An investigation of the effects of language experience on cognitive control in bilingual speakers

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I, Xuran Han, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Focusing on Chinese-English bilinguals, this research project aims to explore the cognitive mechanisms underlying bilingual language processing and the effects of bilingual language experience on domain-general cognitive control in language comprehension and production processes through four behavioural studies. Specifically, it examines (1) how cognitive control adapts to dynamically-changing cognitive demands in language processing; (2) how bilinguals' habitual language use patterns and contexts affect their development of domain-general cognitive control, through the convergence of linguistics and behavioural experiments approach.

Study 1 explored how bilinguals' habitual language experience affects their cued code-switching production and performance in cognitive shifting and inhibition tasks. Similarly, Study 2 also focused on understanding the effects of bilingual language use habits on cognitive shifting and inhibition; however, it investigated the relationship between bilinguals' spontaneous language production and cognitive control. Studies 3 and 4 examine the adaptations of cognitive control in comprehending bilingual utterances in different interactional contexts. Specifically, Study 3 investigates how different language interactional contexts modulate domain-general inhibitory control in bilingual language comprehension. Study 4, consisting of two experiments, compares the effects of bilinguals' code-switching habits and L2 proficiency

on their inhibitory control during language comprehension in habitual and induced language use conditions.

The results show that (1) cognitive control processes are adaptively deployed to produce and comprehend bilingual utterances in different interactional contexts; (2) bilinguals' habitual language use patterns and language proficiency are significant factors modulating their domain-general cognitive inhibition and shifting efficiency; (3) the magnitude of bilingual language use experience effects on cognitive control vary significantly across processing languages in naturalistic and mandatory (i.e., induced) language use conditions.

In general, the project addresses bilingualism being a dynamic process that includes multifarious individual differences that may affect cognitive control. Therefore, more comprehensive measures to characterise bilingual habitual language use experience are needed in future studies.

Impact Statement

It is believed that more than half of the world's population is bilingual. Focusing on bilingual speakers, this is a research project closely related to a significant proportion of the world population. This project explores the interconnections between bilingual language experience and individuals' cognitive control development; moreover, it analyses how cognitive control adapts to dynamically-changing cognitive demands in language processing.

The results not only reveal that bilinguals' successful language control is constantly mediated through a domain-general cognitive control process, they also highlight the dynamic impact of bilingual language experience on individuals' cognitive control development. Specifically, bilinguals code-switching frequently in daily communication, as compared to those code-switching seldomly, are found to have greater efficiency in parallel-tasks shifting, conflict monitoring and interference suppression. Furthermore, the project identifies the significant roles of sociolinguistic factors, such as social contexts and language use patterns, affecting bilinguals' domain-general inhibitory control efficiency.

The comprehensive approaches, including language entropy computation, bilingual spontaneous bilingual speech production assessment and habitual code-switching frequency judgements, adopted in this project provide future works with multiple ecologically-valid paradigms to quantify bilinguals' habitual language use experience, and discuss the impact of individual differences in bilingual language experience on cognitive control.

Due to the impact of the Covid-19 pandemic in the past two years, most of the studies in this project were conducted online. This project, in general, is an important attempt to conduct behavioural experiments and test human participants remotely. Although extra care is needed to control noise in the data collection process, conducting online studies could be a new trend for future research in the post-pandemic era, since it offers a more efficient approach to test participants from more diverse cultural and language communities. In future, more online experiments are expected to improve the validity and reliability of online data collection platforms.

The research also aims to provide the general public, including language educators and bilingual families, with more scientific research evidence to debunk some common misconceptions and “myths” associated with bilingualism and bilingual education, such as the belief that bilingual education will lead to children and young adults’ incomplete language acquisition, or speaking more than one language will result in cognitive deficiencies. In addition, the research elucidates to some communities that have misconceptions or biased views on code-switching that code-switching in speech has nothing to do with “destroying language purity”. In fact, code-switching is a very common communicative behaviour for nearly everyone in today’s society, and it should not be regarded as a taboo in communication.

By shedding light on the adaptations of cognitive and behavioural responses to language use experience, this research project as one component of bilingual research promotes our understanding of the interconnections between neuroplasticity and language learning, which will have the potential to guide health professionals to improve language and cognition assessments, or clinical therapy, on people with impaired cognitive functions.

Acknowledgements

慎终如始，则无败事。

——《道德经》六十四章

Heed the End No Less Than the Beginning, and Your Work Will Not Be Spoiled.

—— *Tao Te Ching*

This project would not have been possible without the support of many people. I would like to express my deepest appreciation to my supervisors, Prof. Roberto Filippi and Prof. Li Wei, for their invaluable guidance and generous support throughout my doctoral research journey. I am proud of, and grateful for my time working with my supervisors. I am also indebted to all voluntary participants taking part in my research project; without their generous contribution, I cannot complete my data collection during the pandemic period. Very special thanks to my dear friend and best mate in my research, Dr. Yi Wang, who is always there with me during my experiment piloting, data collection and analysis, as well as for every time I was down and losing confidence. I would like to acknowledge Dr. Chaoxu Chen from Imperial College London, for providing me his valuable suggestion regarding my paper manuscript proofreading and data visualisation.

It is important to strike a balance with life outside the dark depths of the lab. As such, I cannot stress enough about the importance of my weekly retreat to jogging and hiking with my best friend, Qinbo Qiao. Many thanks to Qinbo, who always drags me out of the darkness and provides me endless courage to continue my research during the pandemic period. Currently, she is a doctoral student in neuroscience in University of Oxford. I am so proud to witness her huge progress in academic career and have her as my best friend.

Lastly, endless gratitude should also go to my family, especially my parents and grandparents. Their belief in me has kept my spirits and motivation high to overcome any difficulties I have faced during this journey. I could not have undertaken this journey without their unconditional encouragements and support. To my family, I give everything, including this.

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List of Abbreviations

ACC	Accuracy
ACH	Adaptive Control Hypothesis
AOA	Age of Acquisition
AX-CPT	AX continuous Performance Task
BDS	Backward digit span
BSWQ	Bilingual Switching Questionnaire
COVID-19	Coronavirus disease 2019
CPM	Control Process Model
CQ Networks	Competitive Queuing Networks
DLC	Dual-language Context
FDS	Forward Digit Span
ICM	Inhibitory Control Model
L1	First language
L2	Second language
LEAP-Q	Language Experience and Proficiency Questionnaire
LexTALE	Lexical Test for Advanced Learners of English
LHQ	Language History Questionnaire
LSBQ	Language Social Background Questionnaire
LTS	Language Task Schemas
RAPM	Raven's Advanced Progressive Matrices
RQ	Research question
RT	Reaction Time
SAS	Supervisory Attentional System
SES	Socioeconomic Status
SLC	Single-language Context

Chapter 1 General Introduction

This chapter provides a brief overview of this research project, introduces the rationale and background of the project, describes its main aims and research questions, and gives an outline of the chapters comprising this thesis.

1.1 Background of the Research

The population of bilinguals is increasing in the contemporary world, and more than half the people in the world use more than one language regularly in their daily lives (Grosjean, 2010). Managing multiple languages in one mind is a remarkable and demanding skill. Bilingual speakers must resolve the competition arising within their linguistic system; that is, to use one language, they must control or inhibit the non-target one(s) (Green, 1986, 1998). Therefore, this practice of constantly activating and inhibiting languages, which imposes additional demands on crucial cognitive control processes, may be a source of possible cognitive advantage for bilingual speakers, that monolinguals do not seem to have (Bialystok, 2017; Festman et al., 2010). The hypothesis of bilingual advantage, in this vein, has been extensively examined by numerous studies through cross-group comparisons of cognitive control performance between bilinguals and their monolingual peers in past decades (see Bialystok, 2017 for a review). However, research in recent years has increasingly found that evidence for the bilingual advantage hypothesis is hard to replicate. Even in studies (e.g., Bialystok, Craik & Freedman, 2007; Kerrigan, Thomas, Bright & Filippi, 2017; Kroll & Bialystok, 2013) showing bilingual advantage in cognitive control, there are conflicting results concerning in which aspects of cognitive control, such as attentional control, cognitive inhibition and cognitive flexibility, bilinguals outperform their monolingual peers. Furthermore, some studies have reported that bilingual advantage in cognitive control is based on small sample sizes, and the positive evidence they present could be due to a failure to control for other individual experience-based factors, such as individual demographic information and socioeconomic status (Paap, Johnson & Sawi, 2015). Therefore, the bilingual advantage hypothesis has been assumed to be restricted to a specific population group or to specific cognitive processes (Bialystok, 2016; de Bruin, 2019; DeLuca, Rothman, Bialystok & Pliatsikas, 2019), and an increasing number of researchers have begun to doubt its robustness and existence in larger sample sizes.

More and more researchers, in recent years, have shifted their attention to explore the link between bilingual language experience and cognitive control within bilingual groups. Individual differences in bilingual language use experience have also been emphasised in affecting the magnitude of modulation on bilinguals' cognitive control. Consequently, one of the most exciting yet controversial topics in current psycholinguistic research is linked to some tantalising scientific evidence revealed in within-group bilingual research that individuals' long-term habitual experience in bilingual language use confers a variety of benefits on their cognitive function associated with both language and nonverbal task processing.

Following the Inhibitory Control Model (Green 1998), which describes how the bilingual language control process is regulated by networks of domain-general cognitive control, numerous studies and theoretical frameworks have focused on exploring the language and cognitive control relationship by accounting for the role of bilingual language experience-related factors in influencing such a relationship. Specifically, the Adaptive Control Hypothesis (Green & Abutalebi, 2013) highlights the variation in cognitive demands imposed by different interactional contexts in affecting bilinguals' cognitive control mechanism underlying language control processes. Its extension, the Control Process Model (Green & Li, 2014), pointed out that bilinguals' cognitive control adaptation in bilingual language processing is also modulated by patterns of bilingual language use (i.e., code-switching patterns). Both recent influential models address the importance of bilingual language use experience in modulating cognitive control in bilingual language processing. Although ample study evidence has shown a range of systematic outcomes for domain-general cognitive functioning caused by sustained bilingual language use experience, many questions remain open on both theoretical and empirical levels, and research in this field has yet to provide a clear-cut answer. For instance, questions related to how to quantify bilinguals' degree of bilingualism, which specific components in cognitive control are significantly affected by long-term bilingual language experience, and how cognitive control is adapted to regulate bilingual language processing in naturalistic communicative settings, still need in-depth investigation. Furthermore, while numerous studies (e.g., Bonfieni et al., 2019b; Filippi et al., 2014; Rosselli et al., 2016) have discussed bilingual language processing and cognitive control interactions based on bilinguals who regularly use two languages with close distances (e.g., Italian-Spanish, or Dutch-German), relatively few have focused on bilingual language processing between two languages with significant differences in their orthographic systems, like Chinese and English.

In this vein, this research project aims to fill some gaps in the literature by examining the cognitive mechanisms underlying, producing and comprehending bilingual utterances in Chinese and English, and by exploring the effects of bilingual language use experience on bilinguals' domain-general cognitive control modulation. Moreover, this project intends to shed new light on the cognitive mechanisms underlying bilingual language processing, and provide new evidence for the dynamic adaptation of cognitive control in processing languages with different patterns and in different interactional contexts.

1.2 Aims of the Research

Focusing on Chinese-English bilingual adults, the whole project is built on three influential theoretical frameworks, ICM, ACH and CPM, to investigate the effects of bilingual language experience on bilinguals' cognitive functioning associated with language and nonverbal task processing through four behavioural studies. The predictions of ACH and CPM are also examined to provide a better understanding of the interactions between the magnitudes of modulations effects on cognitive control and bilingual language use experience. Specifically, it discusses how bilingual language proficiency, L2 exposure, habitual language use patterns and interactional contexts affect bilinguals' cognitive control in language comprehension and production processes.

Accordingly, two studies in this project focus on bilingual language production processes, while the other two studies discuss the bilingual cognitive process in language comprehension. Participants' performance on well-established cognitive tasks, such as a flanker task, a colour-shape switching task, a Stroop task and a Simon task, and tasks related to language processing, including a picture-naming task, spontaneous language production, and bilingual utterances comprehension, were correlated and analysed. These studies are also designed to compare bilinguals' cognitive and language control behaviours in processing languages in experimental manipulated and naturalistic language use conditions. In doing so, this project aims to devise an approach to measure bilingual individuals' both cognitive and language performance in naturalistic language processing to promote methodological improvement in future bilingual research, and further explore whether the magnitude of modulation effects of bilingual language experience on cognitive control in language processing varies across the two conditions. In general, through analysing the complex cognitive control mechanisms regulating the processing of two distant languages (i.e., Chinese and English), the project seeks to further our theoretical knowledge of the relationship between language systems and the crucial domain-general cognitive processes.

1.3 Main Questions of the Research

The main research questions of this project are introduced briefly here to address the aims of the four studies. These questions will be explained in more detail and highlighted in each data chapter.

RQ1：How do bilinguals' individual differences in language use experience affect their domain-general cognitive control performance?

RQ2: How does cognitive control adapt to dynamically-changing cognitive demands in language processing?

RQ3: Do bilinguals with different L2 proficiency levels and code-switching frequencies in daily communication vary in their cognitive control task performance?

RQ4: What is the relationship between bilinguals' habitual language use patterns and their domain-general cognitive control efficiency?

1.4 Overview of the Thesis

Starting with the first chapter and its brief introduction to the aims of this project, the thesis comprises eight chapters in total. An in-depth literature review is conducted in the next three chapters, namely, Chapters 2, 3 and 4. Chapter 2 mainly offers important definitions and classifications on what is bilingual and what bilingualism is about. The interconnection between bilingual language control and cognitive control is discussed in Chapter 3, following an elaborate description of cognitive control and its measurement. The inhibitory control model is highlighted and introduced in this chapter to set up the theoretical foundation for the project. Chapter 4 mainly discusses the effects of bilingual language experience on cognitive control development. The Adaptive Control Hypothesis and Control Process Model are introduced, followed by comprehensive reviews of studies examining models and experiments investigating the modulating effects of bilingual language experience. Some commonly-explored factors related to bilingual language experience development are also highlighted and introduced in this chapter to build the research background for this project.

Chapter 5 is the general methodology section. It briefly introduces the general procedure and design of the studies involved in this project. An overview of the standardised tests, questionnaires and cognitive tasks used in this project is also included. This chapter also presents the demographic information and main characteristics of the participants involved in this project.

The four empirical studies are presented and discussed in two separate chapters, from Chapter 6 to Chapter 7. In each study section, a detailed study design, procedure and results are presented, ending with a separate discussion and a conclusion. After the four studies are discussed, at the end of the thesis, Chapter 8 presents and summarises the key findings of the project and revisits the research questions asked at the beginning. The significance and limitations of the research are explained, and Chapter 8 concludes with suggestions for future directions in bilingualism research.

Chapter 2 Bilinguals and Bilingualism

This chapter focuses on addressing two questions: what is bilingual and how to characterise bilingualism. The path followed to define and describe bilingualism will be gradually illustrated through a conceptual review. A conclusion is presented at the end of the chapter to highlight the key terms and variables which are adopted to guide this project's design.

2.1 Am I a bilingual?

The first question in bilingualism research concerns who should be recognised as a bilingual speaker. Primarily, the general notion of bilingualism indicates the ability to use two languages. Bloomfield (1933) and Weinreich (1953) refer to bilingualism as the ability of native-like control over two languages, and Mackey (1957: 51) defines bilingualism as "*the alternative use of two or more languages by the same individual*". Noticeably, many definitions of bilingualism in previous several decades tended to emphasise balanced proficiency levels across two languages without accounting for the development of two languages and individual differences in language experience.

In fact, such balanced bilinguals, mastering two languages with equivalent proficiency, are rare in practice. Moreover, the languages in bilinguals' repertoire are in constant interaction and competition during their daily communication. Some people tend to co-use their two languages in the same situation or conversation more intensively, while other individuals are prone to use languages in different patterns for distinct communicative goals or in different contexts. Such differences across individuals' language use experience may lead to further variations in multiple aspects associated with their bilingual language development, for instance their language dominance, fluency and language switching habits, and will finally influence their characteristics of bilingualism.

Grosjean (1989) also highlights that a bilingual should not simply be regarded as the sum of two monolinguals in one person or as two separate language competencies in one mind. Comprehensive aspects or more factors, beyond individuals' proficiency levels in their languages, need to be taken into account in describing bilinguals and stressing individual variation in the development of bilingual language experience. For example, the factors associated with people's second language learning process are involved in some researchers' definitions and descriptions of bilinguals. Specifically, Edwards (1994) regards people as bilinguals at any point in the second language learning process, while Bhatia (2004) states that becoming bilingual is the end result of second language acquisition.

Subsequently, increasing numbers of definitions have gradually shifted to describe bilinguals as "people in possession of two languages" (Li, 2007: 7) with little or no emphasis on bilinguals' balanced language proficiency levels. That is, people who have competence in a second language, regardless of their proficiency, and can use both languages in conversational interaction can be recognised as bilinguals. In general, bilinguals should be described and discussed from a dynamic and developmental perspective, and factors like interactional purpose, language proficiency, language context and language mode need to be considered carefully (Grosjean, 1998).

This project follows Grosjean's (1998) idea and takes bilinguals to mean *people who use two, or more, languages (or dialects) in their daily lives*. Furthermore, the definition selected for this project also works as a criterion for sample selection. Indeed, it is rare to find a monolingual who has never been exposed to a non-native language context and does not know at least one word of a non-native language in the current global situation. Thus, addressing the regular use of more than one language in one's life is practical for participant screening. In this project, participants who do not regularly use more than one language in their daily communication will be excluded.

2.2 Variables in characterising bilinguals

Another issue is how to characterise bilinguals. Mackey (1967) lists four aspects, which are degree, function, alternation and interference, to capture the features of bilinguals and their language experience. According to his discussion, degree indicates the proficiency of each language of a bilingual, while the term function focuses on the purpose of a bilingual's language use. Alternation and interference, respectively, discuss the extent of an individual using two languages alternately and separately in daily interactions. Furthermore, Baetens-Beardsmore (1982) conceptualised variety in bilinguals with consideration of bilinguals' age and manner of acquisition, language proficiency level and domains of language use. Therefore, these factors, including age of acquisition (AOA), bilingual proficiency level and the amount of language use, have been commonly considered in categorising and characterising bilinguals in empirical studies (e.g., Baetens-Beardsmore, 1986; Birdsong, 2014; Festman, Rodriguez-Fornells, & Münte, 2010; Wu & Thierry, 2013). Noticeably, these factors are not mutually exclusive; rather, they are interconnected with each other to different extents. For example, a speaker's knowledge of one specific language may relate to their amount of using this language in daily life, and vice versa. These three factors are now discussed below.

2.2.1 Age of Acquisition (AOA)

Age of acquisition is defined as the age at which a person starts to acquire a second language. It distinguishes between people who learn more than one language from birth and those who acquire a second language later in life. Both early and late bilinguals learn a second language after acquisition of their first language is complete; the difference is when their second language acquisition starts.

After full acquisition of L1, those who began to learn L2 before puberty or 12 years old (Lenneberg, 1967) are recognised as *early bilinguals*; otherwise, people are considered *late bilinguals*. However, even though the majority of early bilinguals usually reach native-speaker level of proficiency in L2, some aspects related to language proficiency (e.g., language processing, L1 accent) are still different from *simultaneous bilinguals* (Filippi, 2011; Flege, 1999; Hakuta, Bialystok & Wiley, 2003). According to Baetens-Beardsmore (1986: 29), simultaneous bilinguals are described as “people whose two languages present from the onset of speech”. Besides, simultaneous bilinguals can manage both languages with balanced high proficiency, like native monolinguals in each language, and the most prominent distinguishing characteristic is that they learned two languages at the same time from birth (Costa & Sebastián-Gallés, 2014).

2.2.2 Bilingual Proficiency

Bilinguals may show variation in the competence levels between their languages. While some attain equal proficiency in their languages, for most bilinguals one of their languages dominates as their languages constantly develop and compete with each other. Baetens-Beardsome (1986) uses the term “equilingual” to indicate “balanced bilinguals” who are capable of mastering two languages equally well. However, bilinguals tend to select a specific language to use for a particular purpose in a given domain. As

Fishman (1971) states, bilinguals are rarely equally fluent in both languages on all topics, for the purposes of language in society are usually unbalanced. Therefore, the majority of bilinguals are dominant in one language and subdominant in the other (Filippi, 2011).

Measuring bilingual proficiency is not easy; commonly, skills and levels in two languages should be assessed through four modalities: listening, speaking, reading and writing (Mackey, 1968; MacNamara, 1967). Practical tests for bilingual proficiency assessment were summarised into four types by MacNamara in 1967, i.e., rating scales, fluency tests, flexibility tests and dominance tests. In this project, bilingual participants' language proficiency is commonly assessed through their self-rated scores and an objective English proficiency test, *Lexical Test for Advanced Learners of English* (LexTALE) (Lemhöfer & Broersma, 2012), to control for their L2 competence and knowledge of their two languages. Some specific approaches to bilingual language proficiency and fluency are also involved in different studies for the specific purposes of the study. Tasks and standardised measures used in bilingual language proficiency assessment will be introduced in detail in the general methodology Chapter 5.

2.2.3 Amount of language use

A bilingual speaker's language proficiency and communication purposes are mutually linked to their amount of language use. In this project, the amount of language use is a crucial variable for the study design and participant screening, which includes aspects related to bilinguals' code-switching patterns and frequency, and language exposure.

Code-switching commonly exists in bilingual language practices and imposes high demands on coordinating two languages in one integral utterance. Measuring bilinguals' code-switching patterns is essential to identify which specific kind of code-switchers they are, and to differentiate linguistic co-activation levels in bilingual utterances (Muysken, 2000) This project follows Muysken's (2000) classification of code-switching, in which three commonly-observed code-switching patterns in bilingual communication, i.e., insertion, alternation and congruent lexicalisation or dense code-switching, are highlighted. The typology of code-switching will be discussed further in Chapter 4.

Besides code-switching patterns, the frequency of bilinguals' language switching is an essential factor to classify bilinguals into frequent code-switchers or non-switchers. A self-assessment psychometric bilingual switching questionnaire is commonly used to measure bilingual language switching performance (Rodriguez-Fornells et al., 2012). In this questionnaire, bilinguals need to rate their language-switching frequency per week on a scale of 0–7, where 0 indicates no language switching occurs during a whole week and 7 indicates that they switch between languages every day. Bilinguals in many previous studies (e.g., Bonfieni, Branigan, Pickering, &

Sorace, 2019; Yang, Hartanto, & Yang, 2016; Yang, Ye, Wang, Zhou, & Wu, 2018) were also required to report for how long or how often they were immersed in a monolingual or bilingual environment. This procedure helps researchers to understand in which language context these bilinguals habitually reside.

Furthermore, the environment that bilinguals are habitually exposed to or use their languages in is another factor to describe the amount of language use. Grosjean (1985, 1994, 1998) argues that bilinguals inhabit various language modes on a monolingual-bilingual mode continuum and their language control mechanism changes based on which language mode they are in. Green (2011) indicates that language switching in different contexts can lead to varied inhibitory control processes. Green and Abutalebi (2013) further identify that bilinguals use their languages separately, without switching, for different purposes and audiences, when they are in a single-language environment; while bilinguals switch between their languages alternately or mix their languages in one utterance when more than one language is required in a given linguistic environment. In conclusion, code-switching patterns and frequency measure the daily amount of language use, while language exposure calculates the general amount of habitual language use.

