Context

Drawing inspiration from the Adaptive Control hypothesis, we proposed a new contextual-based attentional control mechanism, and identified language context differences between the more and less-balanced bilinguals that could have contributed to the differences in attentional control. Two particular

language contexts were highlighted: that the more-balanced bilinguals had more exposure to their weaker language and less exposure to their dominant language as compared to the less-balanced bilinguals; and that more-balanced bilinguals had more language switching opportunities than less-balanced bilinguals. Using the experimental manipulation in Study 3 to induce particular language frames in the child participants, it was found that short term exposure to both the weaker language context and the language switching context could improve subsequent performance on the attentional control task, as compared to exposure to a dominant language context. Hence, the findings highlight the importance of language contexts. Our finding is supported by a previous study by Byers-Heinlein (2013) that examined how parental language mixing affected their young children's comprehension and production vocabularies. The results showed that the amount of exposure of English language in their study (their weaker language) was a predictor of English vocabulary size, and more interestingly, children whose parents code-mixed languages frequently had smaller comprehension vocabularies at age 1.5, and also smaller production vocabularies at age 2. Together, these results highlight the importance of context that bilingual children are exposed to as a direct effect on the extent of their bilingualism, and our study results suggest that this bilingualism experience can also be extended to the attention domain. Recently, a study by Ooi, Goh, Sorace and Bak (2018) compared bilingual adults in the same population as the present study (Singapore) with bilinguals in Edinburgh, in order to examine the effect of language switching on attentional control. Bilinguals in Edinburgh are less likely to switch between languages in the same context, while the converse is true for Singaporean bilinguals. It was found that

Singaporean bilinguals performed better on the conflict network of the ANT as compared to the Edinburgh bilinguals, suggesting a relationship between language switching and conflict management in attention control. The findings of this study are in line with our results that increased language switching improves attentional control, although in our study the consistent results are more domain-general instead of in the conflict network specifically.

Additionally, our short term context manipulation alludes that language contexts have an immediate effect on the task performance depending on the demands of the language frame in which the task is in, and hence indicate that the variations in language contexts in a child's life, over time, is likely to be the driver of how balanced a bilingual he or she becomes, which would then affect his or her attentional control. As one of the first studies to use such language frame manipulation to understand the mechanism underlying bilingualism balance and cognitive control, we provide a novel perspective to the design of studies examining bilingualism balance, and also provide strong evidence for our contextual-based attention control mechanism underlying bilingualism balance and attentional control.

Additional Finding: The Independence of ANT Components

As mentioned in the literature review, there is not yet a consensus on the independence of the ANT network components and scores. Some researchers (including those who defined the network) believe that the networks are independent (Posner & Petersen, 1990; Fan et al., 2002), while others have shown that performance on the different cue and flanker conditions do actually affect each other (summarised in MacLeod et al., 2010). The independence of

the ANT networks is important to determine, since isolating the attention networks is a fundamental prelude towards identifying independent relations between the attention networks and other variables, as well as when trying to modify or train the separate aspects of attentional control. In our paper, results across both studies suggest that the ANT components are not measured independently; there were some interactions found between cue and flanker performance across both accuracy and reaction times. We contend that the design of the ANT itself is likely to result in inter-network effects on the results; for example in Study 2, we found that the lack of cues affects performance on the incongruent flankers differently than the congruent flankers. Although we used new calculations proposed by Wang et al (2014), a better method would be to redesign the ANT in order to minimize the interference of one attention network over another. To address the problems inherent in the design of the task, Wang et al. (2015) redesigned the task to separate the different network tests into separate blocks so as to reduce interference on each other, and non-orthogonal methods to completely separate each different condition for each network. This allowed for the network scores to be more independent and less correlated with each other, and reliabilities for the networks also improved. Hence, future studies intending to examine the constituent networks of the ANT should consider using the redesigned task in order to ensure independence.

Limitation and Future Directions

There are some limitations to the studies detailed here that should be highlighted.

Firstly, the use of PPVT and EVT as measures of proficiency in the present study is not without its drawbacks. As previously mentioned in the discussion section of Study 1, there are no norms for standardized vocabulary tests in English or Mandarin Chinese for our current population, hence tests were adapted from existing measures (PPVT and EVT) normed in the United States. This poses problems in terms of the uncertainty of the relevance of the tests in the measurement of actual vocabulary size in our sample. Keeping this in mind, Study 1 was carried out to examine the relevance of the vocabulary test scores in relation to parent reported levels of exposure and production of their child in each language, and significant moderate to strong correlations were found, suggesting that comparing within the sample, the vocabulary scores did reflect the relative difference between participants in terms of language experience reported by parents. However, as we compared the vocabulary scores for each language against each other in order to calculate the ratios, we operated under the assumption that the sensitivity of the tests in both languages are approximately equal, which we were unfortunately unable to ascertain in our sample. Hence, in future attempts to replicate or build on this research, it would be imperative to develop and use a locally standardized Mandarin Chinese vocabulary test, and to have norms for both the English and Chinese test for the current population. Nonetheless, our research findings set a direction for which future studies may consider working along.