2.3 Summary of this chapter

In this chapter, the main concepts of bilingualism and categories of bilinguals have been reviewed. Important factors associated with bilingualism characterisation, such as age of acquisition, language use amount and language proficiency, are also introduced and highlighted. In general, this chapter sets up a scenario related to bilingual participants for this project. Questions related to cognitive control and its relationship with bilingual language experience will be discussed in the following chapters.

Chapter 3 Bilingualism and Cognitive Control

This chapter starts with an introduction to cognitive control, and two specific aspects, namely, inhibitory control and cognitive shifting, in domain-general cognitive control process are also discussed to address the aims of this project. An in-depth review of the interconnection between bilingual language and cognitive control from both theoretical and empirical perspectives follows. Some gaps in and limitations of existing research on bilingual language processing are also presented at the end of this chapter.

3.1 Introduction of Cognitive Control

Cognitive control (also referred to as “executive functions” in some literature) enables individuals to behave well by planning, judging and adapting and avoiding behaviour ill-advised by intuition, habits or instincts. Therefore, cognitive control is a collection of top-down mental control processes which monitor and rectify individuals’ voluntary actions to achieve goal-directed and adaptive behaviours (Diamond, 2013; Yang, 2015). A key issue in cognitive control research is how different mental processes coordinate and cooperate to fulfil complex cognitive tasks (Diamond, 2013; Miyake et al., 2000; Monsell, 1996). To address this question, different theoretical models of cognitive control mechanisms have been proposed. The dissociable model proposes that cognitive control is made up of separable processes or different cognitive aspects. It highlights that various processes work independently, following different developmental paths (Diamond, 2002). From a unitary perspective, cognitive control is theorised as a unitary and domain-general cognitive construct, and various highly-integrated subprocesses in cognitive control work as an entity in different conditions (Carlson, Mandell & Williams, 2004; Filippi, 2011; Yang, 2015).

Differently, Miyake et al. (2000) suggest that the building blocks of cognitive control are integrative but mutually separable components: inhibition of irrelevant information, shifting and information updating. Since the integrative framework of cognitive control addresses both the cooperation between and the distinct roles of each cognitive subprocess, it has become more widely adopted by studies in recent decades. Similarly, Diamond (2013) further summarises these aspects as (1) inhibitory control (2) cognitive flexibility and (3) working memory. Inhibitory control matches Miyake et al.'s (2000) definition of "inhibition", which indicates the ability to control one's attention, behaviour or emotions in order to concentrate on one target without being distracted by other non-targeted issues. Two subcomponents, interference suppression and response inhibition, of inhibitory control are also discussed. Interference suppression indicates the ability to ignore distracting information and select and focus on relevant information, while response inhibition is believed to control and suppress already-generated behavioural responses (Diamond, 2013). Cognitive flexibility, which corresponds to "mental-set shifting", indicates the ability to adjust to changing demands through changing one’s perspective or shifting back and forth between multiple tasks (Monsell, 1996). This notion involves updating links closely to working memory (Miyake et al., 2000). It requires the monitoring and coding of incoming relevant information and actively manipulating it to realise learning processes and solve problems, rather than passively storing information. This current project adopts Miyake et al.’s (2000) integrative model of cognitive control to investigate how bilingual language experience shapes bilinguals’ inhibitory control (inhibition) and cognitive flexibility (shifting). According to Miyake et al.’s (2000) and Diamond’s (2013) discussion of cognitive control, Figure 3.1, below, presents the interconnections between the three components of cognitive control.

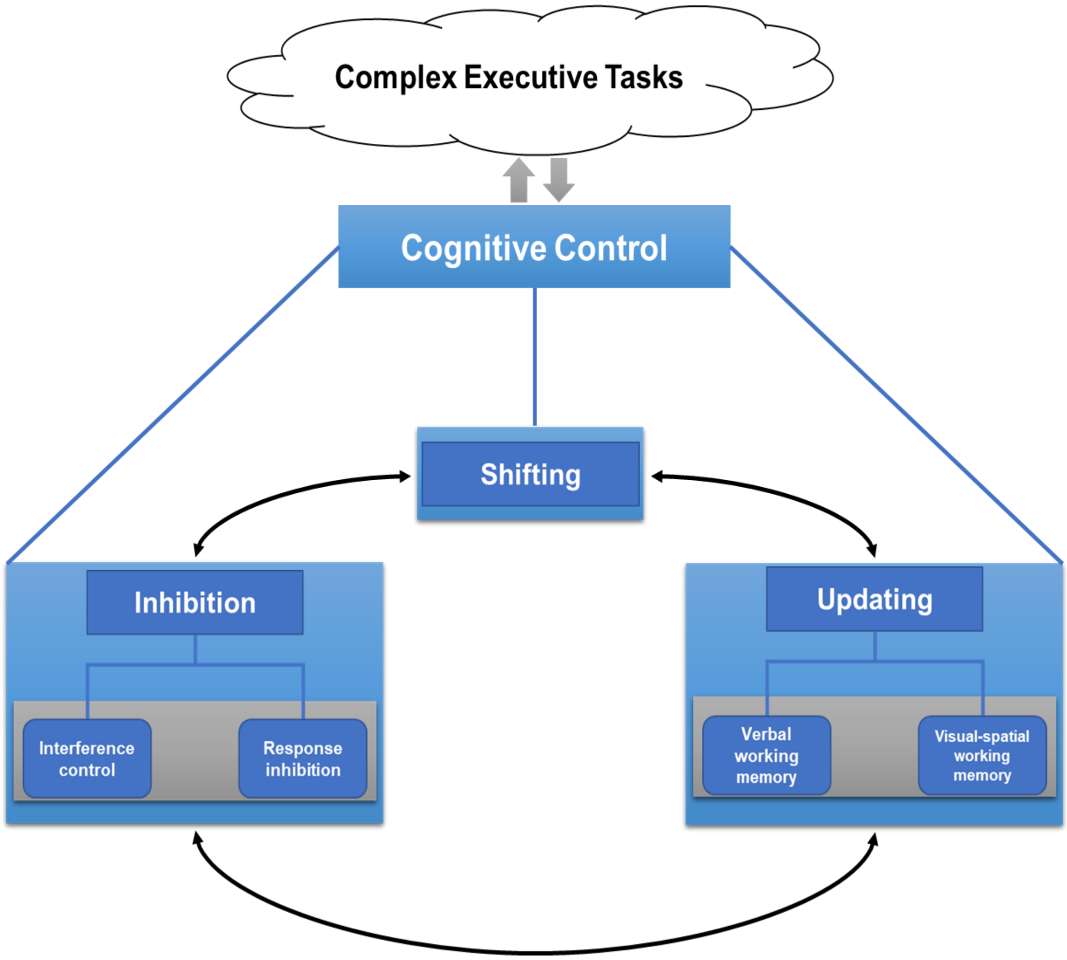

Figure 3.2 The three aspects of domain-general cognitive control and their relationship in fulfilling complex executive tasks

Noticeably, measuring a specific aspect of cognitive control is challenging, and the most vexing problem is task impurity (Miyake et al., 2000; Miyake & Friedman, 2012). According to Miyake and Friedman (2012), any target cognitive control aspect should be embedded within a specific task context and any results derived from the task inevitably contain non-targeted cognitive process-related variances. That is, domain-general cognitive control is a complex integrative mental process, consisting of mutually correlated and specifically separable components. It is so complex that executive tasks are used in experiments involving different cognitive functions that cooperate and contribute differentially (Miyake et al., 2000). For example, the Tower of Hanoi task is frequently described as a measure of “planning and decision making” ability (Miyake et al., 2000); indeed, multiple cognitive processes, such as cognitive inhibition and updating, are also involved in assessing individuals’ ability to complete this task. Tasks labelled as “measure of inhibition” (e.g. Stroop task) can also put demands on working memory. Furthermore, various tasks seem to require working memory but, apparently, they are not mutually exclusive and equivalent. As Valian (2015: 7) emphasises, “*good performance on one executive function task does not entail good performance on other executive function tasks*”; it is hard to have pure cognitive task measures only for one specific executive process or cognitive control component. It has to be admitted that current knowledge on the cognitive control mechanism and the tasks used in experiments is restricted. Table 3.1, below, summarises the behavioural tasks used in this project to measure bilingual participants’ cognitive control, especially cognitive inhibition and shifting performance. The detailed design and structure of these tasks will be introduced in each study-specific chapter.

Table 3.2 Summary of behavioural response tasks used in this project for measuring specific cognitive control components

Task	Cognitive Control Component Measured	General Description
Flanker task	Inhibition (Interference control)	Participants need to identify the direction of the central item (target) while ignoring the

		directions of the surrounding four items (flankers). The surrounding items can point in either the same or a different direction as the central item.
Go/No-go task	Inhibition (Response inhibition)	In this project, this task is in the form of a 'whack the mole game'. It instructs participants to respond immediately when a go-stimulus (i.e., a mole) appears, but to withhold their response once they see a no-go stimulus (i.e., an aubergine).
Simon task	Inhibition (Interference control)	Participants are asked to respond to visual stimuli by making a rightward response to one stimulus and a leftward response to another stimulus.
Verbal Stroop task	Inhibition (Interference control-verbal)	Participants need to identify the ink colour of the colour words while ignoring the meaning of the coloured word. For example, RED presented in green ink. Participants should respond "green" rather than "red" when the word appears.
Spatial Stroop task	Inhibition (Interference control-nonverbal)	It is an adapted version of the Stroop task with no verbal resources involved. it instructs participants to identify an arrow's pointing direction rather than its location.
Colour-Shape Switching task	Shifting	Participants need to make colour or shape

		judgements of stimuli based on cues.
Forward and Backward digit span task	Updating (Verbal-related working memory)	Participants are instructed to listen to a series of digits one at a time (e.g., 3, 4, 2, 8). In the forward-span variant, at the end of each listening, participants need to recall and speak the digits in the order they heard them. In the backward-span variant, at the end of each list participants need to recall and speak the digits they just listened to in reverse order.

3.2 Cognitive Control and Bilingual Language Control

It is known that people’s communication is cognitive demanding, requiring a series of cognitive control processes to realise a specific communicative goal cooperatively. Managing two languages in bilingual communication, however, requires increased cognitive effort. In bilingual communication, bilingual individuals not only have to solve the linguistic interference within one specific language, they also need to select appropriate words from competing alternatives and simultaneously suppress competing words from unintended language (Zantout, 2019). Researchers also regard this process as “lexical selection” or “language control” (Jylkkä et al., 2018), and this association between language and cognitive control is regarded as the rationale of the bilingual advantage hypothesis. Although cognitive control is broadly reported to play a necessary role in language regulation and activation (e.g., Bialystok, 1999, 2011; de Groot, 2011), the magnitude of the correlation between bilingual language processing and cognitive control is intensively discussed, aiming to clearly understand how bilinguals manage more than one language and avoid interference from non-targeted languages in bilingual language comprehension and production processes.

3.2.1 Inhibitory Control Model

One of the influential theoretical frameworks discussing the relationship between bilingual language control and domain-general cognitive control is Green's (1998) Inhibitory Control Model (ICM). The model was proposed and developed in a series of his papers from 1986 to 2007 (Abutalebi & Green, 2007; Green, 1986, 1998), and its basic presumption is that control processes for regulating human language and non-language-related actions have much in common.

Before the ICM was proposed, the language selection problem in bilingual language processing prompted intensive discussion of the nature of bilinguals' lexcio-semantic system (e.g., Green, 1993; Kroll & Stewart, 1994; Weinreich, 1953; Votaw, 1992). However, most of them linked bilinguals' language selection process to the process of language translation equivalents production. Specifically, bilinguals are supposed to develop a direct lexico-semantic link between their L2 and its translation equivalents in L1 (Potter, So, Von Eckhardt & Feldman, 1984). Kroll and Stewart's (1994) revised hierarchical model further explains that bilinguals' translation equivalents are produced through the mediation of both L1-L2 bidirectional links and concepts. However, their model does not suffice to explain the lexico-semantic system of bilinguals' non-translation equivalents production.

To explore the mechanism of language control in bilinguals, Green (1998) proposes an overlap between control processes in regulating human language and non-language-related actions. Additionally, based on Kroll and Stewart's model, he further adds that bilinguals select languages through a lexico-semantic system, comprising words with language tags. It is used to specify which language a word belongs to. Language tags are presumed to limit the activation of lexical items and to select the most activated target language. Consequently, Green (1986, 1998) developed the Inhibitory Control Model, discussing the relationship between bilingual language control and domain-general cognitive control.

The principle of the ICM is that multiple levels of control are required for the regulation of bilinguals' lexico-semantic system. Inspired by the Supervisory Attentional System (SAS, Norman & Shallice, 1986), Green (1998) indicates three different control levels in the ICM: language task schemas are involved on the first level to regulate output control through altering the activation degree of representation and inhibiting other schemas; the second level acts on the lemma layer, selecting target language items through language tags;

the third level operates at the bilingual lemma level to activate words marked by correct language tags by suppressing linguistic items with incorrect tags. Taken together, ICM proposes that lexical items in both languages are simultaneously activated, requiring bilinguals to retrieve target items to produce and inhibit non-target ones; in addition, the degree of inhibition is determined by the activation extent of non-target linguistic items.

In general, the model highlights the role of inhibitory control in mediating bilinguals' language selection and control communication, and further addresses how the conceptual system and lexical representations of both languages are co-activated and all activated lexical items compete for selection even in producing single-language utterances (Kroll et al., 2015; Rodriguez-Fornells, De Diego Balaguer, & Münte, 2006). Figure 3.3 displays Green's proposed inhibitory control model. This model assumes that language production is a communicative action, which is analogous to common non-linguistic physical actions (Pivneva et al., 2012). As physical actions involve different schemas, so bilingual language production involves multiple mental task schemas, which are mental networks implemented by a *Conceptualizer* for individuals to achieve specific tasks.

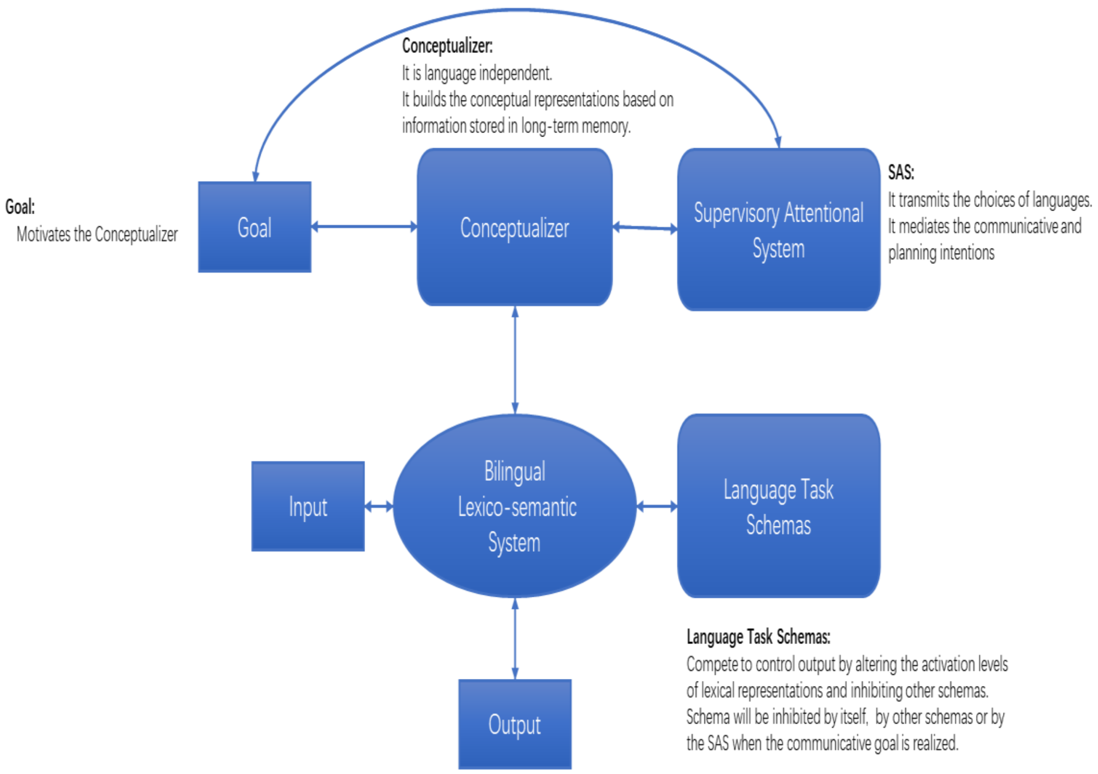

Figure 3.3 Illustration of Green's Inhibitory Control Model (1998) with explanatory notes adapted from Díaz (2006)

Noticeably, the *Conceptualizer* and *Language task schemas* shown in the above figure are independent of the *lexico-semantic system*. To achieve communicative goals, the *Conceptualizer* builds conceptual representations based on information in long-term memory (Green, 1998: 69), and it devises different *Language Task Schemas (LTS)*, more or less automatized, relying on language dominance and proficiency, to control output. Then, *Language Task Schemas* are activated for given goals and compete strongly to control output by altering the activation levels of linguistic representations and reactively inhibiting output from untargeted languages. Moreover, the *Supervisory Attentional System* (Shallice & Burgess, 1996), linking communicative goals with task schemas, monitors whether bilinguals realise communicative goals and modifies existing task schemas accordingly through regulating lexical activation levels while inhibiting the output of non-target languages (Mercier, 2015). In this vein, interference suppression and response inhibition are jointly included in such task schemas' regulation processes.

For example, a bilingual speaker in communication initially needs to identify to which language (L1 or L2) the spoken words he/she receives belong. The conceptualizer operates language schemas to recognise and access the meanings of words (e.g., L2 words) and then conveys the input from the bilingual's lexico-semantic system to the SAS. Then, the highest activated lexical items in the target language (L2) are transmitted through the SAS to language task schemas, and unintended language (L1) is globally suppressed by the SAS before output. Therefore, bilinguals' language processing in communication is an inherently competitive process (Abutalebi & Green, 2007).

In addition, neural-based evidence further underpin the overlap in the brain network during bilingual language control and nonverbal cognitive control processes (Abutalebi & Green, 2007; Luk et al., 2012). Abutalebi and Green (2007) explored the neurocognitive basis of bilingual language control mechanisms discussed in the ICM. Consistently, they suggest that lemmas from bilinguals' two languages are co-activated during bilingual language production. They further identify that bilingual language production is a dynamic process requiring a network of cortical and subcortical brain regions to resolve language competition and select targeted language. The cognitive mechanism that resolves conflicts between parallel activated linguistic representations/ lemmas is not language-specific; instead, brain neural circuits for the domain-general inhibitory control mechanism are involved to manage such cognitive conflicts.

Specifically, tasks involving cognitive control are operated by the frontostriatal and frontoparietal networks (Gold, 2015); while the neural networks underlying bilingual speech are dependent on the activation of brain regions including the dorsolateral prefrontal cortex, the supplementary motor area, the anterior cingulate cortex, the bilateral caudate and the cerebellum, which overlap with cortical and subcortical networks for domain-general cognitive control (Abutalebi & Green, 2007; Calabria et al., 2018; Luk et al., 2011). In other words, the integration of neural systems for domain-general cognitive control is also applicable to function cognitive processes related to bilingual language control. Moreover, the increasing cognitive demands of using two languages are predicted to enhance bilinguals’ efficiency in cognitive control processes beyond language domains.

In sum, Green’s ICM and its extension (Green, 1998; Abutalebi & Green, 2007) discuss the cognitive mechanism underlying bilingual language control, and explain how inhibitory control mediates language selection and production in bilingual communication. Based on this model, unbalanced bilinguals are supposed to make more cognitive effort to switch back into their dominant language (L1), since highly active lemmas in L1 are strongly inhibited before their L2 production. In addition, the increasing cognitive demands of using two languages are supposed to enhance bilingual's efficiency in cognitive control processes beyond language domains, which provides a theoretical rationale for the bilingual advantage hypothesis. Bilinguals who regularly deal with cross-language switching and competition are predicted to achieve higher efficiency in domain-general cognitive control, such as inhibitory control, than monolinguals.

3.2.2 Empirical evidence for cognitive control in bilingual language processing

The proposal of cognitive control in mediating bilingual language control in the ICM provides a theoretical rationale for researchers to discuss the "bilingual advantage hypothesis", which supposes that bilinguals have a significant advantage in cognitive control, as compared to their monolingual peers, as their intensive experience of managing two languages in communication trains their cognitive control efficiency. Besides, the joint activation of bilinguals' repertoire highlighted in the ICM is the central point to explain the interconnection between bilingualism experience and cognitive outcomes. Compared to monolinguals, bilingual speakers' two languages are jointly activated and are in constant competition for selection. In this vein, bilinguals have to control and monitor languages with higher cognitive demands in a way that monolinguals do not experience. Therefore, as Bialystok (2017) discusses, using and managing two languages, as a most intense, sustained and integrative life experience of bilinguals, has potential modulation effects on not only the cognitive functions associated with language processing but on nonverbal cognitive performance. Empirical studies focusing on the association between domain-general cognitive control and bilingual language control, and studies exploring bilinguals' cognitive control outcomes, will be reviewed in the following sections.

The role of domain-general inhibitory control in bilingual language control

Evidence for the deployment of domain-general inhibitory control to manage the joint activation of two languages in bilingual language selection and control is observed in both behavioural and neuroimaging studies with tasks related to picture-naming and lexical decisions (e.g. Beauvillain & Grainger, 1987; Costa & Santesteban, 2004; Grainger, 1993; Hernandez, Bates &Avila, 1996; Marian & Spivey, 2003; Meuter & Allport, 1999; Prior & Gollan, 2011; Thierry & Wu, 2007). In lexical decision tasks, bilinguals' response time in classifying target words into corresponding semantic categories was found to be influenced by the inclusion of cognates from the non-target language (e.g., Grainger, 1993; Guttentag, Haith, Goodman & Hauch, 1984). Incorporating neural activities measures, some studies (e.g., Martin et al., 2009; Rodriguez-Fornells et al., 2002) provide more straightforward evidence for cross-linguistic interference and the joint activation of linguistic repetitionsduring bilingual language processing. For example, Thierry and Wu (2007) conducted an ERP study to explore how L1 influences bilinguals' L2 processing. They instructed Chinese-English bilinguals studying in an English (L2) environment to decide whether English words they saw in pairs were matched in semantic meaning or not, and at the same time collected their neural response data. In the experiment, prime and target words in each trial were either semantic meaning related or not. Half of the word pairs' Chinese translation equivalents designed in this task have repetition of one Chinese Mandarin character, aiming to explore the effect of the co-activation of the native language on bilinguals' L2 processing. The results indicated that these Chinese-English bilinguals were automatically affected by or inclined to refer to their native language knowledge in L2 processing, even if L1 was not in use during the task (Thierry & Wu, 2007). Therefore, their study provides evidence for the simultaneous co-activation of the non-targeted language in bilingual language processing. Subsequently, Martin et al. (2009) consistently found the automatic semantic access to and joint activation of both languages in highly proficient Welsh-English bilinguals' language processing. Furthermore, their results revealed the roles of executive control, including selective attention and cognitive updating, in operating bilinguals' language control processes related to L1-L2 interference monitoring and selective control of non-targeted linguistic resources.

The simultaneous joint activation of non-targeted language (e.g., L1 Russian) in bilinguals' English (L2) word matching task performance was also observed in an eye-tacking test conducted by Marian and Spivey (2003). In their study, Russian-English bilinguals were required to use eye movements to match a spoken word with one of three pictures they saw. Some stimuli with cross-language interference, like objects whose name is phonologically-similar to the target English word, were included in this task. Results showed that these Russian-English bilinguals tended to make eye movements towards those cross-language distractor stimuli initially, although the linguistic resources in these distractors were totally unrelated to the word-matching process. In general, these studies consistently highlight the joint activation of bilinguals' repertoire even when only one targeted language is being processing, which provides evidence for the Inhibitory Control Model.

In addition to the joint activation of two languages, ICM (Green, 1998) also refer to inhibitory control in operating bilingual language control and suggest that switching between languages interconnects to changes from a previous inhibitory status for a given communicative task. In this vein, language switching takes time and requires cognitive effort. A study carried out by Meuter and Allport (1999) provided evidence of switching costs in a digit-naming task that is consistent with Green's assumption. In their study, 16 unbalanced bilingual adults with L2 English were tested using a bilingual numeral-naming task. They were asked to speak out digits in L1 or L2 aloud, cued by the background colours of the digits. Their study found that bilinguals took longer to switch from L2 to their dominant language (L1) but less time to switch from L1 to L2. This asymmetry indicates that more inhibition of their dominant language was required when bilinguals produced utterances in their non-dominant language (L2); and when switching back to L1 after naming digits in L2, it took longer and more cognitive effort to reactivate previously inhibited L1. Also, asymmetric switching costs were found among L1 dominant unbalanced bilinguals. After classifying their participants into an L1 dominant group (Group 1) and a more balanced group (Group 2), Meuter and Allport (1999) noticed that language proficiency contributed to smaller switching cost asymmetry. Their study first revealed asymmetric switching costs and supported the prediction of the IC model that the degree of inhibiting non-targeted linguistic representation is determined by the activation levels of linguistic items. Another typical study, by Costa and Santestban (2004), obtained results comparable to Meuter and Allport (1999) when considering the language proficiency of bilinguals. In their study, they carried out five language experiments to test the switching performance of highly proficient Spanish-Catalan bilinguals with English as L3, unbalanced Spanish-Catalan bilinguals and unbalanced Spanish-Korean bilinguals. All three groups did a picture-naming task in which they were asked to name the pictures they saw on a screen in switching or non-switching trials. Consistent with Meuter and Allport's results (1999), asymmetric switching costs were found among unbalanced bilinguals, and symmetrical patterns were found among high-proficiency trilingual speakers, even when they switched from L1 to non-proficient L3 English. According to the IC model, asymmetric switching patterns may also exist when switching from the dominant language (L1) to a low proficiency language (L3). Costa and Sentesteban (2004) explain that language proficiency affected the bilinguals' language switching, and they also postulate that the more balanced in both languages that bilinguals become, the more flexibly they manage two languages.

Later, Finkbeiner et al. (2006) tested English as L1 but mixed-L2 adult bilinguals through three experiments, including a bilingual digit-naming task, a pattern-naming task and a word-colour-naming task. In the first experiment, participants had to name digits in the cued language and complete an L1-only picture-naming task. The experiment's results replicated those reported by Meuter and Allport (1999), that is, in a digit-naming task, participants took longer to switch to L1 than to L2. However, the asymmetric language switching costs incurred with bivalent digit stimuli did not extend to univalent picture stimuli. As the nature of language suppression remains largely unclear, Finkbeiner et al. did a second experiment on 16 bilinguals using a digit-naming task and a dot-pattern naming task. This time, they tested the modified lexical suppression hypothesis, which holds that during bilingual language production, not all lexical items in unintended language are suppressed; instead, only competing lexical nodes in non-target language are inhibited. Their two experiments suggested that even asymmetric switching costs were found in the digit-naming task, which had nothing to do with language switching per se, and the characteristic distinguishing between L1 or L2 switching is the ease status of L1 or L2 production (Finkbeiner et al., 2006). They conducted a third experiment to investigate whether the factor of “ease of processing” could explain the relationship between asymmetric switch costs and language switching. They asked 32 bilingual speakers to name the colours of words. When a word was against a black background, participants had to name the colour of the word; but when the word was against a grey background, they had to speak the word. Words were classified into “fast response words” (i.e., high frequency, short in length, multiple-meaning words) and “slow response words” (i.e., low frequency, long and limited-meaning words). Their results support that “ease of response” is an essential factor in predicting switching costs. They found that participants showed greater switching costs in response to “fast” word trials than “slow” word trials. Finkbeiner et al. (2006) suggest that the speaker’s intent might increase the activation level of target lexical items, but this claim is similar to what the ICM proposes: the activation of target linguistic items interacts with communicative task demands.

Multiple studies have used cued switching tasks (e.g., digit-naming task, picture-naming task) to investigate bilinguals' language switching, though code-switching in bilinguals' natural communication is voluntary rather than cued (Gollan & Ferreira, 2009). Gollan and Ferreira (2009) carried out three picture-naming experiments with young and elderly Spanish-English bilinguals to compare their performance on voluntary language switching and cued language-switching tasks. Differently, they instructed the participants to name pictures in their dominant language only, L2 language only and in both languages voluntarily. They revealed that unlike cued switching, even unbalanced bilinguals exhibited relevant symmetrical switching costs during voluntary switching. Their results indicated that the freedom to mix languages allowed bilinguals to switch like balanced bilinguals.

Another key point addressed in the ICM and its extension (Abutalebi and Green, 2007; Green, 1998) is the role of domain-general inhibitory control in bilingual language management, and it also suggests that there is an overlapping cognitive mechanism for individuals to realise efficient control of both linguistic competition and tasks beyond language domains. As one component of the domain-general cognitive control mechanism, the role of inhibitory control in regulating bilingual language selection and managing cross-language interferences should be recognised (e.g., Linck, Schwieter, & Sunderman, 2012; Kroll, Bobb, Misra & Guo, 2008).

Festman et al. (2010) claim that stronger language control ability contributes to general executive function advantages, especially in the aspects of inhibition, self-monitoring, problem-solving and generative fluency. Festman et al. (2010) classified 29 late bilinguals into “switchers” and “non-switchers” based on their performance on a picture-naming task and then compared the two groups’ cognitive control through a battery of tasks. Their results confirmed that bilinguals’ language control ability was related to domain-general cognitive control rather than linguistic-specific inhibition, but the direction of the relationship between general inhibitory control and language control was not clear.

To examine the relationship between non-linguistic inhibitory control and language switching, Linck and colleagues (2012) conducted a study to test trilingual speakers using a Simon task and a picture-naming task. They predicted that better inhibitory control would lead to smaller switching costs when switching into or from the dominant L1. Specifically, switching costs might be greater when participants switch from dominant L1 to less dominant L2 and L3 compared to switching between less dominant languages (Linck, Schwieter, & Sunderman, 2012). They tested 56 trilingual participants using a trilingual picture-naming task after a Simon task, and the results supported their prediction that enhanced inhibitory control would correlate with reduced switching costs, especially when switching into L1 or switching from L1 to L3, while inhibitory control did not significantly modulate language-switching performance from L1 to L2. Their study supported general inhibitory control being negatively correlated with multilinguals' switching costs during language switching, even though this relation was only found when participants switched into L1 and switched to their weaker L3 from L1.

More recently, Declerck, Graninger, Koch and Philipp's (2017) conducted three experiments to compare switching costs in language switching and task switching performance and to investigate the overlap between language control and executive control. A positive correlation between language- and task-switching in all three experiments was found, indicating an overlap between cognitive control, underlying language control and general inhibitory control. Their findings are in line with the ICM, and confirm that managing parallel activated languages is not linguistic-specific, but is a domain-general conflict-resolving mechanism of the brain.

Jylkkä et al. (2018) investigated the role of general inhibitory control and cognitive shifting processes when naming pictures in Finnish and English. Simon and flanker tasks were used to assess these Finnish-English bilinguals' non-linguistic inhibitory control and a number-letter task tested their cognitive monitoring. Basically, longer response latencies were found during the participants' switching from L2 to L1. This switching cost effect was in line with the ICM, reflecting that the extent of inhibition in one specific language is related to its activation level. The lower a bilingual's L2 proficiency, the more intensive inhibition of L1 is needed to ensure successful L2 production, which contributes to greater L2 to L1 switching costs among these unbalanced bilingual speakers (Jylkkä et al., 2018). However, bilinguals' performance on nonverbal executive tasks (i.e., Simon and flanker tasks) was not found to interconnect with their language switching performance; specifically, the Simon/ flanker effects on participants' performance were not positively associated with mixing costs in their language switching task. Such results were inconsistent with the ideas discussed in the ICM, in which reactive inhibition in bilingual language production is supposed to be mediated by the domain-general executive control system, and should be closely linked to their domain-general inhibitory control performance. Therefore, Jylkkä et al. (2018) suggested that bilinguals' language switching processes might not be directly mediated by cognitive inhibition; instead, conflict monitoring and domain-general set shifting are supposed to be engaged in these processes.

Numerous studies have examined the cognitive control underlying bilingual language comprehension processes. Bultena et al. (2015a, 2015b) found that the magnitude of switching costs in language comprehension was associated with bilinguals' language proficiency. Specifically, larger costs were found for L1 to L2 comprehension switching than L2 to L1 (reversed asymmetric switching costs). Different from the top-down language control schema in language production, these results reflect the bottom-up lexical activation schema in language comprehension. That is, higher proficiency and frequency of use of one language may facilitate its activation, which can further result in a shorter time delay (i.e., faster reaction time) to switch to this language. In contrast, Declerck and Grainger (2017) identified an asymmetric switching cost pattern (i.e., L2 switch costs < L1 switch costs) during bilinguals' language comprehension, similar to the pattern observed in bilingual language production. Their results indicate that the cognitive control mechanisms underlying both language production and comprehension processes overlap.

Heightened use of cognitive control and dynamic recruitment of conflict-control are supposed to assist in monitoring and resolving cross-linguistic conflicts, as well as revising meaning misinterpretations efficiently during real-time code-switching comprehension processes (Hsu & Novick, 2016). This suggestion has also been examined in several language comprehension studies (e.g., Adler et al., 2020; Bosma & Pablos, 2020; Declerck et al., 2017; Dijkstra & van Heuven, 2002). By including an intermittent flanker task in self-paced code-switching utterances reading, Adler et al. (2019) revealed the involvement of a top-down cognitive control mechanism to resolve cross-linguistic competition during the manipulated language comprehension process. Consistent with this, Bosma and Pablos' study (2020) also supports the engagement of cognitive control in language comprehension. It also indicates that stronger inhibition of L1 is engaged when processing L1 to L2 switching utterances, supporting the proposal that cognitive control is required to facilitate sentence reinterpretation processes and efficiently solve comprehension difficulties in real-time language comprehension (Hsu & Novick, 2016). Hence, cognitive control has been argued to mediate bilingual language processing, albeit with mixed findings for cognitive control schemas in language comprehension and production.

In general, studies have discussed the joint activation of both languages and the role of domain-general inhibitory control in the bilingual language control process, providing different evidence for an overlapping cognitive mechanism between general cognitive task and language-specific processing. Noticeably, the mediating role of domain-general cognitive control in bilingual language processing raises another heated discussion concerning the association between bilinguals cognitive control outcomes and their sustained experience in language control.

Bilingual effects on cognition and the debates over the bilingual advantage hypothesis

By controlling for the socioeconomic status (SES) of children, Peal and Lambert (1962) revealed that bilinguals significantly outperformed monolinguals in a majority of verbal and non-verbal cognitive control tasks, especially in the aspect of cognitive flexibility. Their study started a discussion on bilingual effects on cognition development and repudiated previous claims for detrimental effects of bilingualism. The bilingual advantage hypothesis has, since then, gradually been formulated and raised, with more and more research attention shifting towards exploring the consequences of being a bilingual on cognitive control development (e.g., Bialystok et al., 2012; Bialystok & DePape, 2009).

Numerous studies have explored whether the magnitude of cognitive effects varies between monolingual and bilingual groups, and they have attempted to reveal specific aspects of cognitive control in which bilinguals have an advantage (e.g., Bialystok et al., 2004; Calvo & Bialystok, 2014; Filippi et al., 2019; Janus & Bialystok, 2018; Martin-Rhee & Bialystok, 2008; Singh et al., 2018). To capture the lifelong bilingual effects on cognitive control, studies have measured individuals from different stages of their lifespan (i.e., from children to older adults) and discussed the trajectories of human cognitive development while accounting for their bilingual language experience. A large body of experimental evidence from behavioural studies has shown that bilinguals may outperform their age-matched monolingual peers on domain-general cognitive functions involved in attentional control (e.g., Bialystok et al., 2005; Costa et al., 2008; Martin-Rhee & Bialystok, 2008; Yamasaki et al., 2018; Zhou & Krott, 2018), interference control (e.g., Bialystok et al., 2004; Naeem, Filippi, Periche-Tomas, Papageorgiou, & Bright, 2018), working memory (e.g., Bialystok et al., 2014) and cognitive shifting (e.g., Prior & Macwhinney, 2010; Kerrigan et al., 2016). Elderly adults with long-term bilingual language use experience have been reported to have a delayed onset age of cognitive degeneration and to be able to mitigate the effects of cognitive dementia (e.g., Alladi et al., 2016; Bialystok et al., 2007; Chertkow et al., 2010).

Specifically, empirical studies have broadly adopted a series of behavioural tasks, such as the flanker task, Simon task and Stroop task, in which the cognitive inhibition mechanism is closely involved to measure bilinguals' inhibitory control ability. For example, the flanker task, which was introduced by Erikson and Erikson (1974) and adapted by Fan et al. (2002), is an approach to measure an individual's interference control. A brief introduction to this task is given in Table 3.1. As participants doing this task are instructed to only concentrate on the direction of the central target stimulus, they have to inhibit and suppress distractions from surrounding stimuli.

Studies (e.g., Poarch & Bialystok, 2015; Yang & Lust, 2011; Yoshida, Tran, Benitez & Kuwbara, 2011) comparing bilingual and monolingual children's performance on a flanker task have reported positive evidence for bilingual advantage in interference control. Bilingual children have been found to significantly outperform their monolingual peers in their reaction times on a flanker task, showing their enhanced ability in nonverbal interference control and distraction control. The Simon task is another task for measuring interference control, and is similar to the flanker task. Participants doing this task were required to press a key on the left side of the keyboard when they saw a red stimulus and a key on the right side when they saw a blue stimulus, regardless of the position of the stimulus. Such trials are congruent when stimuli appear at the same side as the corresponding key; otherwise, trials are incongruent. The difference in reaction time or accuracy for congruent and incongruent trials is calculated as the Simon effect, reflecting participants' efficiency in inhibitory control. Attentional effort and cognitive demands on inhibitory control are intensively engaged in completing this task. Compared to monolingual children (mean age around 5–9), a series of studies (e.g., Bialystok, Martin & Viswanathan, 2005; Martin-Rhee & Bialystok, 2008; Morales, Calvo & Bialystok, 2013; Tse & Alrarriba, 2014) have consistently revealed that bilingual children perform much better due to their greater efficiency in controlling interference stimuli in this task. However, bilingualism is not always found to be a positive factor associated with children's cognitive inhibition enhancement. Some factors beyond the linguistic domain, such as socio-economic status, might also play a role in affecting children's cognitive control development. For instance, Morton and Harper (2007) administered a Simon task to bilingual and monolingual children with identical SES backgrounds and found that while bilingual and monolingual children performed comparably, participants from higher SES families significantly outperformed those with lower SES backgrounds in conflict monitoring and interference suppression. Calvo and Bialystok (2014) investigated 175 children to understand SES' impact on cognitive control. Both bilingual and monolingual children were classified into low- and middle-SES background groups and they were instructed to complete verbal and non-verbal attention tasks. The results indicated that the children performed equivalently on basic cognitive tasks and bilinguals' cognitive control performance was independent of their SES background, but bilingualism accelerated their cognitive control development. Later, Nair et al. (2017) investigated the effect of bilingualism on illiterate middle-aged adult bilinguals and monolinguals with lower SES using Simon and flanker tasks. The results indicated that bilingual advantage was not less when participants had a low SES background.

Bilingual children and bilingual adults may also give different performances on cognitive control tasks (Bialystok, 2010; Filippi, D'Souza, & Bright, 2018; Filippi et al., 2015). In addition to testing children's performance, a large number of studies have compared bilingual and monolingual adults' performance on cognitive control tasks. For example, Costa et al. (2008) administered an Attentional Network Task (a variation of the flanker task) on a large scale to early balanced bilingual and monolingual adult participants with a mean age of 22 years. Their results showed that early bilinguals with high proficiency in both languages outperformed monolinguals in altering network and executive control. Similarly, Luk, De Sa and Bialystok (2011) tested bilinguals' and monolinguals' inhibitory control using a flanker task, and they observed that early bilingual adults demonstrated significant smaller flanker effects as compared to late bilinguals and monolinguals. Their results indicated that early bilinguals are more efficient in dealing with conflicting information and suppressing untargeted responses. Similar results, showing bilingual adults' better performance on inhibitory control tasks, have also been broadly reported in studies testing participants with different repertoires and cultural backgrounds (e.g., Blumenfeld & Marian, 2011, 2014; Calabria, Hernandez, Martin & Costa, 2011; Coderre et al., 2013; Verreyt et al., 2016; Woumans et al., 2015; Yang & Yang, 2016).

Furthermore, conflict monitoring and cognitive shifting have also been broadly investigated in studies. Conflict monitoring indicates that the cognitive mechanism for detecting and resolving conflicts derives from competitive responses or co-activated tasks (Botvinick, 2007; Zantout, 2019). This cognitive mechanism further supports individuals in adapting and changing their behaviours or responses efficiently. Therefore, some studies adopted cognitive tasks related to task-set switching (e.g., colour-shape switching task, card sorting task) to examine participants' cognitive monitoring and cognitive shifting abilities (e.g., Prior & Macwhinney, 2010b, 2010b; Soveri et al., 2011; Yim & Bialystok, 2012). Some studies discussing the relationship between bilingualism and cognitive control argue that frequent language switching contributes to lower switching costs (Houtzager et al., 2017; Prior and Gollan, 2011; Wiseheart et al., 2016), because frequent language monitoring and switching during bilinguals' communication trains their cognitive shifting ability, while some other studies have failed to find such an advantage in cognitive shifting (Paap and Greenberg, 2013; Mor et al., 2015). Prior and MacWhinney (2010) found that young bilingual adults outperformed their monolingual peers on a task-set switching task, while bilinguals performed more efficiently in shifting their attention between different tasks and giving corresponding responses accurately.

Morales et al. conducted a series of studies (Morales, Gomez-Ariza & Bajo, 2013; Morales, Yudes, Gomez-Ariza & Bajo, 2015) using the AX continuous Performance task (AX-CPT; Braver et al., 2001), and they reported bilinguals' outperformance on this task compared to monolinguals. In the AX-CPT task, participants need to identify the occurrence of the letter combination "AX" among a continuous stream of letters. That is, they are required to constantly monitor the letters they see and only make responses to the presentation of the letter A followed by X. Trials with an A followed by Y or an X preceded by B are distractors; therefore, participants also need to control this interference both proactively and reactively during the task. In this vein, Morales et al.'s results reflected that bilinguals, as compared to monolinguals, develop greater strength in conflict monitoring to facilitate efficient cognitive inhibition.

However, positive results for bilingual advantage in conflict monitoring and cognitive shifting are not always consistently reported. Gathercole et al. (2014) reported that no significant advantages in task-set switching were found among bilinguals with fewer unbalanced language gaps as compared to monolingual participants. Furthermore, Paap and colleagues (2017) tested a large sample of monolingual and bilingual participants through three different cue-switching tasks (i.e., colour-shape switching task, letter-number task, animacy-size task), and they did not find significant differences in two groups of participants' cue-switching performance. In general, it seems that the empirical evidence on whether or not bilinguals obtain cognitive advantage in conflict monitoring, inhibitory control and task-set switching is discrepant.

Besides the advantages of cognitive control in young people, older adults are also discussed and involved in empirical studies examining the bilingual advantage hypothesis. Bialystok et al. (2004) found that older bilinguals outperformed age-matched monolinguals in one of the most used cognitive tasks, the Simon task. Their study reported that bilinguals responded faster in both congruent and incongruent trials with a smaller Simon effect in general compared to their monolingual counterparts, indicating higher efficiency of inhibitory control. Later, Bialystok et al (2005) conducted a series of studies tracing inhibitory control difference in childhood and young and ageing adulthoods. A Simon task was used in all groups from children to ageing adults. The results indicated that bilinguals were more proficient than monolinguals in controlling their attention to override habitual responses and adjust to a more intentional one through their lifespan (Bialystok et al., 2005). Even though the sample size in each age group was unbalanced, with 34 children, 96 young adults, 20 middle-age adults and 20 ageing adults, the study addressed the protective effects of bilingual experience on age-related cognitive inhibition decline.

Even the cross-sectional studies mentioned above have reported positive evidence for bilingual advantage in executive functioning beyond language domains, though they have a limited sample size, approximately 30 participants in the group. The restricted number of participants is prone to increase the probability of falsely rejecting the null hypothesis and reduce the power of the experiment to correctly reject the null hypothesis (Bakker et al., 2012; Paap & Liu, 2014; Paap & Sawi, 2014). It is recommended to increase the sample size to increase the replicability of experiments and avoid underpowered studies. Specifically, Paap and Sawi (2014) suggest that "*If the effect of bilingualism on EF was generously estimated to be of medium size (Cohen's d = 0.5), if the effect was tested with an alpha of 0.05, and if a researcher was willing to accept a power of only 0.67, then one would need 36 participants in each of two language groups given a one-tailed test and 48 in each group for a two-tailed test*" (p.3).

With a larger sample size (108 monolinguals and 125 bilinguals), Lee Salvatierra and Rosselli (2010) examined the effects of bilingualism on inhibitory control using simple and complex versions of a Simon task. Their results indicated that older bilinguals (mean age = 64.12) were more proficient in inhibiting interference information with a smaller Simon effect than their monolingual peers in the simple Simon task but not the complex one. Such results partially replicated the findings of Bialystok et al. (2004), who found bilingualism faciliatory effects on the inhibitory control of ageing people in both simple and complex Simon tasks. Furthermore, their study reflected that the potential source of different results in existing studies was due to variation in the definition of bilingualism and the selection criteria of bilingual participants across studies (Lee Salvatierra & Rosselli, 2011).

Contrary to previous studies demonstrating the positive effects of bilingualism in older bilinguals in adulthood, other studies (Antón et al., 2016; de Bruin et al., 2015; Kirk et al., 2014; Kousaie & Phillips, 2012; Papageorgiou et al., 2019) have been unable to find behavioural evidence for bilingual advantage in executive functions among ageing people. For example, de Bruin et al. (2015) failed to find an overall bilingual advantage in inhibitory control and cognitive shifting among older adults. However, they noticed that active bilinguals outperformed inactive bilinguals and monolinguals on raw switching costs in the task-switching paradigm, suggesting the different performance on cognitive tasks between bilinguals and monolinguals was due to the language use and switching practices of the two languages, rather than their knowledge of both languages (de Bruin et al., 2015a). The authors further endeavoured to reconsider the description of bilingualism, not only based on the knowledge of the languages they speak but by characterising their bilingual language use in life. It seems that bilingual advantage might exist in specific undetermined circumstances (Antón et al. 2016; Paap et al., 2015), and the enhancement of cognitive control in an individual's adulthood might accounted for by other experience in life rather than bilingualism. Older bilingual adults seem to have later onset of cognitive dementia compared to monolinguals (Bak & Alladi, 2014; Bialystok et al., 2004; Bialystok et al., 2008; Martin-Rhee & Bialystok, 2008).