Secondly, for the purposes of examining language exposure and production independently, we used the receptive vocabulary test to represent language exposure, and the expressive vocabulary test to represent language production. However, as identified in the Adaptive Control hypothesis (Green

& Abutalebi, 2013), the entire language production process includes comprehension, which precedes the actual speech in an interactional context. The expressive vocabulary test is not high in real-world ecological validity; it is unlikely that individuals produce speech without some prior comprehension, especially in a conversational context. Hence, future studies could consider incorporating conversational contexts that include both language comprehension and production in the measurement of bilingualism balance. In such a multifaceted context, it is likely that this measure of bilingualism balance may also be directly related to both Alerting and Conflict aspects of the attention network.

Thirdly, although all participants of the present thesis were shown to be English-Mandarin bilinguals, the distribution of language dominance in the population sampled resulted in a larger proportion of English dominant, as compared to Chinese dominant, bilingual children. The uneven distribution of these two groups may affect the interpretation of the results, since Mandarin dominant bilinguals in the population are more likely to be balanced bilinguals than the English dominant ones.

Hence, caution must be taken when generalizing the results.

Fourthly, we designed the present thesis to examine the relations between bilingualism language contexts, bilingualism balance, and the effect on attentional control. Although we propose that language contexts are what affect bilingualism balance over time, we did not manage to directly manipulate bilingualism balance to see the effect such change would have on attentional control. Thus, future studies can consider examining language balance change over time in a longitudinal study, or train participants to improve their

bilingualism balance. To improve bilingualism balance is time consuming; it likely involves improving the proficiency of the child's weaker language. Alternatively, another possibility, building on the results of the present study, could be to increase exposure to single, weaker language contexts or language switching contexts to see if this increase in exposure to contexts would help improve bilingualism balance, and subsequently attentional control. Since the short-term exposure to such language frames are able to allow a carry-over effect to the attentional control task, it is probable that more exposure will have greater benefits on attentional control through improving bilingualism balance.

Finally, as an extension, more aspects of cognitive control such as executive functioning could be examined in relation to bilingualism balance and attentional control; attentional control could be examined as a mediator between the relationship of bilingualism balance and executive functioning. This would be in line with the contextual-based attentional control proposal highlighted in the present paper, regarding how attention control may be what underlies the relationship between bilingualism and cognitive control. Previous studies have identified relations between bilingualism and different aspects of executive functioning such as cognitive flexibility (Bialystok, 1999; Carlson & Meltzoff, 2008; Kalashnikova & Mattock, 2014) or working memory (Morales, Calvo, & Bialystok, 2013), but mostly comparing between bilinguals and monolinguals, and not taking into account attentional control. Only one study to date has examined all three variables of bilingualism balance, attention, and executive function together (Sorge, Toplak, & Bialystok, 2017), and they only considered the separate roles of bilingualism and attention on different

executive functioning tasks. Hence, this is one possible future direction of research.

Implications

Despite the limitations identified, the present thesis has provided both theoretical and practical implications on the field of research between bilingualism balance and attentional control. We detail them below.

Theoretical Implications

Firstly, the findings in the present thesis, taken together, contribute to the understanding of the fringe conditions of how the experience of bilingualism affects cognitive control in preschool children. Given that there is inconsistency in the field regarding whether bilinguals in general have better cognitive control abilities than monolinguals, it is likely that there are some specific factors in the bilingualism experience that determines if there has been a need for a bilingual to develop heightened cognitive control. One of these conditions seems to be bilingualism balance, or the relative difference in language experience across languages. Although we did not directly test monolinguals, by taking monolinguals as an “extreme end” of the bilingualism spectrum, our findings theoretically show that, at an increased level of equivalent experience (more-balanced bilinguals), attentional control is more fine tuned than at a less equivalent level of language experience (less-balanced bilinguals). Given that attentional control is a fundamental pillar in general cognitive control, these findings are likely to extend to other aspects of cognitive control. Hence, in order to benefit from greater cognitive or

attentional control abilities, one not only needs to be a bilingual, but also needs to aim to be a balanced bilingual.

Secondly, the relations we found between different aspects of the bilingualism experience (exposure and production) and attentional network (Alerting and Conflict network) contributes to the field a more in depth understanding of the relation between bilingualism balance and attention, an area which did not quite have consistent prior research findings due to difficulties in measurement of bilingual linguistic experience. The findings allow us to identify aspects of the bilingualism experience, such as exposure to both languages to a more equivalent extent, in order to benefit levels of alertness and conflict management. This would allow us to design interventions or other experimental manipulations in order to examine the relations in greater detail.

Finally, the findings specifically in Study 3 highlight the importance of language context in bilingualism research. We managed to modify attentional control task performance by manipulating the language frames in the task that participants were doing prior to the attentional task. This suggests that future research needs to take into account the context of which their research tasks are conducted in; a difference in context is itself possibly enough to affect cognitive task performances. This is due to the demands of the language frame context in which the participant is in; the higher (lower) the demands, the more (less) attentional effort the participant is likely to put into the task, and hence the effort is likely to carry over to the cognitive task. Any variation in language frames between participants may interfere with the variables of interest. Hence,

it is important to consider the language context when designing research dealing with bilingualism and cognitive control.