Moreover, bilingualism is also discussed as playing an active role in delaying the onset of ageing-related cognitive degeneration and protecting against cognitive dementia symptoms in later adulthood (see Abutalebi et al., 2015; Abutalebi & Green, 2016; Bialystok, 2017; Bialystok et al., 2016, for reviews). Bialystok et al. (2007) examined the protective effects of bilingualism on cognitive functioning and ageing-related cognitive dementia among 93 older bilinguals and 91 age-matched monolingual patients. They found that older people with lifelong experience of using bilingual languages had a delayed onset of cognitive degeneration, approximately four years later than older monolinguals. Additionally, Bak et al. (2014) found that even acquiring a second language in adulthood (after 11 years old) with regular use in life can positively affect one's cognitive ability and mitigate the cognitive degeneration caused by healthy ageing. Moreover, such a positive effect is independent of childhood intelligence, and participants whose intelligence scores tested in childhood were lower can still largely benefit from bilingualism. However, these findings should be interpreted with caution since other studies have provided weak evidence for the protective effects of bilingualism or failed to replicated such findings (e.g. Chertkow et al., 2010; Zahodne et al., 2014). For example, Chertkow et al. (2010) found a weak protective effect from speaking more than two languages among immigrant participants on cognitive dementia symptoms. Later, Zahodne and colleagues (2014) evaluated the association between older bilingual participants' episodic memory, working memory and task-switching ability and their dementia conversion. The results revealed neither a protective effect as regards delaying cognitive decline among bilinguals nor reported an association between the language proficiency of bilinguals and cognitive dementia conversion.

The discrepancies in empirical evidence discussed so far do not paint a clear picture of bilinguals' cognitive control outcomes, and in which specific aspects of cognitive control bilinguals have an advantage; it raises the question of whether bilingual advantage really exists.

In the next section, the complexity of bilingualism's consequences and the limitations in discussing the cognitive outcomes of bilingualism through bilingual-monolingual cross-group comparisons will be summarised.

3.2.3 Embracing the complexity of bilingualism's consequences

Increasingly, recent studies have had difficulty in replicating positive evidence for the bilingual advantage hypothesis, so researchers have started to shift their research focus from bilingual-monolingual cross-group comparisons to understanding the role of bilingual language experience in terms of affecting bilingual individuals' cognitive control ability through within-group investigations. If experience has the potential to influence human neurocognitive mechanisms, bilingualism might be one small component of human multifaceted life experience, and the excessive emphasis on the power of bilingualism to modify human minds may create bias in bilingual research, as the adult brain and mind are open to various experience (Kroll & Bialystok, 2013).

One possible reason for such inconsistencies in findings in cross-group comparison studies is the lack of a standard and reliable instrument to describe and assess the degree of bilingualism across studies (Anderson et al., 2018). For example, Bialystok, Craik and Freedman (2007) included older bilingual adults who had spent the majority of their lives, at least from early adulthood, using two, or more than two languages, in their study; while Cox et al. (2016) had broader participant selection criteria and recruited multilinguals who were able to use more than one language in life. Leivada et al. (2020) indicate that bilingual is an umbrella term that includes quite a different population. The positive effects of bilingualism on an individual's superior executive functioning are assumed to stem from the overlapping system between nonverbal cognitive control and language control; and the demands that using two languages impose on the cognitive control system are predicted to test the efficiency of executive functioning. However, bilingualism is difficult to define, both its encompassing of a broad typology of speakers (Costa & Sebastián-Gallés, 2014) and its dynamic character. Since it is hard to determine at which arbitrary point a second language speaker becomes bilingual, bilingualism is increasingly understood as a dynamic and interactive life experience with internal and contextual features (Grosjean, 2013; Mackey, 1968; Surrain & Luk, 2019). Specifically, as Celik et al. (2020) discussed in their systematic analysis, their confounding variables, including language proficiency, age of language acquisition, habitual language use patterns, immigration status and life-style related factors, all have the potential to affect bilinguals' performance on neurocognitive tasks and cannot be ignored in seeking to understanding the complicated relationship between bilingualism and cognitive outcomes.

Therefore, the relationship between bilingualism and cognitive control outcomes cannot be oversimplified as there is a continuum of complicated and multifaceted aspects/ indicators in one's bilingual experience trajectory that impose different demands on cognitive control systems and affect neural plasticity. Instead of comparisons between bi/monolingual groups, additional studies using a within-group analysis approach should consider how multiple bilingual experience-related factors, such as language proficiency, language use history, bilingual exposure and habituated language switching practices, interact with neurocognitive adaptation across one's lifespan.

In addition, as it is hard to control for the "task impurity" problem in measuring one specific component of cognitive control, cognitive tasks used in different studies may have varied or inconsistent psychometric validity.

Specifically, Paap et al. (2015) indicate that the tasks used in studies to measure bilingual advantage lack convergent validity and tend to reflect task-specific mechanisms rather the domain-general executive functions. For example, although a Simon task is frequently used to assess inhibitory control performance, multiple aspects of executive functions (e.g. working memory) might be involved during task performance and test-retest reliability is seldom discussed or considered in most cross-sectional studies (for a discussion see Karalunas et al., 2016; Leivada et al., 2020; Soveri et al., 2018). As Soveri et al. (2018) indicate, using tasks with low test-retest reliability in studies with limited sample sizes is likely to result in difficulty in detecting performance differences across groups or weaker statistical evidence for hypothesis testing. Researchers should be careful to deal with null findings for bilingual outperformance in executive tasks and also contemplate whether nonsignificant results are related to task reliability or whether the tasks selected are fit for purpose.

Furthermore, bilingual advantage might be restricted to specific sample groups or presented to the public with publication bias. Publication bias, as discussed before (Adesope et al., 2010; de Bruin, Treccani & Della Sala, 2015; de Bruin & Della Sala, 2015; Lehtonen et al., 2018; Leivada et al., 2020; Paap et al., 2015; Papageorgiou et al., 2019; van den Noort et al., 2019), can also prevent a full understanding of bilingual effects on executive functioning. Paap et al. (2015) also stress that the less frequent appearance of insignificant bilingual advantage in existing studies is probably due to the results for publication bias in studies with null findings or insignificant evidence for bilingual advantages being rarely accepted. Bias seems to have inflated bilinguals' advantage in cognitive function and led to a "file drawer problem" in bilingual research (Franco et al., 2014). Through an overview of accepted conference abstracts from 1999 to 2012 in the strand of bilingualism and executive control, de Bruin, Treccani and Della Sala (2015) found that compared to studies with evidence fully supporting bilingual advantages, those studies challenging the bilingual advantage hypothesis were the least likely to be published. Admittedly, the quality of studies themselves cannot be neglected when discussing publication rates. Research results, to some extent, may closely align with the validity of experimental designation, sample size or theoretical motivation (Bialystok, 2017). However, whether a study is publishable or not does not monolithically rely on how well its results support bilingual advantage, even studies that failed to find positive bilingual impact on cognitive function may contribute a baby step to reveal the full picture of bilingualism and cognition. Moreover, Bialystok (2017: 40) discusses the "absence of evidence and evidence of absence", in that studies that failed to reveal neurocognitive outcomes should not be interpreted as there being no advantages for bilingualism since any consequences of bilingualism are not restricted to appearing in lab-based tasks, but are more likely to happen gradually with fundamental changes in the brain throughout one's life (Bialystok, 2017; Vīnerte & Sabourin, 2019).

Therefore, individual difference in bilingual language experience in recent decades has been significantly stressed when discussing its effects on bilinguals' cognitive control development (e.g., DeLuca et al., 2019; Ooi, Goh, Sorace & Bak, 2018; Surrain & Luk, 2019). For example, more studies (e.g., Beatty-Martínez, Navarro-Torres, Dussias, Bajo, Guzzardo Tamargo & Kroll, 2020; Gullifer et al., 2018; Han, Li & Filippi, 2022; Singh & Kar, 2018; Verreyt, Woumans, Vandelanotte, Szmalec & Duyck, 2016) have started to take language experience-related factors, such as L2 proficiency, habitual language use context and L2 exposure, into account to investigate the interconnection between bilingual language experience and cognitive control. Furthermore, recent theoretical frameworks discussing the cognitive mechanism of bilingual language processing have also been developed on the basis of the ICM accounting for the effects of bilingual language experience and socio-linguistic factors. Specifically, the Adaptive Control Hypothesis (Green & Abutalebi, 2013) and the Control Process Model (Green & Li, 2014), which will be introduced in the next chapter, are two very influential theories that discuss the roles of social context and language use factors as they affect the bilingual language control process. Again, it might be more promising to investigate to what extent bilingual language experience imposes modulation on bilingual individuals' cognitive control performance, rather than insisting on discussing the existence of bilingual advantage.

3.3 Summary of this chapter

In this chapter, the interconnection between bilingual language and domain-general cognitive control has been discussed along with the orientation of the ICM. Empirical evidence for overlapping mechanisms of language and cognitive control, and cognitive outcomes of bilinguals as compared to monolinguals, has also been reviewed. Given the limitations and gaps in the investigation of bilingual advantage, this chapter has highlighted the importance of shifting the research methodology from cross-group comparisons to the investigation of within-group individual differences, and focusing on exploring the modulating effects of multifaceted factors in bilingual language experience on bilingual individuals' cognitive control development. In Chapter 4, several essential factors of bilingual language experience, including code-switching, language proficiency, habitual language use patterns and their interaction with bilingual language and cognitive control, will be addressed.

Chapter 4 Effects of bilingual language experience on language and cognitive control

4.1 Introduction

As increasing numbers of studies have emphasised the complexities inherent to and continuum-like features of bilingual language experience, it is important to carefully characterise bilingual language experience by accounting for multifaceted factors, especially sociolinguistics-related factors, before discussing its interaction with bilingual individuals' cognitive control performance. To fill the gaps in existing studies, this project focuses on exploring how individual difference in bilingual language experience interacts with bilinguals' cognitive control performance.

In this chapter, the Adaptive Control Hypothesis and the Control Process Model, along with a combination of empirical evidence on bilingual language experience-related factors of cognitive control modulation, will be discussed to set up the theoretical scenario for this project and the following data chapters.

4.2 Bilingual code-switching

4.2.1 Defining and classifying code-switching

Code-switching is common in bilingual communication and imposes high demands on coordinating two languages in one integral utterance. Ferguson (1959) defines code-switching as a situation where more than one language or variety co-exist and are specialized according to the function (cf. Romaine, 1995).

Typically, to create an utterance with two languages, co-existence involves selecting one language to create a grammatical framework and inserting certain linguistic items from another language. Poplack (1980) identifies three types of code-switching: *tag-switching, inter-sentential switching* and *intra-sentential switching.* Later, Muysken (2000) proposes three patterns of code-switching: *insertion, alternation* and *congruent lexicalisation* or *dense code-switching*, which are commonly observed in bilingual communication. Both Poplack's and Muysken's classifications are based on the degree of integrity, and bilinguals' language proficiency differs in these three kinds of switching.

In producing utterances with the pattern of *insertion*, one language is used as the matrix language (Myers-Scotton,1993), providing the grammatical framework for the sentence, and bilingual speakers can flexibly embed linguistic items from another language (also known as the "non-matrix language") into the matrix language framework to create a whole sentence. However, *congruent lexicalisation* breaks down the boundary between different languages further so that linguistic items from both languages are intensively mixed up within one single utterance. Producing utterances with this code-switching pattern involves the joint activation of a bilingual's two languages at both the grammatical and lexical levels; moreover, the two languages share one linguistic structure through dense mixing of lexical items from both languages. Generally, both insertion and congruent lexicalisation/ dense code-switching, as language switching happens within utterances, are regarded as “intrasentential code-switching” in a broader sense. The *alternation* pattern, in fact, is also known as “intersentential code-switching”, indicating that bilinguals switch between languages at the clause level or, alternatively, use two languages across structurally independent sentences.

Besides the distinctions in language structure across the three code-switching patterns, Muysken (2000) argues that the degree of lexical activation and language linguistic systems vary across the three different patterns of code-switching. Stretches of words from two languages are structurally separated in the pattern of alternation, therefore, language activation shifts across two languages. However, activation of one language in insertion is supposed to be temporarily decreased, allowing the language system to be ready for lexical mixing. In dense code-switching, both languages are co-activated, which makes it possible for two languages to share their processing systems on both syntactic and lexical levels (Deuchar, Muysken, & Wang, 2007; Zantout, 2019).

Furthermore, according to the integration degree of lexical items and grammatical framework across two languages, different cognitive control strategies are deployed in producing varied code-switching patterns (Ng & Yang, 2021; Treffers-Daller, 2009). For example, as bilinguals can choose to use lexical items from the language to hand, and combine both lexical and grammatical items from both languages flexibly within one utterance, dense code-switching is the least cognitively control demanding as compared to the other two types of code-switching, but it is considered to facilitate bilinguals' language production in naturalistic communication (Yang et al., 2016; Green and Abutalebi, 2013). In contrast, language alternation (intersentential code-switching) involves heightened cognitive control demands because bilinguals have to constantly monitor and control the co-activated languages to keep lexical and grammatical items from two languages separate in utterance production.

This project mainly adopts Muysken's (2000) classification of bilinguals' code-switching patterns. Table 4.1, below, shows a summary of the three code-switching patterns with Chinese-English examples. Noticeably, the three patterns of code-switching are not mutually exclusive; theoretically, a bilingual can produce any of the three different types of code-switching during communication as long as the person has the necessary linguistic proficiency (Green & Li, 2014).

Table 4.1 Summary of different code-switching patterns with examples (English translation of each example is shown in square brackets)

Pattern	Example
Alternation (intersentential switching)	努力地工作赚钱，that is the only thing I can do. [Working hard to make more money, that is the only thing I can do.]
Insertion (intrasentential switching)	这个项目需要招一个 volunteer 来帮忙。 [A volunteer is needed to help complete this project.]

Dense code-switching (intrasentential switching)	等你见完 supervisor，也 submitted 了你的 final thesis，我们就 go hiking 去。 [After you have met your supervisor and submitted your final thesis, we could go hiking.]

In addition to the three code-switching patterns mentioned above, researchers have also conducted different studies to explore bilinguals' cued and non-cued (i.e. voluntary) code-switching performance; and the distinctions in both behavioural and cognitive performance underlying these two kinds of code-switching processing are also addressed. Cued switching paradigms (e.g., picture-naming task, digit naming task) are commonly used to examine bilinguals' code-switching performance (e.g., Costa & Santesteban, 2004; Meuter & Allport, 1999; Prior & Gollan, 2011). Blocked and mixed conditions are commonly employed in these paradigms. In the mixed condition, bilingual participants are instructed to switch between their two languages based on cues given experimentally, such as background colours or national flags; while in the blocked condition, they are required to use only one pre-specified language throughout all testing trials. Therefore, bilinguals in cued code-switching tasks are not able to switch between languages freely or in their habitual way. Cued switching costs are usually measured to reflect the fact that bilinguals' naming responses time is greater in switching trials as compared to non-switching trials, and to further index that cued code-switching takes cognitive effort and is governed by top-down control processes (de Bruin et al., 2018; Gollan, Kleinman, et al., 2014).

Noticeably, cuing bilinguals to switch between languages may not be able to reflect bilinguals' habitual code-switching patterns, that is, bilinguals are instructed to switch based on cues in code-switching tasks, although they do not habitually switch between languages in that way. In this vein, investigating bilingual code-switching through a more ecologically valid approach and focusing on bilingual's code-switching behaviours in naturalistic contexts without cues have been highlighted in a number ofstudies (e.g., Blanco-Elorrieta & Pylkkänen, 2017; Gardner-Chloros et al., 2013; Gollan & Ferreira, 2009; Gross & Kaushanskaya, 2015). For example, Gollan and Ferreira (2009) instructed their participants to name pictures in their dominant language only, L2 language only and in both languages voluntarily. They revealed that unlike cued switching, even unbalanced bilinguals exhibited relevant symmetrical switching costs during voluntary switching. Their results indicated that the freedom to mix languages allowed bilinguals to switch like balanced bilinguals. Jevtović, Dunabeitia and de Bruin (2020) reported that bilinguals were more effortful and had slower responses in cued code-switching as compared to voluntary code-switching. Their study reflected that switching between languages spontaneously could be relatively "cost-free" (Kleinman & Gollan, 2016), since code-switching in naturalistic communication gives bilinguals more freedom to switch based on lexical accessibility, leading to making dealing with cross-linguistic interference and competition less cognitively demanding.

Contrary to cued code-switching paradigms, voluntary switches are unprompted, sociolinguistic context-oriented and occurring smoothly in bilinguals' naturalistic speech (Zantout, 2019). Furthermore, bilinguals produce bilingual utterances containing different patterns of code-switching in their naturalistic communication. In addition to switching between two languages freely, bilinguals in naturalistic communication also need to choose which specific pattern of code-switching to produce and decide which language to switch into based on interlocutors and socio-interactional contexts. As mentioned above, cued code-switching requires top-down control processes because bilinguals' code-switching is driven by explicit cues; however, both top-down and bottom-up control processes are required to regulate bilinguals' voluntary switching, as bilinguals have to monitor sociolinguistic factors to format their code-switching and select appropriate language to use based on lexical accessibility (de Bruin, Samuel, & Duñabeitia, 2018; Gollan & Ferreira, 2009).

Even though direct comparisons of bilinguals' cognitive control mechanisms underlying voluntary and cued code-switching production were conducted in some studies, participants were usually tested in two separate code-switching-related tasks within one study, and these tasks mainly measured bilinguals' single-word or separate expression switching production between languages, which is not frequently observed in bilinguals' naturalistic communication. Instead of word-level language switching, bilinguals produce bilingual utterances containing different patterns of code-switching in their naturalistic communication. How bilinguals habitually combine their two languages and produce utterances with code-switching in spontaneous language production processes is an issue requiring more elaborate measurement to assess and quantify.

This project, therefore, aims to adopt more comprehensive approaches to measure bilinguals' habitual language use practices, and to explore how individual difference in bilingual language experience affects bilinguals' both cued and voluntary code-switching processing and efficiency in cognitive control.

4.2.2 Measuring code-switching

Code-switching in bilingual language production is commonly measured from multiple aspects, including switching frequency, switching pattern and switching fluency, and through numerous approaches. However, each approach for measuring bilinguals' code-switching has its limitations.

In most studies, questionnaires are adopted as a useful tool to collect information related to bilingual individuals' frequency of switching between languages or intensity of exposure to code-switching contexts in daily interaction. Some widely-used questionnaires (e.g., Anderson et al., 2018; Hartanto & Yang, 2016; Rodriguez-Fornells et al., 2012) also distinctively measure bilinguals' frequency of producing each specific type of code-switching in their daily life. Consistently, 5-point Likert scales (i.e., never 1 – always 5) are involved in these questionnaires, such as the bilingual switching questionnaire (BSWQ), to quantify bilinguals' self-rated code-switching frequency in different conditions. Bilinguals in many previous studies (e.g., Bonfieni, Branigan, Pickering, & Sorace, 2019; Yang, Hartanto, & Yang, 2016; Yang, Ye, Wang, Zhou, & Wu, 2018) were also required to report for how long and/or how often they were immersed in a monolingual or bilingual environment. This procedure helps researchers to understand in which language context these bilinguals habitually reside. A specific introduction to the bilingual code-switching questionnaires used in this project is presented in the following Chapter 5 and each data chapter.

In addition to minimising the randomness and inaccuracy in bilinguals' self-rated code-switching frequency rating in questionnaires, researchers have also adopted some specific tasks as objective tools to measure bilinguals' code-switching practices. For example, the code-switching frequency judgement task (Hofweber et al., 2016, 2020) was introduced to assess bilinguals' code-switching frequency along with accounting for their habitual code-switching patterns. Bilinguals in this task are instructed to imagine that they are in a casual conversation with their bilingual friends who share the same repertoire, and then to rate how frequently they would encounter bilingual utterances similar to the stimuli on a Likert scale. Chapter 5 introduces this task in more detail. This task, through presenting bilingual individuals with authentic bilingual utterance stimuli with different types of code-switching, considers the ecological validity of code-switching assessment, and creates naturalistic language use conditions to quantify how bilinguals use their languages in daily communication.

Although self-rated questionnaires and tasks for code-switching quantification are efficient approaches to measure bilinguals' code-switching frequency, it is still challenging to capture their language use patterns and code-switching practices in spontaneous bilingual speech or naturalistic communicative settings. Two bilingual production tasks, a naturalistic conversation task and a bilingual story narration task, are adopted in this project to assess bilinguals' habitual language use patterns and quantify the frequency of each type of their code-switching in spontaneous speech. In fact, these two self-designed spontaneous bilingual language production tasks can be considered to be non-cued code-switching tasks, in which bilinguals are permitted to use and switch between their languages in their habitual way to narrate a story and introduce their favourite activities at the weekend (see the detailed task introduction in Chapter 6). The number of monolingual and bilingual utterances, and the frequencies of different code-switching utterances (i.e., intersentential switching and intrasentential switching), produced by participants in their spontaneous speech are calculated. To facilitate subsequent quantitative data modelling, the percentages of each specific type of code-switching utterance produced by bilinguals in their spontaneous speech are computed as indexes of their language use habits (the computation and a detailed introduction to this task are discussed in Chapters 5 and 6). In general, all the measures used to capture bilinguals' code-switching frequency and patterns aim to characterise individual difference in bilingual language use in a more ecologically valid way.

In the cued code-switching paradigm, switch costs and mixing costs are two broadly calculated factors to efficiently measure the extent of cognitive demands on inhibition and shifting involved in bilinguals' code-switching processes. Blocked and mixed language conditions are commonly designed in the cued code-switching task paradigm (e.g., bilingual picture naming task), and both repetition and switch trials are involved in the mixed language condition. Bilinguals are only allowed to use one specific language (e.g., Chinese or English) in the blocked language condition, while in the mixed language condition, bilinguals are instructed to switch between their languages based on external cues. If the target language is the same as the one required in the preceding trial, this kind of trial is regarded as a 'repetition' trial in a mixed language condition. Otherwise, 'switch' trials indicate that the target language to be used is different from the current trial and the previous one. Existing studies (e.g., Bobb & Wodniecka, 2013; Bosma & Blom, 2019; Linck et al., 2012; Meuter & Allport, 1999) calculating bilinguals' response differences between switch and repetition trials (i.e., switch costs) have shown that bilinguals' responses in switch trials are typically less accurate and significantly slower than in repetition trials. Switch costs in the bilingual code-switching domain reflect the cost of switching between two languages driven by bilinguals' local control mechanisms, and reflect a reactive and transit language control process (Barbu et al., 2018; Declerck & Philipp, 2015). Meuter and Allport (1999) found that bilinguals who are dominant in L1 make more cognitive effort and need more retrieval time when switching from L2 to L1, rather than from L1 to L2. These asymmetric patterns reflect that more active suppression of the competitive L1 is required when L2 is in production and assume that language control is part of domain-general cognitive control, in particular, inhibitory control processes (Linck, Schwieter and Sunderman, 2012; Meuter & Allport, 1999). In the study by Linck, Schwieter and Sunderman (2012), they observed trilinguals' language switching practices and performance on a Simon task, which revealed that better inhibitory control ability leads to reduced switching costs only when participants switch into or out of the dominant language (English). However, bilinguals with relatively balanced high proficiency in L1 and L2 are prone to pay more symmetric switch costs when switching between their two languages (e.g. Costa and Santesteban, 2004; Declerck, Grainger, Koch, & Philipp, 2017; Nicoladis et al., 2018). For example, Costa and Santesteban (2004) found that unbalanced bilinguals paid a greater switching cost when they switched back to their dominant language, while in a balanced bilingual group, they did not find these asymmetric switching patterns.

Mixing costs is another factor which is typically computed in the cued code-switching paradigm. It indicates the differences between bilinguals' responses in repetition trials among mixed language conditions and trials in blocked language conditions (de Bruin et al., 2018; Gollan, Kleinman, et al., 2014). Differently, mixing costs represent bilinguals' sustained and global control of linguistic interference in bilingual language processing. Noticeably, when examining bilinguals' switch and mixing costs in the cued code-switching paradigm, it is important to take the effects of bilinguals' language proficiency into account (Zantout, 2019). The two factors involved in indexing bilinguals' code-switching performance and the cognitive mechanism in bilingual language processing are discussed further in the following data chapters.

Code-switching fluency is another aspect that has been commonly assessed and discussed in bilingual studies. It is defined as a temporal measure of "the degree of fluidity" in speech while interacting with multiple features in speech production, including speech rate, lexical repetitions, pausing and other hesitation phenomena (Derwing, Munro, Thomson, & Rossiter, 2009; Zantout, 2019). In this project, the fluency of bilingual language production adopted the notion of "utterance fluency", referred to by Segalowitz (2010). To measure bilinguals' code-switching fluency in naturalistic communicative settings, the non-lexicalised pauses (i.e., breakdown fluency) (Skehan, 2003; Tavakoli & Skehan, 2005) in each bilingual's spontaneous speech are measured and analysed. The non-lexicalised pauses in bilinguals' speech comprise both silent pauses and filled pauses which contain a series of meaningless lexicalisations such as 'uh', 'eh' or 'um'. Noticeably, bilinguals' language proficiency can also affect the frequency of pausing in spontaneous speech and their utterance fluency (e.g., Révész, Ekiert, & Torgersen, 2016); therefore, correlation analysis between the factors of language proficiency and code-switching fluency in bilingual language production is conducted in this project. Both methodology and data chapters introduce approaches to quantify bilingual language proficiency and code-switching fluency in naturalistic bilingual speech.

4.3 Adaptive Control Hypothesis

The relationship between code-switching and cognitive control has been intensively discussed in theoretical frameworks and empirical studies (Abutalebi & Green, 2007, 2008; Dijkstra & van Heuven, 2002; Green, 1998, 2011, 2018; Green & Abutalebi, 2013; Green & Li, 2014). As the extent of cognitive control demands for bilingual code-switching processing may vary across different contexts (e.g., voluntary contexts vs mandatory contexts), and the different behavioural ecology of bilingual speakers permits different neural circuits to mediate language control, Green (2011) addresses that it is necessary to discuss language selection and control processes with careful consideration of bilinguals' individual differences in community contexts. The recent theoretical frameworks on bilingual language control further discuss the role of interactional contexts and code-switching patterns in terms of affecting bilinguals' deployment of cognitive control.

In the Adaptive Control Hypothesis (ACH), Green and Abutablebi (2013) discuss how bilinguals' language use and cognitive control demands vary across three commonly observed interactional contexts: single-language, dual-language and dense code-switching contexts. Besides interactional contexts, they also distinguish eight control processes that emerge in the cognitive control system. The recurrent demands on cognitive control in three contexts are varied. In the single-language context, languages are use separately in distinct situations (e.g., use Chinese at home but speak in English at work). As two languages are not co-used in the same situation, code-switching seldomly happens. Therefore, cognitive demands are direct and simple for speakers in this context, in which bilinguals need to constantly monitor linguistic competition and efficiently control lexical interference from their co-activated languages to ensure successful single-language production in a given situation. Cognitive processes, including goal maintenance and interference control, are supposed to be actively involved to motivate bilinguals' language production in this context.

More complicated situations are associated with dual-language contexts, in which speakers need to handle the control dilemma and detect salient cues to realise language selection and output. In this context, bilinguals use their languages alternately in one situation or with different interlocutors during communication. Code-switching at the clause level (i.e., intersentential code-switching) is commonly produced by bilinguals in this context. In this vein, more aspects beyond the aforementioned goal maintenance and interference control, in cognitive control processes, are supposed to be involved in the dual-language context, since bilinguals need to monitor and control their code-switching production in speech, and co-use their languages in the same situation. Specifically, cognitive control processes related to cue detection, task engagement and disengagement and selective response inhibition are assumed to play an essential role in bilinguals' language production in this context to mediate their efficient language alternation in bilingual speech.

Different from these two contexts, bilinguals in dense code-switching contexts are allowed to use lexical items from whichever language comes most readily to hand to format their bilingual speech during communications. Therefore, language task schemas cooperate with each other, and only light cognitive demands are imposed in this context (Green & Abutalebi, 2013). As intensive code-switching is involved in the dense code-switching context, a highly active cognitive control process of opportunistic planning rather than interference control and goal maintenance is needed when bilinguals are routinely mixing two languages within utterances.

In conclusion, to avoid intensive code-switching and mixing of words from two languages in single- and dual-language contexts, co-activated lexical interference from both a bilingual's languages is supposed to be strictly controlled and efficiently resolved but with high cognitive demands for goal maintenance and interference control. In contrast, high cognitive effort in opportunistic planning rather than interference control is required when bilinguals are allowed to routinely combine their languages during utterances. Therefore, the ACH summarises that language task schemas compete with each other in single- and dual-language contexts, while they cooperate with each other in a dense code-switching context (Green & Abutalebi, 2013). Adapted from Zantout's (2019) summary and the ACH discussion, a brief description of control processes in each interactional context is presented in Table 4.2, below.

Table 4.2 Description of the three different interactional contexts and cognitive processes highly involved in these contexts for language processing

Interactional context	**Description**	**Control aims and task schemas coordination**	**Control processes with the highest demands**
Single-language	Two languages are used separately in distinct communicative contexts. Code-switching seldomly happens.	To maintain current language goal and avoid cross-language intrusions. Language task schemas: Competition	***Goal maintenance:*** The capacity for maintaining speaking one language rather than another for a target communicative goal. ***Interference control:*** It ensures the maintenance of a current task goal and consists of two subprocesses, *conflict monitoring* (i.e., monitoring potential conflicts which may affect goal achievement) and *interference suppression* (i.e., efficiently suppress interferences).
Dual-language	Both languages are used alternately in the same situation or environment, but are typically used with different interlocutors.	To limit interference from the non-target language and also restrict the speed of responding to a cue signalling a change to that language. Language task schemas: Competition	***Goal maintenance*** ***Interference control*** ***Salient cue detection:*** The process to notice and detect salient cues or signals indicating a change in language use pattern during communication. ***Selective response inhibition:*** Inhibiting a prepotent ongoing behaviour or response. ***Task disengagement:*** Disengaging from a current task to engage in a new task. ***Task engagement:*** To reach a new goal and engage in a new task.

Dense code-switching	Bilinguals intensively switch between their two languages in the course of a single utterance.	To opportunistically use joint lexical activation to create utterances with intensive code-switching. Language task schemas: Cooperation	***Opportunistic planning:*** Making use of whatever resources comes most readily to hand to achieve a specific goal. In bilingual communication, it indicates that bilinguals adapt the words from one language to fit into the synaptic structure of another language.

According to the ACH's basic assumption that bilinguals' cognitive control processes for language processing adaptively vary across three different interactional contexts, the model further makes several predictions on the interconnections between interactional contexts and bilinguals' language and cognitive control processes. It predicts that:

a) Bilinguals habituated in dense code-switching contexts will incur significantly smaller switch costs (no overt switch costs) in language switching as compared to dual-language and single-language contexts. Overt switch costs in bilinguals' code-switching production are supposed to be observed in the other two contexts because bilinguals have to overcome language task schema competition and control the access of unintended language to speech.
b) Bilinguals habituated in dense code-switching contexts are expected to perform less fluently in cued code-switching tasks since they are used to relying on an opportunistic planning process to use both languages simultaneously in their utterances.
c) Bilinguals in dual-language contexts are expected to outperform single-language context bilinguals in cued code-switching tasks.
d) Habitual dual-language context bilinguals are expected to have greater efficiency in cognitive inhibition than in single-language and dense code-switching contexts, while bilinguals' cognitive inhibition efficiency may be less prominent in dense code-switching contexts.

4.4 Control Process Model

Besides the three interactional contexts in the Control Process Model (CPM), Green and Li (2014) further stress cognitive control process variations in processing bilingual utterances containing different patterns of code-switching patterns. They point out that different control regimes, such as competitive control, coupled control and open control, are involved in producing utterances with alternation, insertion and dense code-switching (Muysken, 2000), respectively. Noticeably, the degree of language separation gradually diminishes from alternation to dense code-switching. In dense code-switching, lexical items from both languages are equally activated for selection without requiring proactive inhibition. So, constant cross-linguistic conflict monitoring and opportunistic planning in cognitive control processes are needed to ensure bilingual speakers mix lexical items appropriately from both languages and realise flexible code-switching within utterances. Therefore, it is supposed that frequent dense code-switching might be able to enhance bilinguals' efficiency in conflict monitoring but reduce it in inhibitory control. Differently, producing utterances with language alternation requires bilinguals not only to monitor cross-linguistic conflict, but impose higher cognitive demands on controlling the competition between language-task schemas and inhibiting co-activated language interference to keep the boundary between two languages during code-switching distinct. In this vein, bilinguals' efficiency in more aspects of cognitive control processes, such as inhibitory control, conflict monitoring and cue detections, is expected to improve through their practice of frequent alternation across two languages in communication.

This model adopts the **conceptual stage** (Levelt, 1999), which precedes the phonological output stage, to explain how bilinguals produce words from different languages in serial order. Lemmas in this stage are tagged for each language and selected by task schemas based on communicative goals (Zantout, 2019). Then, words proceed through **competitive queuing (CQ) networks**, which is the planning stage to filter the most activated lexical items at the phonological assembly level, while inhibiting less-activated ones. The next highest activated lexical item is then the next word ready to be produced, and so forth. Language task schemas control the conceptual-intentional system, which connects with language networks by regulating lexical entry into CQ networks and realizing serial order utterances in more than one language. In summary, this model proposes that language control processes are dependent on bilinguals' habitual code-switching and interactional contexts. Figure 4.1, below, shows the control process of each stage in the Control Process Model.

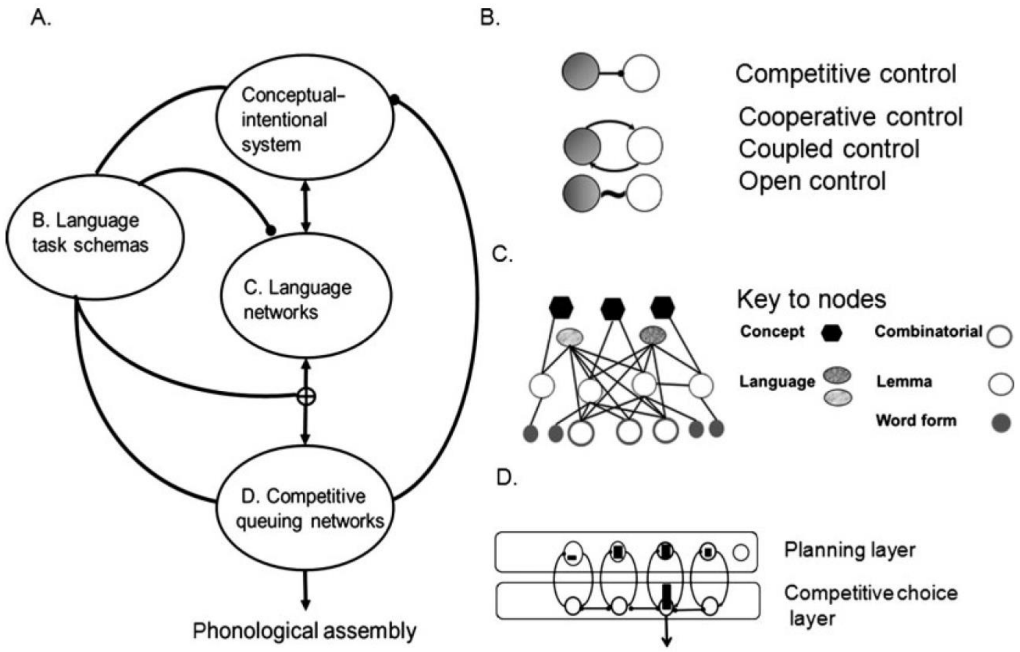

Figure 4.1 Illustration of code-switching processes under the Control Process Model (Green & Li, 2014)

When bilinguals are in communities where two languages are strictly separated according to communicative goals and contexts, they do not habitually switch between languages. It assumes that bilinguals suppress competing unintended lexical items in the planning layer for the entire duration of communication. Therefore, there is a **competitive** relationship between these schemas, as one schema dominates to the exclusion of the other (Green & Li, 2014). However, in code-switching contexts where two languages are used with different interlocutors or for different communicative goals, language control processes change from one language schema to another. Therefore, language schemas coordinate **cooperatively** to realise language switching for different socio-pragmatic purposes. In summary, language control schemas in code-switching contexts cooperate rather than compete to select items to enter the planning layer. Two different ways in which control processes cooperatively coordinate bilingual code-switching, depending on the interactional context, are also discussed in this model.

The **coupled control mode** is suggested to manage co-activated lexical items during language production via inhibition and frequent language-schema switching. It ensures that entry into the language-planning level reflects the intention to use an item or a construction from the other language, and it allows the entry of lexical items by increasing the appropriateness of items from other languages (Green & Li, 2014). Language control schemes for insertion and alternation are in coupled control mode. In dense code-switching practices, **open control** is needed, which imposes the lowest cognitive demands on inhibition during language processing, and has no bias as regards language membership. The open control mode is more feasible but does not mean “no control” at all. Since there is no discrimination of the input from the language control schema, the local context fully determines the language content accessing the planning layer (Green & Li, 2014). Furthermore, the model indicates that high proficiency in both languages is a prerequisite to ensure operational efficiency of the open control mode during dense code-switching.

Languages are jointly activated during dense code-switching and the highest cognitive demands on conflict-monitoring are expected while in the open control mode (Hofweber, 2017), while high cognitive demands on language inhibition in the open control mode are not expected. Therefore, dense code-switching may not require inhibition ability but should involve enhanced monitoring ability; in contrast, alternation may not enhance cognitive monitoring but rather inhibition ability. Figure 4.2 shows the different bilingual language control processes proposed by the CPM.

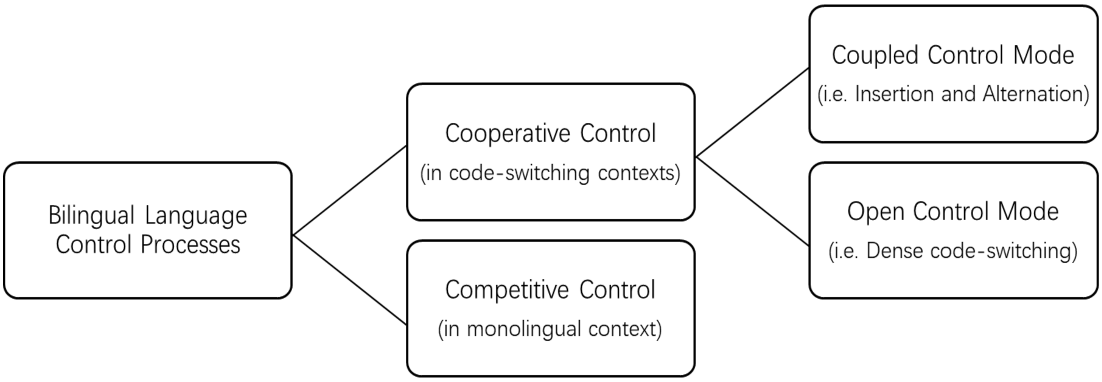

Figure 4.2 Illustration of the relations between bilingual language control processes as discussed in the Control Process Model

To sum up, the CPM indicates how control processes mediate different types of code-switching. Combining ideas from the ACH, this model further claims that language control schemas depend on the interactional context and they mediate how lexical items access the planning layer for speech. In monolingual contexts, a competitive relationship between language task schemas is required to produce speech in the target language and avoid inappropriate utterances due to unintended language accessing the language planning layer. However, for bilingual speakers immersed in code-switching contexts with intensive experience of switching between languages, a cooperative relationship between language task schemas is needed. Cooperative control explains the circumstances in which bilingual speakers plan their speech by utilising lexical items from more than one language to form an entire linguistic construction containing different code-switching patterns. In this cooperative relationship, a coupled control mode is required to allow bilinguals to realise language insertion and alternation, while the open control mode allows them to densely switch across languages flexibly. In the coupled control mode, control passes from one language to another within an utterance, but in the open control mode, there is no target language and output mirroring fitness with the speech plan is consistent (Green & Li, 2016).

In addition, the CPM further proposes and extends specific predictions based on the framework of the ACH, addressing how bilinguals' domain-general cognitive control is influenced by different interactional contexts and processing utterances with different code-switching patterns. It predicts that:

a) A dual-language context enhances cognitive control over that displayed in a single-language context because the greater potential interference of languages for control will train general cognitive control. Moreover, a single-language context may require enhanced cognitive control compared to a dense code-switching context, because in a single-language context, bilinguals will constantly block the interference from unintended language to avoid code-switching.
b) Transferring control processes from cooperative control to competitive control (i.e., transiting from code-switching to monolingual utterances) requires more effort, along with longer pauses and more hesitation,

than within competitive control process adjustments (i.e., transiting to speak a single language from a dual-language community).

c) Bilinguals in dense code-switching contexts produce higher quality novel forms faster, given a visually presented phrase or clause.

In general, both the ACH and CPM describe how language control processes adaptively change when bilinguals manage more than one language during speech. However, as using languages differently tends to alter control networks, individual varieties of code-switching and adaptive changes in their neural implementation of control processes need further investigation.

4.5 Empirical evidence for bilingual language experience effects on domain-general cognitive control

4.5.1 Effects of bilinguals' code-switching habits

The association between bilinguals' code-switching practices and cognitive control performance has been intensively investigated (e.g., Jylkkä, Soveri, Wahlström, Lehtonen, Rodríguez-Fornells & Laine, 2017; Verreyt et al., 2016; Yang, Hartanto, & Yang, 2016). Some studies (e.g., Prior & Gollan, 2011; Houtzager, Lowie, Sprenger & De Bot, 2017; Wiseheart, Viswanathan & Bialystok, 2016) have shown how frequent code-switching practices facilitate some aspects of bilinguals' cognitive control, such as cognitive shifting and inhibition. The correlation between the language switching and cognitive control of bilinguals has also been intensively investigated (e.g., Jylkkä et al., 2017; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016; Yang, Hartanto, & Yang, 2016).

Some studies argue that frequent language switching contributes to lower switching costs (Houtzager et al., 2017; Prior and Gollan, 2011; Wiseheart et al., 2016), because frequent language monitoring and switching during bilinguals' communication trains their cognitive shifting, while some other studies have failed to find such facilitation on cognitive shifting (Paap and Greenberg, 2013; Mor et al., 2015).

Prior and Gollan (2011) investigated how language switching frequency affected bilinguals' task-switching capacity by comparing monolinguals with Spanish-English and Mandarin-English bilinguals with different self-reported language switching frequencies. Their results showed that Spanish-English bilinguals who frequently switched between languages had smaller switching costs than monolinguals, suggesting task-switching benefits attributable to frequent language switching. Furthermore, Verreyt and colleagues (2016) compared the performance of three groups of bilinguals on flanker and Simon tasks. They found that more frequent code-switchers outperformed other bilinguals on both tasks and had the lowest flanker and Simon effects, suggesting a positive correlation between bilinguals' code-switching frequency and inhibitory control efficiency.

However, other studies have failed to obtain similar positive results for bilinguals' cognitive shifting performance (e.g., Paap & Greenberg, 2013; Mor Yitzhaki-Amsalem & Prior, 2015; Kang & Lust, 2018). For instance, Paap and Greenberg (2013) failed to observe a modulation effect of frequent language switching on inhibitory control and task-switching ability. Similarly, Jylkkä and colleagues (2017) also did not find any correlation between bilinguals' language switching frequency and their performance on cognitive control tasks. In these two studies, the frequency of language switching was assessed through different approaches. Paap and Greenberg (2013) calculated the percentage of daily L1 to indicate the amount of use of L2 and switching frequency in communication, while Jylkkä et al. (2017) used a self-reporting questionnaire to measure language switching frequency. The validity of these measures is plausible since self-reported scores of language switching may not objectively reflect one's actual language use; furthermore, bilinguals' percentage of daily L1 usage does not always indicate the frequency of language switching (Yang et al., 2016). In addition, Woumans et al. (2019) investigated the effect of language switching on cognitive inhibition and shifting by comparing monolingual and bilingual adults. Their results revealed bilingual advantages for shifting but not for inhibition, but the shifting advantages of bilinguals did not correlate with their language switching practices (Woumans et al., 2019).

In addition to studies on bilingual adults, Kang and Lust (2018) tested the code-switching and executive function performance of 43 Chinese-English simultaneous bilingual children. They found that bilingual children's code-switching performance did not significantly predict their task-switching and inhibitory control performance measured individually through a semantic fluency task and a Stroop task (Kang & Lust, 2018)

Numerous studies have also discussed the relationship between bilinguals' habitual code-switching patterns and cognitive control performance (e.g., de Bruin et al., 2018; Hofweber et al., 2020; Jevtović et al., 2020; Kang & Lust, 2019; Lai & O'Brien, 2020), and mixed results have been reported. Soveri et al. (2011) investigated how different types of code-switching affected a group of adult Finnish-Swedish bilinguals' cognitive control. They found that frequent intrasentential code-switching practices resulted in increased switch costs but decreased mixing costs, suggesting that frequent intrasentential code-switching modulated bilinguals' top-down management of competing task sets but did not task-set switching abilities (Soveri et al., 2011). Similarly, to explore the effects of different code-switching patterns on German-English bilinguals' cognitive control performance, Hofweber et al. (2016, 2020) found that enhanced efficiency in cognitive monitoring and response inhibition was positively associated with bilinguals' intensive practice of dense code-switching in daily lives. These results indicated a key role for dense code-switching practices in modulating bilinguals' domain-general cognitive functioning, and reflected that frequent practice in monitoring and controlling cross-linguistic competitions to realise feasible switching between two languages further trained bilinguals' efficiency in conflict monitoring and inhibition beyond language domains.

In contrast, Lai and O'Brien (2020) observed the efficiency of goal maintenance and interference control associated with bilinguals' natural inter-sentential switching; however, they failed to find significant language control adaptation across bilinguals' habitual language use environments. They explained their findings as a showcase for the continuous experience of bilingualism, in which bilinguals have fluidity of engagement in different language environments. That is, a bilingual can engage in both intrasentential and intersentential switching during daily communication as long as the person has the necessary linguistic proficiency and the boundaries of the three interactional contexts are vague (Green & Li, 2014).

4.5.2 Effects of bilingual's language proficiency and exposure

Another important factor that has been shown to play a role in bilingual language processing and cognitive control is language proficiency (e.g., Declerck & Kormos, 2012; Kheder & Kaan,2019; Pivneva, Palmer & Titone, 2012). Although bilinguals' languages are activated in parallel with their proficiency level, the proficiency level of each language can modulate co-activation to different extents (e.g. Blumenfeld & Marian, 2013; Kheder &

Kaan, 2021). Since the lexical items from two languages are more balanced and automatically activated among highly proficient bilinguals, cross-linguistic interaction might emerge and need to be solved earlier, as compared to less proficient bilingual peers (Kheder & Kaan, 2019, 2021). L2 proficiency also shows an association with bilinguals' language control strategies and inhibitory control performance. For example, less proficient bilinguals, compared to more proficient ones, were found to globally inhibit L1 to facilitate L2 processing (Van Assche et al., 2013). As the degree of inhibiting the unintended language is considered to be associated with its activation level, increased L2 proficiency strengthens the competition between lexical items from two languages, causing language selection and control to become more cognitively demanding. Therefore, intensive experience of managing two highly-proficient languages enhances bilinguals' language control efficiency; furthermore, it enhances their cognitive control going beyond language domains.