Practical Implications

Our results showed that more-balanced bilingual children are better able to control their attention according to task demands as compared to less-balanced bilingual children. This suggests that in both educational and parenting contexts, it would be beneficial to promote balanced bilingualism in young children. Additionally, since manipulation of language frames in the present research was able to effect a change in attentional control task performance, this also indicates that even in daily lives, the language frames that young children are exposed to may be related to their bilingualism balance and thus, attentional control. Our results suggest that rather than a single, dominant language context, it would be more beneficial to the child if he or she were exposed to a good mixture of both languages. In a parenting context, this means that if a parent is fluent in both languages, the parent should make a conscious effort to communicate to the child in both languages, not only the language that the child is dominant in. We acknowledge that this might not be entirely possible; not all parents are equally proficient in both languages, thus parents can consider increasing opportunities for children to be exposed to their weaker language, such as by visiting friends or relatives who speak the language. In an educational context, it may be beneficial if the amount of time schools expose the children to each language is more equal, so that not one particular language is the dominant language in school. In both situations, a

good mix of languages may be also beneficial to the learning of the child, if the effects of the language frame carry over to the learning process.

Conclusion

Through the three studies described in this thesis, we have presented evidence to advance our understanding of the relationship and underlying mechanisms between bilingualism balance and attentional control in preschool children. We first ensured that our chosen measure of bilingualism balance, the ratio of vocabulary scores, was theoretically sound and corresponded to real-life parent reported levels of language experience in the bilingual children. Then, we examined the variability of bilingualism balance within the preschool population, and how that related with attentional control. Bilingual preschoolers with higher balance in language exposure and production showed better alerting and conflict monitoring abilities than those with lower balance. The final step was to understand the mechanism underlying this relationship; we identified that bilingualism balance was an outcome of different levels of exposure to each of the bilingual's languages, as well as the likelihood of language switching. Putting them together, we manipulated language frames in order to emulate different bilingualism balance levels, and examined how those manipulations would affect attentional control. It was found that in general, engaging in the weaker language frame and a language switching frame was more beneficial to attentional control than a dominant language frame. The findings expand our understanding on how bilingualism balance relates to attentional control, and the verification of the bilingual balance ratio allows for it to be used in future research. The present thesis has hence made both theoretical and methodological contributions to the research field of

bilingualism and cognitive control. The findings also can provide practical suggestions for parenting or educational programs on the importance of context in improving bilingualism balance and attentional control in the future.

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Appendix A

Sample Survey Items

Language Use

Please complete the following table **for all major caretakers** of your child outside school. **An example table has been provided for you.**

Please also **rate the language proficiency** of the caretaker for both English and Mandarin Chinese, using the following scale:

Persons who spend time with child	Percentage of language person speaks to child (Should add up to 100%)			Does this person mix English & Chinese in one conversation when talking to child? (Yes/No)	Percentage of language child speaks to person (Should add up to 100%)			Does the child mix English & Chinese in one conversation when talking to person? (Yes/No)	Person's Proficiency in language (see scale above)	
	English	Chinese	Others (Language Hokkien)		English	Chinese	Others (Language Niu)		English (0 to 4)	Chinese (0 to 4)
<i>Example</i>										
Father's side grandmother	0	50	50	No	5	95	0	Yes	1	3

Persons who spend time with child (Number 1 spends most time with child, followed by number 2, etc.)	Percentage of language person speaks to child (Should add up to 100%)			Does this person mix English & Chinese in one conversation when talking to child? (Yes/No)	Percentage of language child speaks to person (Should add up to 100%)			Does the child mix English & Chinese in one conversation when talking to person? (Yes/No)	Person's Proficiency in language (see scale above)	
	English	Chinese	Others (Language _____)		English	Chinese	Others (Language _____)		English (0 to 4)	Chinese (0 to 4)
(1)										
(2)										
(3)										
(4)										
(5)										
(6)										

Language that your child is better at:

☐ English OR ☐ Mandarin Chinese

Appendix B

List of Items for Picture Identification Task

Target Item		Distractor 1	Distractor 2
(English)	(Chinese)		
dog	gou3	frog	goat
cat	mao1	bat	mouse
fish	yu2	kiss	bee
book	shu1	hook	glue
boat	chuan2	float	barn
hand	shou3	sand	toe
leg	jiao3	egg	cow
car	che1	star	stir
sit	zuo4	knit	door
eat	chi1	sweet	chair
drink	he1	sink	head
sing	chang4	ring	car
run	pao3	sun	cow
sleep	shui4	sheep	sea
jump	tiao4	drum	cow
walk	zou3	clock	sew
stand	zhan4	hand	sun
laugh	xiao4	bath	cow
cry	ku1	tie	shoe
blue	lan2	shoe	sun

Manipulation Check Items

ball	qiu2	doll
door	men2	pour
red	hong2	bed
write	xie3	light

Note: Only one target and one distractor present on the screen at any time.