Evidence has shown that balanced bilinguals tend to outperform dominant bilinguals on a series of cognitive tasks related to inhibitory control, cognitive shifting and conflict monitoring (e.g., Abutalebi et al., 2012; Bialystok & Craik, 2010; Bonfieni et al., 2019; Luk et al., 2011). In Mishra, Hilchey, Singh and Klein's (2012) study, proficient Hindi-English bilinguals were found to outperform their bilingual peers with lower L2 proficiency level on a target detection task, reflecting the modulation effect of L2 proficiency on interference and attentional control. Singh and Mishra (2012) provided eye-tracking evidence for the modulation of higher L2 proficiency in bilinguals' conflict resolution and oculomotor inhibitory control performance. Similarly, Yow and Li (2015) found an association between balanced bilingual proficiency and stronger inhibitory control and cognitive shifting ability. Later, in a study by Singh and Kar (2018), bilinguals' L2 proficiency was reported to significantly influence proactive inhibitory control efficiency in a go/no-go task.

Noticeably, language proficiency is one component of bilingual language experience and is closely interconnected with how bilinguals use their languages (Gullifer et al., 2021; Kheder & Kaan, 2021). Specifically, various components, such as length of L2 exposure, diversity of social language usage and language dominance in distinct contexts, can affect the extent of language proficiency in bilinguals. For instance, Luk and Bialystok (2013) found a significant correlation between daily language use and language proficiency, emphasising the intercorrelation of these two factors and the multifaceted nature of bilingualism.

In fact, bilingual language use is closely linked to language proficiency level, so that code-switching only occurs when proficiency in both languages reaches a certain level (Kheder & Kaan, 2021, p. 3). Bilingual speakers, especially highly proficient bilinguals, are able to use their languages actively and produce code-switching on a daily basis, even if they are from different social communities. For instance, by controlling participants' language proficiency, Beatty-Martinez and Dussias (2017) found that frequent Spanish-English code-switchers showed different processing difficulty levels when processing commonly and rarely attested code-switches, while similar performance was not observed among non-switchers. Consistently, Barbu et al. (2018) found an association between frequent code-switching and better performance in task-set shifting, suggesting that code-switching frequency among proficient bilinguals is likely to boost cognitive shifting efficiency.

As for language exposure, it is regarded as the quantity (i.e., the duration of time) and quality (i.e., whether bilinguals actively co-use their languages) of bilinguals' linguistic input, and significantly interrelated with bilinguals' language dominance, L1 maintenance and processing (Chamorro, Sorace & Sturt, 2016). Heidlmayr et al. (2014) tested the relation between language use frequency and inhibitory control on a group of high-proficiency French-German bilinguals through a Stroop colour word task. They found that frequent L2 exposure did not noticeably improve the inhibitory control of bilinguals. However, the findings reinforce the notion that the capacity of inhibitory control can be improved by using more than one language, and as language exposure duration increases, bilinguals' top-down inhibition ability is gradually trained, which leads to reduced cognitive effort. Bonfieni et al. (2019) investigated 83 Italian-English and Italian-Sardinian bilingual speakers through a cued language switching task and found that bilinguals' language switching costs were closely related to the duration of L2 exposure. They reported that higher L2 exposure frequency significantly predicted reduced switching and mixing costs in L1 because the longer duration of L2 exposure reduced the burden of inhibiting L1. Bonifieni et al.'s study (2019) indicates that active linguistic practice and language use can enhance cognitive control.

Therefore, it is insufficient to capture the full picture of the effects of bilingual language exposure and proficiency on cognitive control without considering their connections to other aspects of bilinguals' language use (e.g., habitual communicative contexts, code-switching frequency), since bilingualism is multifactorial, and multiple continuous aspects in bilingual language experience are interconnected and jointly impose long-term effects on bilinguals' cognitive control development.

4.5.3 Effects of interactional contexts and the degree of bilingual language use

Although the available evidence discussed above has suggested that code-switching frequency plays a role in facilitating bilinguals' cognitive control performance, the participants in these studies were from different communities and social backgrounds (Hofweber et al., 2016; Kheder & Kaan, 2021). Care should be taken when interpreting the results from bilingual participants who belong to different social communities or interactional contexts, as bilinguals tend to have a homogeneous language repertoire. As Verreyt et al. (2016) mention, Hispanics in southern California use Spanish and English more interchangeably and engage more in switching compared to Spanish-English bilinguals in other communities in the US, such as San Francisco. Therefore, numerous studies have been conducted to examine the ACH and the CPM, and positive evidence for the varied degree of modulation effects of different interactional contexts or code-switching patterns on bilinguals' cognitive control has been found (e.g., Choo, Keat & Price, 2021; Han et al., 2022; Hartanto & Yang, 2016; Ng & Yang, 2021; Wu & Thierry, 2013).

To understand whether mastering dual languages is associated with enhancements to general cognitive control, Wu and Thierry (2013) tested 18 Welsh-English bilinguals using a non-verbal flanker task intermixed with the presentation of English, Welsh and two languages mixing word stimuli to manipulate different language contexts. Participants were instructed to complete a flanker task, pressing keys corresponding to a central arrow. Single-language and dual-language word presentation during flanker task trials was used to manipulate fast-changing language contexts. It was revealed that when participants were in a Welsh-English mixed language context, they showed enhanced interference suppression capacity in incongruent flanker task trials compared to exposure to a single language context. The findings suggested that the dual-language context enhanced their inhibitory control capacity in conflict handling. Wu and Thierry's (2013) study inspired further studies to manipulate different language contexts in experimental designs testing the interactions between bilingual language contexts and cognitive control.

Similar findings have been reported in later studies with a bilingual language processing inducement design (e.g., Choo et al., 2021; Jiao et al., 2019; Yang et al., 2018; Ye et al., 2017). Adapted from Wu and Thierry's (2013) study, Ye et al. (2017) instructed Chinese-English bilinguals to complete a flanker task interleaved with Chinese and American culture-specific pictures (e.g., the Great Wall of China and the Statue of Liberty). They found that these proficient bilinguals performed consistently better on incongruent trials in a mixed, rather than a single, cultural block, showing enhanced bilingual inhibitory control efficiency in a dual-language context. The language-related stimuli (either word or pictures) designed for these two studies created a relatively complicated mixed language context, which bilinguals often experience, and processing languages in these contexts further raised bilinguals' inhibition and conflict monitoring levels.

Similarly, Yang et al. (2018) investigated the influence of language context on bilingual inhibitory control. They collected data from 30 adult Cantonese (L1)-Mandarin (L2)-English(L3) trilingual speakers via a picture-naming task and a flanker task. Participants were highly proficient in both L1 and L2 and frequently switched between these two languages, while they were moderately proficient in L3, with less frequent switching across L1-L3 or L2-L3. Three picture-naming task blocks were presented initially, and participants had to name pictures in two languages alternately, specifically in L1-L2, L2-L3 and L1-L3. Participants did a flanker task immediately after each picture-naming block. In the flanker task session, participants in all three dual-language contexts performed faster in congruent trials compared to incongruent trials. However, in the L1-L2 dual-language context, participants had similar accuracy rates for both congruent and incongruent trials, without a significant flanker interference effect. This situation reflected the facilitation effects of the L1-L2 context on bilingual speakers' inhibitory control processes. Their study provides empirical evidence to support the interactional context modulating language control processes by adaptively altering cognitive control circuits.

Through analysing bilinguals' flanker task performance after Chinese-English language comprehension inducement, Jiao et al. (2019) further supported the facilitatory effects of bilingual language processing on inhibitory control efficiency. Specifically, Chinese-English bilinguals performed more efficiently in both congruent and incongruent trials subsequent to a Chinese-English mixed language comprehension task. Their results support the prediction of the ACH from the perspective of bilingual language comprehension, suggesting that bilinguals are able to adapt their cognitive control engagement in a dual-language context and perform more efficiently in conflict monitoring and inhibitory control.

A more recent study carried out by Choo et al. (2021) examined the consequences of bilingual experience and interactional contexts for cognitive control. Their results revealed significant facilitation of bilingual experience on inhibitory control performance in a mixed language condition; moreover, the magnitude of the facilitatory effect of bilingualism was found to be associated with the language contexts bilinguals were immersed in. In particular, the positive relationship between bilingualism and inhibitory control efficiency was significantly modulated in a dual-language context, providing evidence to support the predictions of the ACH.

In sum, these studies have examined how disparate language contexts affected the language control and general cognitive control processes of multilingual speakers by manipulating different language conditions in their experiments. However, how these bilinguals' habitual language environments interact with their cognitive control needs more investigation.

Hartanto and Yang (2016) tested 133 Chinese-English bilinguals to investigate the ACH and the CPM. In their study, bilinguals were classified as habituating a single-language context or a dual-language context from their self-reported scales for code-switching frequency and types across different occasions. Hartanto and Yang (2016) predicted that bilinguals who reside in dual-language contexts, frequently using two languages alternately, might have greater cognitive control ability than those constantly engaged in dense code-switching and those living in a single-language community. They used a colour-shape switching task to measure bilingual participants' cognitive flexibility and monitoring ability. Regression analysis was applied to mirror participants' general task-switching ability. They found that bilinguals in a dual-language context had lower switching costs than those immersed in a single-language context; however, these advantages in switching costs were driven by group differences in task-set reconfiguration. Furthermore, their findings indicated that inter-sentential code-switching positively correlated with task-switching ability, while intra-sentential code-switching practices negatively correlated with task-switching ability. They interpreted the results as meaning that bilinguals use whatever language comes most readily to hand in dense code-switching practices and such practices facilitate language production by lightening the cognitive load of language-set reconfiguration (Green & Abutalebi, 2013; Hartanto & Yang, 2016). Inter-sentential code-switching trains task-set reconfiguration while intra-sentential code-switching does not exercise it enough and finally leads to switching cost impairment. Although Hartanto and Yang's (2016) study supports what the ACH and the CPM predict, language exposure and bilinguals' habitual code-switching practices were measured through subjective self-reported questionnaire responses. It is still hard to understand how bilinguals' natural language use affects their cognitive control (Zantout, 2019). To investigate the variations in cognitive effects attributed to lab-based and naturalistic bilingual language contexts, Blanco-Elorrieta and Pylkkänen (2017) carried out a study using MEG to compare bilingual language switching performance in multiple interactional contexts ranging from an artificial switching condition to a fully natural conversation condition. In the study, they administered a picture-naming task to 19 Arabic-English bilinguals. The task included three scenarios for both language production and comprehension, which were a bilingual-interlocutor-context, a monolingual-interlocutor-context and a laboratory-colour-cued condition. In the comprehension block, participants were instructed to comprehend an auditory stimulus and press a button to judge whether the picture presented on the screen matched the utterance they heard; while in the production block, participants had to name pictures presented on the screen according to the rules in each scenario.

Later, with rigorous measurement of the participants' habitual language use contexts, Hartanto and Yang (2020) found that bilinguals with higher intensity of dual-language context engagement had lower switching costs in a switching task than those who habitually use language in single-language contexts. Modulation effects have also been reported in levels of interference control. Ooi et al. (2018) found that in a dual-language context, bilinguals were more engaged in interference control than bilinguals who habitually use language in a single-language context.

Inconsistently, some studies (e.g., de Bruin et al., 2018; Kałamała, Szewczyk, Chuderski, Senderecka & Wodniecka, 2020) have failed to identify the impact of bilinguals' habitual language use contexts in support of the predictions of the ACH and the CPM. For example, Gardner-Chloros, McEntee-Atalianis, and Paraskeva (2013) investigated the code-switching of two groups of English-Greek Cypriot dialect bilinguals in naturalistic language settings by assessing “pausing length”. The two groups of bilingual participants were from London and Cyprus, respectively, and it was supposed that code-switching was the default mode for the London community, whereas code-switching was less prevalent in the Cyprus speech community. They predicted that bilinguals who resided in the community without prevalent code-switching practices, i.e., Cyprus, would have greater switching costs compared to the group located in a frequent code-switching speech community, i.e., London. Specifically, they hypothesised that Cyprus-based bilinguals would be more fluent in the Greek-Cypriot dialect monolingual condition but would pause more in code-switching passages (Gardner-Chloros et al., 2013). Their results were inconsistent with the prediction that bilinguals in the London community would outperform Cyprus-resided bilinguals, as frequent code-switching practices tend to exercise the ability to engage and disengage task schemas. That is, they failed to find that intensive engagement in code-switching contexts enhanced bilinguals’ task engagement and disengagement efficiency.

In addition, Hofweber et al. (2016) reported that bilinguals who habitually engaged in dense code-switching practices showed significant enhancement of inhibitory control efficiency in a high conflict-monitoring task. Similarly, the factor analysis conducted by Kałamała et al. (2020) showed no evidence of any association between bilinguals' intensity of using languages in a dual-language context and response inhibition efficiency.

In general, the discrepancies in existing studies examining the effects of bilingual language experience on cognitive control suggests the need to discuss the cognitive control involved in bilingual language processing in naturalistic conditions. However, it is still challenging to settle on a standard approach, such as computing language entropy (Gullifer, Kousaie, Gilbert, Grant, Giroud, Coulter, Klein, Baum, Phillips & Titone, 2021; Gullifer &Titone, 2020), that can assess not only the quantity of bilingual switching but also measure the traits of interactional context involvement in daily life. To address the interactive impact of bilingual habitual language use experience, this project adopted comprehensive approaches, including self-rated questionnaires, code-switching pattern quantification and a non-cued language production task, to capture bilingual participants' language use habits in naturalistic communication. Therefore, this project seeks to shed some light on understanding how multifaceted factors in bilingualism jointly affect bilinguals' language processing and further modulate their domain-general cognitive functioning.

4.6 Summary of this chapter

In this chapter, the interactions between bilingual language experience and cognitive control, as well as two influential models of bilingual language control, have been discussed. Some important factors related to bilingual language experience, such as bilingual's L2 proficiency, code-switching habits and habitual language use contexts, are highlighted in investigating the dynamic modulating effects of bilingualism on bilinguals' cognitive control development. Existing evidence indicates that bilinguals who reside in a code-switching environment with intensive experience of managing and controlling co-activated languages have different behaviour and neural responses in cognitive control tasks as compared to those who habituated to a diglossia community where two languages are always used separately. Therefore, individual differences in bilingual language use experience are essential to discuss when exploring the variations in bilingualism effects on cognitive control.

In addition, numerous studies have acknowledged the adaptive engagement of cognitive control in processing bilingual utterances with different code-switching patterns and in difference interactional contexts through a lab-based paradigm (e.g., interactional context manipulation, cued code-switching), but a better understanding of cognitive control in bilinguals' language processing in a naturalistic setting (i.e., voluntary switching), along with addressing its interconnection with their language use habits. is needed. In the following chapters, an elaborate introduction to the research questions, general methodology and studies included in this project will be presented.

Chapter 5 General Methodology

5.1 Introduction

Chinese-English bilingual adults with Mandarin as their native language took part in this research project. These participants are late bilinguals who learned English as a second language after their Chinese was well-acquired (Table 5.1). In this chapter, participants' characteristics and the methodological procedure in each study are introduced. General data collection and analysis methods are also described.

Table 5.1 Brief introduction of the studies and participants included in this research project.

Study	Participants	Study overview
Study 1	31 Chinese Mandarin-English bilingual adults (mean age: 28), living in English-speaking countries	[online study] Effects of habitual code-switching in bilingual language production on cognitive control
Study 2	41 Chinese Mandarin-English bilingual adults (mean age: 26), living in English-speaking countries.	[online study] Effects of bilingual language use experience on code-switching production and cognitive control
Study 3	36 university students (mean age: 24), living in London who are Chinese Mandarin-English bilingual adults	[study in lab] Modulations of interactional contexts on cognitive control in language comprehension
Study 4	40 Chinese Mandarin-English bilingual adults (mean age: 25), living in English-speaking countries.	[online study] Effects of code-switching processing and L2 proficiency on cognitive control in habitual and induced language use conditions

5.2 Ethics

The studies met the requirements and gained the approval of the Ethics Committee of the Institute of Education, University College London (UCL data protection registration number: Z6364106/2019/03/108), concerning empirical studies with human participants. An information sheet and a consent form were provided to individuals who expressed interest in this study so that they could decide whether to participate or not. No data were collected until participants signed an informed consent form. Before each study started, the researcher briefly introduced the participants to the general procedure and instructions of this study in Chinese. After participants completed the whole study, the researcher explained the goals of the study they had just participated in. Participants were also asked not to share information related to the study goals to anyone they knew who might be participating in it.

All data collected for this research project were safely stored in my password-protected computer; only my supervisors and I have access. As data were collected and stored pseudonymously, any information relating to participants' identities was not recognised. Since the data are one part of my dissertation, they will be archived as one section of my thesis for the Institute of Education after submission.

5.3 Research design

Focusing on the effects of bilingualism on domain-general cognitive control rather than a discussion of bilingual advantage, this research project is a within-group investigation and aims to explore the interaction between bilingual language experience and cognitive control in language production and comprehension processes. It examines how Chinese-English bilinguals perform in language and domain-general cognitive control tasks, and discusses how cognitive control is deployed differently during bilingual language comprehension and production. The project also explores the role of individual difference in bilingual language experience, such as code-switching habits, interactional contexts, language proficiency and L2 exposure, as it affects bilinguals' cognitive control development; therefore, this project adopts a series of comprehensive approaches to measure participants' language comprehension and production performance in both cued and natural (i.e. non-cued) conditions (e.g. switch/ mixing costs, ratio of pause frequency in conversation), and to quantify their bilingual language use experience (e.g. language entropy). Additionally, the project also compares the cognitive effects of bilinguals' habitual language use experience in manipulated and habitual language use conditions, highlighting the differences between fast modulation and the long-term effects of bilingualism on their cognitive control.

Two empirical studies focusing on bilinguals' cognitive control in language comprehension are included in the project, to address bilinguals' adaptive deployment of cognitive control in speech comprehension while accounting for the impact of their everyday language use experience, especially their habitual interactional contexts and habitual code-switching practices. The cognitive control underlying participants' both bilingual dialogue-listening comprehension and self-paced bilingual sentence reading comprehension is investigated. The project also includes two studies investigating bilinguals' cognitive control in language production processes. These two studies discussed the impact of bilingual language use experience on bilingual speakers' cued- and non-cued language switching production performance, respectively, and stress the differences across cognitive control in mediating bilinguals' cued- and non-cued language switching production.

Overall, these four studies are conducted to boost the existing understanding of the interplay between bilingualism and cognitive control among adult bilinguals with two very distinct languages. Furthermore, it aims to examine the theoretical frameworks of the Adaptive Control Hypothesis and the Control Process Model from both language comprehension and production perspectives, providing more evidence to inform theory and practice.

5.4 General Description of the Participants

Chinese-English bilingual adults

All 148 bilingual participants recruited for this research project are healthy late bilingual adults, they are Chinese-Mandarin native speakers and learnt English as their second language after Chinese was well-acquired. These participants were living in the UK or other English-speaking countries (i.e., America, Australia and Canada) at the time of data collection. They were reached and chosen through different online and offline channels, such as Twitters, Facebook, Wechat, advertisements on the UCL campus or through word-of mouth. The majority of these participants were university students, while some of them are early-career professionals in different occupational sectors. In general, all of them were raised in Chinese Mandarin-speaking families, and had their formal education in China before moving to the UK and other English-speaking countries in adulthood for higher education or work.

Information about the participants' age, gender, L2 exposure and L2 proficiency in each study is presented in Table 5.2 below.

Table 5.2 Participants' gender, L2 environment and L2 proficiency information in each study

Study	Subjects	Mean Age (SD)	Age Range	Gender	L2 Proficiency (LexTALE)	L2 Exposure (years)
1	31	27.68 (4.53)	22~42	13 males	64.46	3.81

2	41	26.17 (2.92)	21~33	9 males	63.75	3.49
3	36	24.25 (2.90)	19~30	12 males	64.79	1.90
4	40	25.08 (2.58)	21~29	9 males	66.31	2.97

It is noticed that the participants in this project had not reached their early thirties on average. At the beginning of each study, all participants completed a Chinese-translated questionnaire relating to their language learning history and measurement of their bilingual language use experience (see section 5.5 for details of the questionnaire). The adapted questionnaire used in these studies can be found in Appendix I: Questionnaires used in this project to measure Chinese English bilingual participants' language use experience. Participants' L2 proficiency was measured through their self-rated competence in English listening, speaking, writing and reading, and through a LexTALE test (Lemhöfer & Broersma, 2012), an objective assessment of bilinguals' L2 proficiency. Noticeably, the participants involved in each study all had good competence in English (i.e., average LexTALE score over 60%).

Additionally, since these participants were living in an environment where Chinese was not the dominant communicative language, they consistently reported that they had experience of using or switching between their two languages on a regular daily basis. Specifically, they consistently use Chinese to communicate with their family members at home in China, but speak in English in the classroom or workplace. Over half of them reported that they frequently experienced Chinese-English language switching in their daily lives and like to code-switch in conversations with their Chinese-English bilingual friends. Details of the bilingual participants' language use experience and demographic information are presented in the following chapters for each study.

5.5 Standardised Tests

Different materials and visual/auditory stimuli in various tasks were used according to the language comprehension and production paradigms adopted in each study. They are described in subsequent chapters. Standardised tests and questionnaires used in this project are introduced in the following sections. A summary of the standardised tests and questionnaires used in this project is presented in Table 5.3, below.

Table 5.3 Summary of standardised tests and questionnaires used in studies of the project

Study	Tests and Questionnaires	Description
1, 2, 3, 4	LexTALE test	Objective and valid measure of bilinguals' L2 vocabulary knowledge and proficiency
3, 4	Raven's Advanced Progressive Matrices	Standard nonverbal fluid intelligence and cognitive reasoning test
3	Forward and Backward Digit Span Test	Standard working memory and attention test
3	Language History Questionnaire (LHQ)	A valid tool to assess the linguistic background and language proficiency of these bilingual participants
1, 2, 4	Bilingual Switching Questionnaire (BSWQ)	A validated tool to measure bilinguals' habitual code-switching behaviours

1	Language Social Background Questionnaire (LSBQ)	A validated and comprehensive tool to measure multiple aspects of participants' bilingual experience and degree of bilingualism, including proficiency, habitual language use contexts, code-switching patterns.
2	Language Experience and Proficiency Questionnaire (LEAP-Q)	A validated questionnaire to collect information relating to bilingual participants' language proficiency and language learning experience
2, 4	Code-switching and Interactional Context Questionnaire	An innovative questionnaire tool to quantify bilingual participants' habitual code-switching patterns, and habitual interactional contexts

5.5.1 Participants' linguistic ability assessments

The Lexical Test for Advanced Learners of English (LexTALE test)

The Lexical Test for Advanced Learners of English (LexTALE test – Lemhöfer & Broersma, 2012) is a valid and standardised test for assessing medium to highly proficient adult English as a second language learners' vocabulary knowledge and language proficiency. It is in the form of a simple un-speeded visual lexical decision task. Consisting of 60 trials, this task, on average, only takes participants about 5 minutes to complete. Therefore, it is a free, practically feasible and quick test which can be conducted online (https://www.lextale.com/), or it can be easily downloaded in the format of MATLAB or Praat and implemented on a computer to run under any experimental software locally. Testing items and instructions were also available to download for those who intended to do a paper and pencil test. Apart from the standardised and validated English version of LexTALE, there are also German and Dutch versions available.

The English version of LexTALE consists of 60 items, including 40 true English words and 20 non-words/fake English words. Lemhöfer and Broersma (2012) report that the words used in this test are between 4 and 12 letters long (mean: 7.3), and the 40 true words have a mean frequency of occurrences per million of 6.4 according to the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995). The "fake words" they created for this test are nonsense strings of letters which are orthographically legal and pronounceable. None of the "fake words" exist in other relevant languages, like Dutch or German.

Participants taking this test are shown a series of items, which can be either true English words or fake words. They see one item at a time on the screen. They need to indicate whether each item is an existing English word or not by pressing either the "Y" key (for yes) or the "N" key (for no). If they are uncertain or have any doubts over their lexical decision, they are instructed to respond no. As this test is un-speeded, participants' reaction times for each item judgement are not calculated; furthermore, they are told not to use a dictionary during this test.

Participants' final scores on this test are automatically calculated and presented if they take it online. In general, the score includes a participant's percentage of correct responses, corrected for the unequal proportions of words and nonwords in the test by averaging the percentages corrected for these two item types (Lemhöfer & Broersma, 2012). The formula for LexTALE score calculation is:

$$\frac{\left[\left(\frac{number\ of\ words\ correct}{40}\right)+\left(\frac{number\ of\ nonwords\ correct}{20}\right)\right]\times 100}{2}$$

The higher the score an individual gets, the higher proficiency level in English the person has. This test was used for an objective assessment of bilinguals' L2 proficiency to contrast with their self-reported L2 competence in all four studies.

5.5.2 Participants' non-linguistic ability assessments

Raven's Advanced Progressive Matrices

The Raven's advanced progressive matrices Set 1 (RAPM; Raven, Raven, & Court, 1998) was used in studies 3 and 4 to measure bilingual adults' baseline nonverbal cognitive ability, assuming that all of them had comparable levels of fluid intelligence.

This set of tests consists of 12 trials, arranged in order of difficulty. Each trial is a line-drawing picture with a missing part. Below the trial, a multiple choice of eight possible parts is provided from which participants select the most suitable one to complete the picture. Only one of these provided parts fits in the empty space in the picture. Figure 5.1 below shows an example of this test.

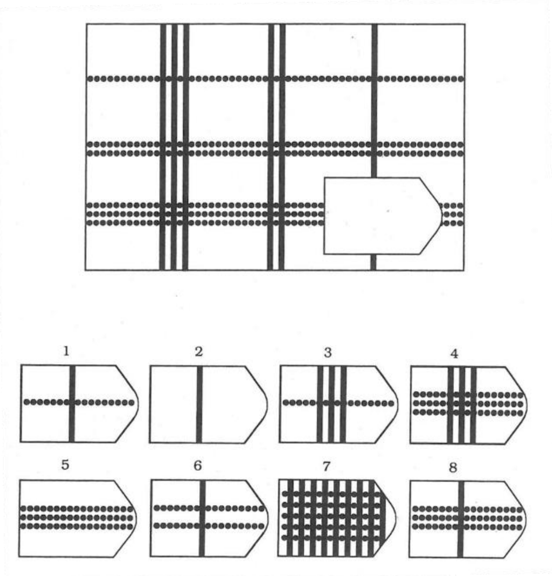

Figure 5.1 An example from the RAPM Set 1 in which participants are required to select one of the eight segments provided below to complete the blank part in the picture above. In this case, no.8 is the correct answer.

Each participant was given 30 seconds to respond to each trial, and the next trial would automatically pop up if the individual failed to give a response within 30 seconds. Missing responses and incorrect responses were all marked as wrong answers in the data analysis. Percentages of the participants' correct responses in this task were calculated as an index of their nonverbal intellectual ability.

Forward and Backward Digit Span Test

The forward and backward digit span test (Hoosain, 1979) was used in the pre-experimental stage in study 3 to ensure that all participants had similar abilities in attention and working memory. In this test, participants listened to two types of digit spans: forward digit span (FDS) and backward digit span (BDS). Both FDS and BDS were pre-recorded in Chinese Mandarin, at the rate of one digit per second. In forward digit span trials, participants were instructed to repeat the digit string they heard as quickly and accurately as possible. As for trials with the backward digit span, participants needed to reverse the order of the digit string they heard and speak it in reverse order immediately as accurately as possible. The length of the digit span for each trial increases during the test, progressing from 2 digits to 9 digits, which makes the test become increasingly difficult. Thirty trials of digit spans were included in this test, with 16 forward and 14 backward digit spans. The list of digit spans used in this test can be found in Appendix III: Digit span lists used in the forward and backward digit span task.

The percentages of participants' correct-response trials in FDS and BDS were calculated respectively, and these were added up to give a score for their baseline ability in working memory and attention. Failures to respod after they listened to the digit span and incorrect responses were always marked as wrong answers, and excluded from test scoring.

5.5.3 Measures of participants' bilingual language experience

Self-reported questionnaires were used as the main instruments to measure participants' linguistic background and bilingual language use experience in their daily lives. The questionnaires used in the various studies are summarised in Table 5.5. above. Based on the characteristics of these Chinese-English bilingual participants, all the questionnaires used in the project were adapted accordingly and translated into Chinese.

Language History Questionnaire (LHQ)

Participants in study 3 first completed an online language history questionnaire (Li, Sepanski & Zhao, 2006) before they started the experimental tasks. This questionnaire, consisting of three parts, collected information related to individuals' language proficiency and usage in different environments.

Some general questions relate to individuals' demographic information, including age, age of L2 acquisition, gender and years in L2 environment residence, are included in the first part of the questionnaire. Participants also need to self-rate their L2 proficiency in reading, writing, speaking and comprehension on 1–7 Likert scales in this part to indicate their linguistic proficiency and language learning background.

The second part mainly focuses on bilingual individuals' language usage and habitual language use environment. One set of questions asks how the participants usually use their languages in different environments (e.g., at home and in the workplace) or with different interlocutors (e.g., parents and colleagues). Participants need to indicate the percentages of Chinese and

English used in each given situation, and these two percentages should add up to 100%. Another set of questions in this part asks participants to estimate how long in general they use each language in doing different activities, for example, how many hours they spend per day watching TV in English/Chinese. The last set of questions is related to participants' bilingual language use habits, such as how frequently they switch between their languages, and which languages they habitually use in different situations and activities. Questions on perceived accent and dialect information of participants are also included in this questionnaire to obtain a more comprehensive understanding of their L2 acquisition and use experience. The last part of this questionnaire is an optional open-ended question, asking participants to provide additional information (if applicable) related to their language learning and use background.

Participants' responses to the LHQ in study 3 allowed the researcher to screen individuals with an inconsistent and heterogeneous language background from the sample. Four participants in study 3 were excluded from subsequent data analysis due to their very limited proficiency in English and nil experience of using two languages in their daily lives. Therefore, finally, 36 participants remained for study 3.

Bilingual Switching Questionnaire (BSWQ)

The adapted and Chinese-translated bilingual switching questionnaire (BSWQ- Rodriguez-Fornells et al., 2012) was used in studies 1, 2 and 4 in this project, to assess bilingual participants' habitual code-switching experience. This questionnaire consists of 12 items, offering a reliable measure of bilinguals' language switching behaviours in four distinct constructs (three items for each construct): L1 switching tendencies, L2 switching tendencies, contextual switch and unintended switch.

In the questionnaire, L1 switching tendencies focus on bilinguals' degree of tendency to switch from L2 to L1, while L2 switching tendencies relate to their tendency to switch from L1 to L2. The two constructs aim to assess bilinguals' language switching behaviours affected by linguistic-related factors, such as their unbalanced competences and semantic differences in two languages (Han, Li & Filippi, 2022). The construct of contextual switch in the BSWQ measures to what extent bilinguals switch their languages affected by sociolinguistic factors, including communicative purpose, situation and interlocutor. Unintended switch, however, measures bilingual speakers' tendency to engage in "unintended" language switching which is not explained by sociolinguistic and linguistic factors. Therefore, it reflects bilinguals' uncontrolled activation of lexical resources from their non-targeted language during communication.

Besides the four constructs of these questions, two additional questions assessing bilinguals' habitual code-switching patterns (i.e., intersentential and intrasentential switching) were added at the end of the questionnaire. Table 5.4 below shows the two additional questions added to the original BSWQ.

Table 5.4 Additional two questionnaire items added to the original BSWQ

	Questions
Item 13	When I switch languages, I switch individual words. (intrasentential switching) Never☐ Very frequently☐ Occasionally☐ Frequently ☐ Always☐
Item 14	When I switch languages, I switch clause and sentences. (intersentential switching) Never☐ Very frequently☐ Occasionally☐ Frequently ☐ Always☐

Participants need to answer on a 5-point Likert scale, from 1 (never) to 5 (always), to indicate to what degree each statement provided in each item is representative of the manner that describes how they talk in Chinese and English. Participants' self-rated points for each item in one construct were added up to give their total scores for this construct. Noticeably, the item stating "*When I switch languages, I do it consciously*", in the unintended switch construct, was conveniently reversed in the data coding and calculated participants' total scores for this construct (Rodriguez-Fornells et al., 2012).

Language Social Background Questionnaire (LSBQ)

Participants of study 1 were instructed to complete the Chinese-translated language social background questionnaire (LSBQ- Anderson et al., 2018) before the end of the whole study. Information relating to participants' language use and degree of bilingualism was collected via this questionnaire.

There are three sections in the LSBQ. Participants' general demographic information, such as age, gender, immigration status and education level, is collected in the first section. Then, the second section focuses on information related to bilingual individuals' language background, measuring their language repertoire, age of L2 acquisition, and where they learned their languages (Anderson et al., 2018). Self-rated proficiency in L2 speaking, comprehension, reading and writing is also assessed in this section, where 0 indicates no ability at all, while 10 indicates native-like proficiency. Besides, participants also need to rate their general frequency of using each language in their daily lives on a scale ranging from 0 ("none") to 5 "all the time"). Questions in the third section aim to assess bilinguals' language use in different communicative contexts and life stages (i.e., infancy, pre-school, primary school and high school stages). Participants' responses to the 5-point Likert-scale questions in this section were summarised to calculate their degree of L2 use in different situations. Details of the questionnaire data processing and analysis are given in the Study 1 chapter.

Language Experience and Proficiency Questionnaire (LEAP-Q)

The Chinese-translated LEAP-Q (Marian et al., 2007) was used cooperatively with the LexTALE test (Lemhöfer & Broersma, 2012) in study 2 as a valid questionnaire instrument for assessing bilingual participants' linguistic profiles. Besides language proficiency self-rating, this questionnaire also measures participants' language dominance and language preferences, by asking participants to indicate the dominance order of their languages and which language they prefer to use when reading a text, respectively.

Participants' L2 exposure assessment is another main focus of the LEAP-Q, in which participants not only have to indicate their prior experience related to L2 exposure, but also provide information regarding their current language exposure status in different settings, including social interaction, communication with friends or in other activities.

Code-switching and Interactional Context Questionnaire

The Chinese version of the code-switching and interactional contexts questionnaires used in studies 2 and 4 was translated from Hartanto and Wang's (2016) original version in English. This questionnaire aims to assess bilinguals' degree of engagement in one specific interactional context and their habitual code-switching behaviours through four indexes, their score for dual-language contexts (DLC), index for single-language contexts (SLC), index for intersentential switching and index for intrasentential switching.

Two 5-point Likert scale questions are included for participants' DLC scores assessment, while four 5-point Likert scale (ranging from 1 "never" to 5 "always") questions are included for computing each of the remaining three indexes. In SLC index assessment, participants are asked to indicate general percentages for each language's use in four different settings (i.e., work, school, home and social activities) in their daily lives. As for assessing bilinguals' DLC scores, it requires participants to indicate to what extent they use two languages within one context. However, in calculating participants' habitual code-switching behaviours, participants need to indicate how frequently they use intersentential or intrasentential switching in the four aforementioned settings. The computation method for the value of each index follows the equations provided by Hartanto and Yang (2016), which can be found in Appendix II: Computation of bilingual participants' code-switching indexes and single/dual-language contexts scores based on the code-switching and interactional context questionnaire (Hartanto & Yang, 2016)

A higher DLC score reflects a greater degree of dual-language context engagement and higher frequency of co-using two languages within the same situation in communication. In contrast, a higher SLC index reflects a participant's more intensive practice of using two languages separately. In the same vein, participants who habitually switch between languages within one single utterance will have a higher intrasentential code-switching index; while those who frequently practise switching alternately between languages in communication will have a higher intersentential switching index.

Language entropy

It is found that individuals' information related to language use and communicative contexts exposure is frequently collected through Likert scales in self-reported questionnaires. These scores collected on Likert scales can subsequently be converted into proportions for convenient data analysis; therefore, this project also adopted a recently proposed innovative measure, "language entropy", to quantify bilinguals' degree of language use diversity in one interactional context (Gullifer & Titone, 2020).

Apart from the aforementioned questionnaires used in study 2, participants' language entropy was also computed (Gullifer & Titone, 2018, 2020) in four different communicative contexts: home, workplace, school and social activities. For each language use context, Shannon entropy (H) was calculated as language entropy in this situation. The computation was done in the language Entropy R package developed by Gullifer and Titone (2018), following the equation provided in their paper.

Higher values of entropy indicate more balanced and intensive involvement of two languages in use. As participants in this study are bilinguals with regular use of Chinese and English, their values for language entropy in each context range continuously from 0 to 1. An entropy value of 0 for a communicative context indicates that bilinguals only use one language in such a context, and their language use during communication in this context is highly predictable. However, the value for language entropy will reach the maximum (i.e., 1) if two languages are intensively engaged in a communicative context, that is, two languages are balanced and used perfectly in this context.

5.6 Apparatus and General Procedure

Except for study 3, which was conducted in 2019, before the outbreak of the Covid-19 pandemic, the three other studies were conducted during the pandemic period remotely using experimental online platforms, LabVanced (Goeke et al., 2017) and Pavlovia (https://pavlovia.org/). Tasks used for online experiments were created on the researcher's local computer using PsychoPy (Peirce, Gray, Simpson, MacAskill, Höchenberger, Sogo, Kastman & Lindeløv, 2019).

Similar to the face-to-face study, all participants gave informed consent before joining the online studies. Then, participants were instructed take part in an online study remotely in their own quiet rooms and try to minimise noise distractions during the study procedure.

According to a recent study comparing lab-based and online tasks' RT (Bridges et al., 2020), the online platform PsychoPy (version 2020.1) achieved an RT standard deviation under 3.5 ms on every browser/OS combo.

Furthermore, PsychoPy in Python achieved sub-millisecond precision almost across the board. Specifically, PsychoPy for the Windows 10 system runs on Chrome and Firefox and can achieve mean timing precision of 1.36 ms and 1.84 ms, respectively. As for MacOS, the mean timing precision for PsychoPy running on Chrome and Firefox is 4.84 ms and 2.65 ms, respectively. Therefore, to control for the timing variance caused by different computer OSs, participants were required to use either Chrome or Firefox browsers only for online studies (the Firefox browser is highly recommended if both browsers are available).

As for study 3, the visual and audio stimuli used in each task were presented using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Auditory stimuli used in this study were pre-recorded using Microsoft recorder and stored in mp3 format. These auditory stimuli were presented to participants through headphones. All participants were instructed to complete all the tasks in this study on the same Windows 10 laptop with a 15” monitor in a soundproof room in the Institute of Education. Details of the visual and auditory stimuli used in each study are introduced in the following study chapters.

Before each study started, the researcher introduced the participants to the procedure and instructions for the study in Chinese to make sure they fully understood how to complete each task in the study. After they completed the whole study, the main goals of the study were explained to them. Participants were also asked not to share information related to the study goals with anyone they knew who might be participating in this study. All participants took part voluntarily in this research project without any remuneration.

5.7 Summary of this chapter

In this chapter, general demographic information and characteristics of the bilingual participants involved in this project, study apparatus and general procedure have been presented. Standardised tests for cognitive abilities and linguistic background information have also been described. The four empirical studies included in this project will be introduced and discussed in more detail in the following chapters.

Chapter 6 Investigating effects of bilingualism on cognitive control in bilingual language production

6.1 General Introduction

Bilingual speakers commonly select the appropriate language to use in different contexts, such as using English at work and Chinese at home, or switching between two languages in the same conversation. For a successful code-switching production, bilinguals need to access the appropriate language and resolve the competition from the unwanted (Bonfieni et al., 2019; Green, 1998; Green & Abutalebi, 2013), a process that requires additional demand on general-domain cognitive control mechanisms (e.g., Abutalebi & Green, 2007, 2008, 2016; Calabria et al., 2018).

As an essential feature of bilingual language experience, code-switching is suggested to be an important factor in modulating bilinguals' cognitive control performance. A wealth of previous studies have shown the positive effects of high code-switching frequency on cognitive control performance enhancement (e.g., Barbu et al., 2018; de Bruin et al., 2015; Hartanto & Yang, 2016; Jylkkä et al., 2017; Peeters & Dijkstra, 2018; Yang et al., 2016). In the recent decades, individual differences in bilingual language use experience have been stressed to account for in discussing its effects on bilinguals' cognitive control development (e.g., DeLuca et al., 2019; Ooi, Goh, Sorace & Bak, 2018; Surrain & Luk, 2019). Furthermore, the two above-discussed theoretical frameworks in bilingualism research, Adaptive control hypothesis (Green & Abutalebi, 2013) and Control Process Model (Green & Li, 2014), also discussed the interactive relationship between the deployments of cognitive control and bilingual language use experience. They suggested that bilinguals' cognitive control dynamically adapts to differences in interactional contexts they habitually engaged in and the patterns of code-switching they habitually produced in natural communications.

Although there have been numerous existing studies investigated the effects of bilingual language use experience on bilinguals' cognitive control modulations, no consistent evidence on the modulating effects of bilingual language use experience on cognitive control has been reached, and which specific aspects in cognitive control are significantly modulated by bilinguals' constant experience of bilingualism still remain unclear.

One reason for these inconsistent findings might be the lack of standard measures of bilinguals' habitual code-switching experience. Furthermore, information about sociolinguistic context, such as how languages are switched and used on a daily basis or in various situations, is seldomly reported. In addition, lab-based experimental paradigms measuring the relationship between code-switching and cognitive control may have a reduced ecological validity (Green & Abutalebi, 2013; Green & Li, 2014; Hofweber et al., 2020; Kheder & Kaan, 2021). That is, relatively fewer studies have been conducted to explore cognitive control in bilinguals' language production in naturalistic setting (i.e., voluntary switching) or spontaneous language production with addressing its interconnections with their language use habits. Therefore, when exploring the interconnections of bilingual language use experience and cognitive control, it is crucial to have a more ecological measurement, such as computing language entropy (Gullifer et al., 2021; Gullifer & Titone, 2020), that can assess not only the quantity of bilingual language use in communication but also can capture individual’s traits of language switching in naturalistic settings.

In this vein, this chapter, containing two empirical studies, aims to investigate bilinguals’ cognitive control mechanism underlying their language switching production in cued and un-cued conditions. The interactive relationships between bilinguals’ language use experience and their cognitive control in cued- and un-cued language switching production are also explored. Both of the two studies tested Chinese-English bilingual adults, residing in English-speaking countries, and stressed the roles of their habitual bilingual language use practices in cognitive control (i.e., inhibitory control and cognitive shifting) modulations.

In the study 1, participants’ language switching performance was measured in a cued-switching paradigm via the Chinese-English bilingual picture-naming task, while the study 2 focused on bilinguals’ un-cued (voluntary) language switching performance in a naturalistic communicative setting. The two studies also adopted a series of comprehensive approaches, including both the self-reported questionnaires and language entropy computations, to measure and quantify participants' habitual language use experience for subsequent data analyses.

6.2 Empirical Study 1: Effects of habitual code-switching in bilingual language production on cognitive control

6.2.1 Study introduction

This current study aims to understand the effects of habitual code-switching experience on Chinese-English bilingual speakers' domain-general cognitive shifting and inhibition performance. Three main research questions will be addressed:

1) What are the effects of bilinguals' code-switching habits and language proficiency on cognitive shifting and response inhibition?

2) Does increasing frequency of code-switching lead to better performance in a cued-language switching task and nonverbal cognitive control tasks?

3) Is the bilinguals' performance in verbal and nonverbal switching tasks intercorrelated?

It is predicted that:

1) Higher L2 proficiency and code-switching frequency will facilitate bilingual participants' performance in non-verbal cognitive shifting and response inhibition tasks.

2) Bilinguals with intensive experience of using languages in a single-language context will perform less proficiently in both verbal and nonverbal switching tasks.
3) Bilinguals' language switching performance correlates with nonverbal task-switching performance.

6.2.2 Methods

Only individuals residing in English-speaking countries by the time of the study with daily use of Chinese and English are invited to the study. Information sheet and consent form were provided to individuals who expressed interest to this study to decide participate or not. No data was collected until participants signed the informed consent form. Before the study started, the researcher introduced participants the procedure of this study and instructions of each task in Chinese to make sure the participants fully understand how to complete the study. After the participants completed the whole study, they would receive debriefing explaining the goals of this study and the aims of each task they have just experienced. Participants were also asked not to share the information related to the study goals to anyone they knew who might be participating in this study.

Participants

Thirty-one (18 females; mean age: 28 years old, SD = 4.53, range 22–42 years old) healthy right-handed Mandarin-English bilinguals living in English-speaking countries (i.e., UK, US, Canada, Australia and Ireland) took part in this study. All participants are Mandarin Chinese L1 speakers and have resided in an English-speaking country for 3.81 years on average at the time of the experiment. All the participants have learned English as a second language (L2) in mainstream school settings in China, on average after the age of 9 (SD = 4.81).

Participants' habitual code-switching experience were measured through the Bilingual Switching Questionnaire (BSQW, Rodriguez-Fornells et al., 2012) and the Language Social Background Questionnaire (LSBQ, Anderson et al., 2018). A LexTALE test (Lemhöfer & Broersma, 2012) was used to measure participants' English proficiency. Table 6.1 below shows the participants' demographic information (age, L2 AoA, L2 proficiency, L2 exposure duration) and habitual code-switching information.

Table 6.1 Demographic and linguistic information of the Chinese-English bilingual participants

	Mean	SD
Age	27.68	4.53
L2 AoA	9.81	4.81
English-speaking country resident duration(years)	3.81	3.33
LexTALE score (%)	64.46	11.81
Self-reported L2 reading proficiency (none:1- native-like:10)	7.39	1.48

Self-reported L2 speaking proficiency (none:1- native-like:10)	6.23	1.50
Self-reported L2 understanding proficiency (none:1- native-like:10)	7.16	1.34
Self-reported L2 writing proficiency (none:1- native-like:10)	6.03	1.58
L1 use at home (Maximum:35)	30.94	2.85
L1 use in non-home situations (Maximum:15)	7.23	2.78
L1 use in daily activities (Maximum:60)	33.16	6.60
L2 use at home (Maximum:35)	10.77	2.65
L2 use in non-home situations (Maximum:15)	10.78	2.78
L2 use in daily activities (Maximum:60)	38.84	6.60
Semantic Verbal Fluency Information		
Chinese verbal fluency	19.03	6.78
English verbal fluency	12.87	4.36
Baseline switch costs	12.00	6.07
Bilingual Switching Questionnaire Information		
L1 switching tendencies (never:1 - always:5; Maximum:15)	9.29	1.79
L2 switching tendencies (never:1 - always:5; Maximum:15)	6.84	2.03
Contextual switch (never:1 - always:5; Maximum:15)	8.68	2.61
Unintended switch (never:1 - always:5; Maximum:15)	8.19	2.01
Intrasentential switching (never:1 - always:5; Maximum:5)	3.26	1.03
Intersentential switching (never:1 - always:5; Maximum:5)	2.61	1.05

Materials, design and procedure

Due to the COVID-19 pandemic and subsequent national lockdown and university policies in the UK in 2020-21, face-to-face experiments could not be conducted. Therefore, tasks in this study were created using PsychoPy (Pierce et al., 2019) and hosted by the online platform Pavlovia (http://pavlovia.org/) and LabVanced (Finger et al., 2017).

At the beginning of the session, a semantic verbal fluency test adapted from Woumans et al. (2019) was conducted. This test was used as an objective measure of proficiency in both languages and as a baseline language switching proficiency. In this test, participants were given 60 seconds to name words belonging to a specific semantic category (i.e., animals, vegetables and jobs). The test included English/Chinese single-language and mixed-language conditions. In the single-language condition, participants were asked to produce words belonging to the category in one specific language (Chinese or English), while in the mixed-language condition, participants were required to continuously switch between their two languages when producing words within a given category. Categories and language orders in which the categories were examined were counterbalanced across participants. The mixed-language condition was completed last. The calculation of participants' baseline switch costs was conducted following Woumans et al. (2019) instructions, i.e., calculating differences in the L1 words produced in the L1 single-language condition and the number of L1 words produced in the mixed-language condition.

Before experimental tasks, all participants completed a Chinese-English Bilingual Switching Questionnaire (BSWQ) adapted from Rodriguez-Fornells et al. (2012) to assess their habitual code-switching experience. More description on BSWQ can be found in Chapter 5.

At the end of the experimental task session, all participants completed the Chinese-translated Language and Social Background Questionnaire (LSBQ, Anderson et al., 2018) to collect information about their bilingual language use experience. Variables related to bilingual language use experience were extracted from participants' responses in the questionnaires, which were included as predictors to correlate with participants' performance in the three tasks in regression models. Table 6.2 below showed the variables included in regression models.

Table 6.2 Summary of variables related to bilingual language experience and task performance in further investigations

Bilingual language experience-related variables	Variables in tasks
Bilingual language experience	**Picture-naming task**
Age	
L2 AoA	
L2 proficiency	RT switch costs in English
L2 exposure (yrs)	RT switch costs in Chinese
L2 use at home	RT mixing costs in English
L2 in settings outside home	RT mixing costs in Chinese
L2 use in daily activities	
Bilingual switching experience	**Colour-shape switching task**
L1 switch tendency	RT switch costs
L2 switch tendency	RT mixing costs
Contextual switch frequency	
Unintended switch frequency	**Whack the mole task**
Bilingual intersentential switching frequency	RT in go trials
Bilingual intrasentential switching frequency	Percentages of false alarm
L1 verbal fluency	
Baseline switch costs	
L2 verbal fluency	

Participants’ responses to the Likert-scale questions related to language use in different occasions, social activities and to different interlocutors in the questionnaire were summarised into three main dimensions based on this study purposes, calculating their degree of L2 use at home, in non-home situations and in daily activities. Adapted from Anderson et al. (2018) study, this study aggregated questions in LSBQ into three main factors, L2 use at home/non-home and social contexts. Besides the factors related to language social and non-home use, this study further aggregated questions and included a factor measuring how participants use L2 at home-related settings.

As majority of participants involved in this study are university students studying in English-speaking countries, their language use settings are relatively homogeneous, specifically, mainly at campus/workplace, home-related settings and other occasions beyond these two. Therefore, classifying questions into the three factors matches participants’ bilingual language use ecology.

In addition, to distinguish the degree that participants use their languages separately in different contexts (e.g., use English at university but Chinese at home), this study summarised the questions asking how participants use English with their family members and in home settings as index of “L2 use at home setting”, while these questions were aggregated together as index of bilinguals’non-L1 proficiency in Anderson et al.’s study (2018). It is noticeable that the questions aggregated into language home use are directly opposite with language non-home use. That is, any questions asked participants to self-rate how they use two languages at campus and in workplaces are marked as indexing their language use in non-home settings. As for questions measuring participants' language social use, this study generally adopted Anderson et al.'s (2018) clustering, but excluded any questions which have been marked as measuring language home and non-home uses. In sum, questions for language social use in this study are those asking how bilinguals use their languages in any other settings beyond home and work/study and in any interactions with people beyond the above-mentioned two settings. Table 6.3 below is the summary of questions in LSBQ measuring the extent of L2 uses in the three settings.

Table 6.3 A summary of the L2 use settings investigated in the LSBQ

	Settings/ Activities for L2 Using
L2 in home settings	1. at home 2. communicate with family members/ partners/relatives/roommates
L2 in settings outside home	1. at work 2. at school 3. communicate with classmates/colleagues
L2 in daily activities	1. in social activities 2. using social media 3. doing extracurricular activities 4. shopping 5. writing shopping list 6. having healthcare service 7. reading 8. emailing 9. message texting 10. watching TV/films 11. surfing internet

Participants' language use in their different life stages were not summarised into the three dimensions of language uses because participants in this study moved to English-speaking countries for working or higher education after their high school stages in China, and they consistently reported that majority of time in their different life stages (i.e., from infancy to high school) are exposed to Chinese Mandarin monolingual environment.

Picture-naming task

The picture-naming task in the current study measured the bilingual participants' verbal response accuracy and response latency to look at both switch and mixing costs for their two languages and how these variables were affected by their language proficiency and habitual language use experience.

In this task, participants were required to name black-and-white line-drawn objects in a specific language (i.e., Chinese or English) based on specific cues as quickly and accurately as possible. Their verbal responses were automatically recorded and their response times (RTs) analysed using Praat software (Boersma & Weenink, 2018). Line-drawn objects were selected and adapted from Snodgrass and Vanderwart (1980) and pictures in the Philadelphia Naming Test (Roach et al., 1996). Double cues (Logan & Bundesen, 2003; Zantout, 2019) were used to instruct participants to name objects in Chinese or English. Participants needed to name an object in English if it was presented surrounded by a blue background together with the

British national flag; otherwise, they needed to name the object in Chinese when they saw it presented in a red background with China's national flag. Forty-one different pictures were used in this task and repeated within and between blocks.

This task consisted of one practice session with 10 trials for both Chinese and English naming, two single-language blocks (restricted to the use of the same language) and three mixed-language blocks (choose a specific language according to the cues). Each mixed language block included 57 experimental trials with 28 switching trials (language switch from the previous trial) and 28 repeated trials (same language as in the previous trial) and one practice trial at the beginning. Half of the switch trials were English-to-Chinese in each mixed-language block; 84 trials were evenly allocated to two single-language blocks, with 42 in Chinese and 42 in English. Each picture in this task was presented on the screen for 2500ms followed by a 500ms white blank. The whole task lasted for 30 minutes.

In single language blocks, pictures were randomised across participants to avoid consecutive repetition. In mixed language blocks, the sequence of switch and repeated trials was pseudo-randomized by participants, so that the number of trials for each participant and type was the same. Besides, to avoid the possible effect of the sequential order of the repeated and switch trials, no more than four consecutive trials of the same type (repeated or switch) appeared sequentially. In the mixed language blocks, in order to make sure that participants are not able to predict whether the first trial is a switch or repeated trial, a dummy trial at the beginning was designed. Figure.1a below illustrates the task structure and the trial presentation in each session.

Participants' verbal response accuracy was manually analysed. Reponses were not coded as errors if they used different terms due to their language habits to indicate the same object, for example, “jiandao” and “jianzi” both mean “scissors”. In line with the data pre-processing method in Bonfieni et al.'s (2019) study, responses were coded as errors when participants named an object in the wrong language or did not answer. In this situation, the trial was marked as an error and excluded from analysis of RTs; the following trial was also deleted from the analysis. If participants hesitated, paused or made self-corrections to their answers, the trial was also marked as an error and excluded from further analysis, but its following trial was retained.[1]

Practice trials and RT in error trials were not included in the data analysis. The participants' reaction times, also reported as voice onset time (VOT), were analysed using Praat phonetic software (Boersma & Weenink, 2018;

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[1] If the former trial is named in a wrong language, the switching trial followed should also be excluded because the RTs for the latter trial is not primed by the targeted language. For example, trial 7 is designed to name in English and the trial followed (trial 8) is for Chinese naming. So, trial 8 RT is intended to reflect participants' naming speed in Chinese after English naming (i.e., RT for English to Chinese switching). It will be unavailable to calculate RT for English to Chinese switching once the trial 7 is wrongly named in Chinese. Similar situation also happens in RTs for repeated-language trials in the mixed language block. For example, both trial 7 and 8 were designed to be named in Chinese, however, trial 7 was wrongly named in English; therefore, trial 8 RT is not the RT for Chinese repeated trial, instead, it is the RT for Chinese naming primed by English naming.
Different from the above-mentioned situations, if a participant finally correctly named the trial in the required language, RT for the following trial was not affected, and it is possible to calculate the following trial's RTs as it was correctly primed by the required language. For example, even participants had some hesitations or self-corrections in naming the trial 7 in English, trial 8 RT was correctly primed by English naming and was able to calculated it as RT for Chinese naming switched from English. Similar situation also applies to RTs in repeated-language trials. Considering to minimise the calculation deviation, although the participants finally named the trial (e.g., the trial 7 in above example) correctly, RT for this trial is excluded.

Filippi et al., 2014). An internal *textgrid (silences)* script in the software allows slicing each audio byte into “sound” and “silence” segments. For a segment to be considered “sound”, it had to have a minimum pitch of 100Hz, to have exceeded a -25dB threshold and to have lasted for at least 0.1s. “Silence” segments should last for at least 0.2 s. The starting point of the first “sound” segment was regarded as the voice onset time in the picture-naming task. The response time in each trial was also manually checked to discard trials with unclear voice recording and to revise the response times in some trials due to loud noise interference during participants’ utterances.

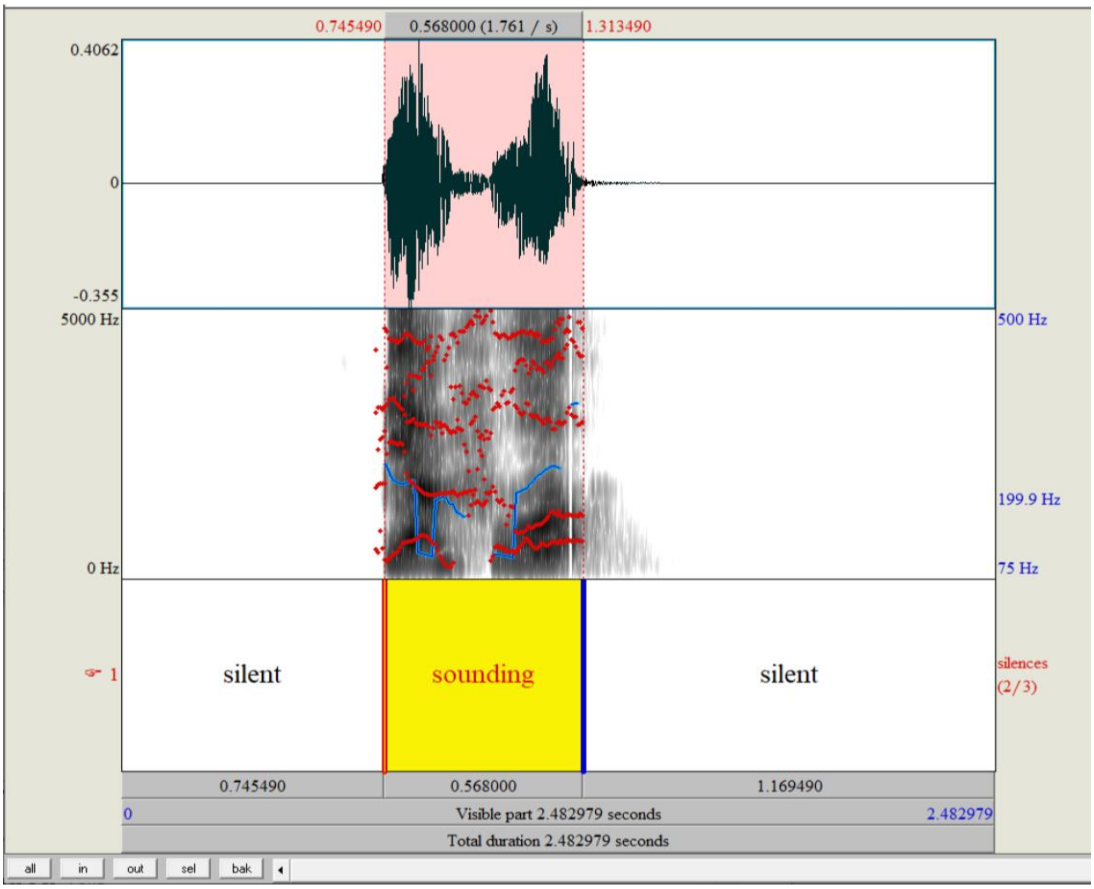

Figure 6.1 An example of voice onset time analysis. The yellow part indicates the sound segment and the red line on the left side of the sound segment represents the voice onset time (568 ms in this example).

Nonverbal colour-shape switching task

The colour-shape switching task used in the present study was adapted from Prior and MacWhinney (2010) to assess the bilinguals' shifting abilities. In this task, participants were instructed to make colour or shape judgements on visually presented stimuli based on cues by pressing specific buttons on the keyboard. The cue for shape judgements was a black heart icon, while a rainbow icon indicated colour judgements. Visual stimuli were circles and triangles, either blue or yellow. Each stimulus was presented after the cue appeared for 250ms. Then, the cue remained on the screen and the stimulus was presented in the centre of the screen for 4,000ms. Participants needed to use both hands to make key-pressing responses during this task. Specifically, two keyboard buttons on the left-hand side, "x" and "c", and two right-hand side buttons, "n" and "m", were corresponding keys for colour and shape judgements. Emails with clear instructions of this task were sent to participants before they started the study, asking them to prepare stickers/paper in corresponding colours (i.e., yellow and blue) and shapes (i.e., circle and triangle) to label on the four targeted buttons (i.e., x, c, n, m) on their keyboards (see Figure. 1b below). The labelled buttons were counterbalanced across participants.

This task was in a sandwich-design (Prior & Gollan, 2011). After 16 practice trials, there were two single-task blocks (colour and shape, order counterbalanced across participants) with 34 experimental trials and 2 initial practice trials included. Then, 16 mixed-task practice trials were followed by three mixed-task blocks. Each mixed-task block consisted of 50 trials in total, with 46 experimental trials and 4 practice trials evenly allocated at the beginning and end of the block. The ratio of switching and non-switching trials in each mixed-task block was 50:50. After the mixed-task blocks, participants performed two single-task blocks again, which were presented in the opposite order from that used in the first session. Participants' reaction time and response accuracy in each trial were automatically recorded.

Go/No-go task: Whack-the-mole task

A whack-the-mole task was used to measure participants' inhibitory control ability (Filippi et al., 2021). Different kinds of moles in this task were the "go" stimuli, requiring participants to give a response (a whack!) by pressing the space bar on the keyboard. Aubergines were "no-go" stimuli, and participants were required to withhold their actions when one of them appeared on the computer screen. Each trial started with picture of a hole in the meadow for 500ms, then a mole or an aubergine appeared for 1800ms (Figure.1c). Participants were instructed to respond as quickly and accurately as possible.

The task included 1 practice block, consisting of 3 no-go and 7 go-signal trials, and 4 formal blocks, including 55 no-go and 185 go-signal trials in total. The no-go withhold percentage is 23%. Participants' reaction time and response accuracy for go trials were recorded; furthermore, unsuccessful response withholding in no-go trials was also calculated as percentages of false alarm for data analysis.

All participants provided informed consent before taking part in this online study. The study lasted about 90 minutes. Participants were instructed to join this study remotely in their quiet rooms and try to minimise noise distractions around them during the study procedure. Prior to any online tasks, participants were given enough time to test their network and set up the experiment platform. Technical problems or issues related to online task loading were detected and resolved by participants with supports from the research at this stage. Participants who still failed to get access to online experiment platform or tasks were excluded in this study. After completing online BSWQ and L2 proficiency test, participants were invited to a one-to-one online meeting with the researcher in which the verbal fluency test was administered. Afterwards, participants were allocated links for the rest three tasks, picture-naming task, Go/No-go task and the colour-shape switching task. All participants were instructed to complete the picture-naming task first, and the order of the two nonverbal cognitive tasks were counterbalanced across individuals. The LSBQ was required to complete online at the end of the experiment session.

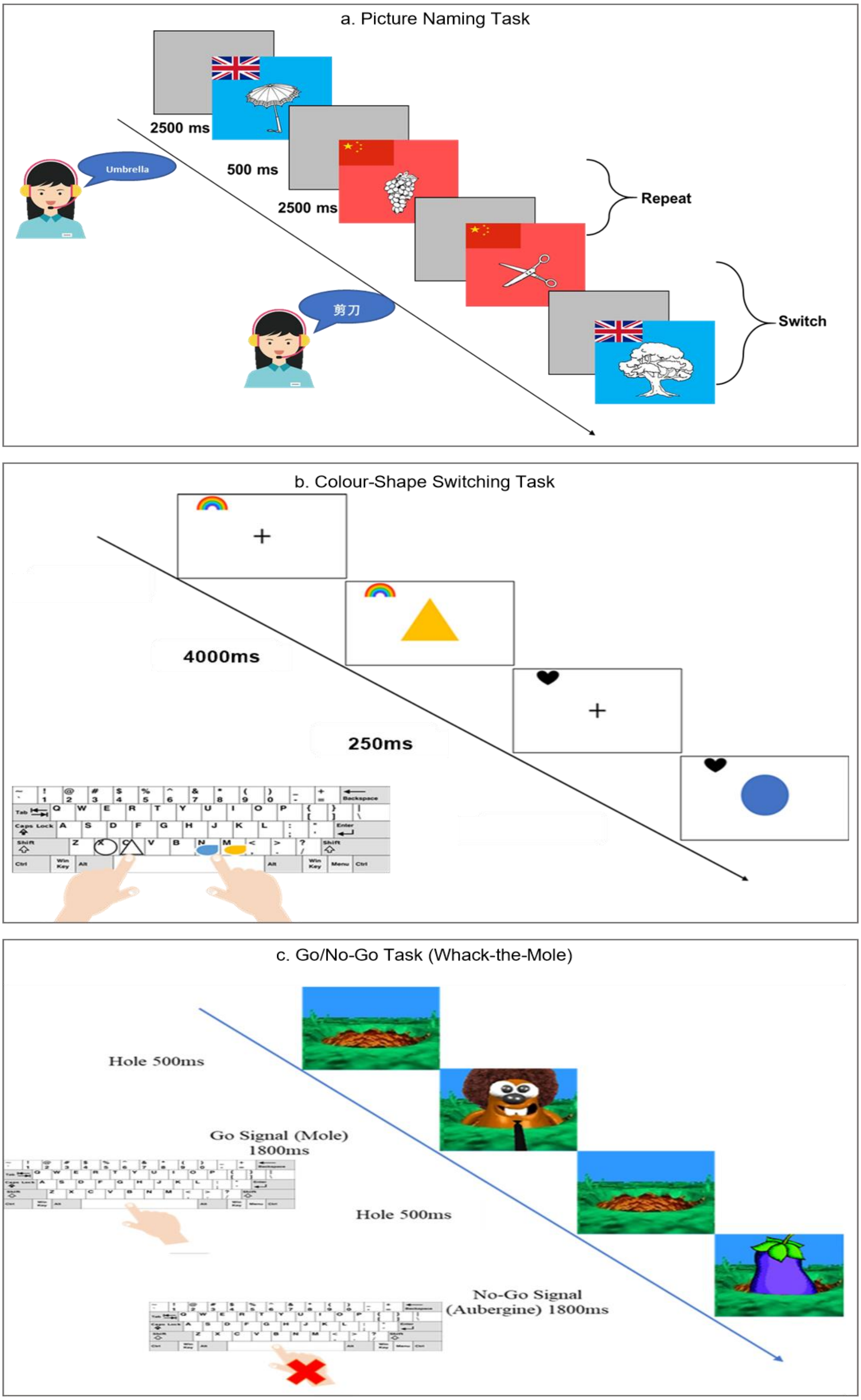

Figure 6.2 Illustration of the picture naming task and two nonverbal cognitive tasks in this study.

Statistics

Participants' reaction time (RTs) and response accuracy in the nonverbal cognitive control tasks and picture-naming task were collected. Only RTs for correct responded trials in these tasks were included into analyses. Both the parametric repeated measures ANOVAs and its corresponding nonparametric method, Friedmann tests, were conducted to explore and compare participants' RTs and response accuracy in each task.

The study applied both multiple linear regression and Bayesian regression analyses to investigate the associations between participants' performance in different tasks (i.e., RTs switch/ mixing costs in verbal and nonverbal switching tasks, RTs and response accuracy in the go/No-go task) and their bilingual language experience. Specifically, variables related to participants' bilingual language experience included in regression analyses as independent variables consisted: L2 proficiency (the LexTALE score), L2 exposure (yrs), L2 use in daily activities, L2 use in non-home situations, L2 use at home, L1 switch tendency, L2 switch tendency, frequency of contextual switches, frequency of unintentional switches, frequencies of intrasentential switching and intersentential switching. Participants' L1 and L2 verbal fluency as well as their baseline switch costs calculated in the semantic verbal fluency task were also included in the regression analyses. The correlations between variables related to bilinguals' language experience were also analysed and were presented in the Table 6.4 below.

Table 6.4 Correlations between variables related to bilingual language use experience

		Pearson's r	***p* - value**
L2outsideHome	L2dailyActivity	.77	<.001
	L2AoA	-.41	0.02
L2inHome	L2dailyActivity	.57	<.001
	L2AoA	-.42	.002
L2 proficiency	L2dailyActivity	.44	.014
	L2exposure(yrs)	.46	.01
L2dailyActivity	L2AoA	-.36	.049
	L2 switch tendency	.38	.036
L2 verbal fluency	L2exposure(yrs)	.45	.001
L1 verbal fluency	Baseline switch costs	.94	<.001
L2 exposure (yrs)	L1 switch tendency	-.51	.004

The analyses revealed that, firstly, L2AoA is an important factor in characterising bilinguals, and it could lead to significant consequences on bilinguals' language use and switching behaviours. Specifically, participants L2AoA negatively correlated with their L2 use frequency in different situations and daily activities. Bilinguals with earlier L2 AoA are found to be more prone to use L2 more intensively in their daily lives (including at home, outside home and dealing with daily activities) in general. Besides, bilinguals' intensive experience of using L2 to deal with daily activities positively correlated with their L2 proficiency and L2 use frequency in different situations (i.e., home vs. outside home). It is reasonable as bilinguals with high proficiency in L2 are able to use more L2 in daily lives; and the more intensive use of L2 could also exercise their L2 proficiency in return. Also, bilinguals with intensive use of L2 in daily activities would be more prone to switch from L1 to L2 (higher L2 switch tendency) in their bilingual communications. This finding further provided evidence on the correlation between high frequency of L2 uses and enhanced proficiency in L2 as well as L2 switching.

The mutually positive correlation between the three variable "L2inHome", "L2outsideHome" and "L2daily Activity" revealed the continuum of bilingualism and the ambiguity of boundaries across different language situations. Multiple factors (both sociolinguistic and linguistic-related) associated with bilinguals' language switching and use behaviours need to be characterised in describing their degree of bilingualism.

In addition, the correlation analyses revealed the associations between L2 exposure and bilinguals' language proficiency. The longer time bilinguals immersed in the L2 environment was found to enhance their L2 verbal fluency and lead to reduced L1 switch tendency in their bilingual communications. such results addressed the effects of language exposure on bilingual language experience and language proficiency modulation. Given the small percentages of error rates and participants all performed high accurately in language and task switching tasks, their response accuracy in the two tasks were not included in further analyses (Bonfieni et al., 2019).

Outliers were detected before data analysis. Participants' responses in the L2 environment exposure (yrs) were not normally distributed, and there was one extreme data (value:17) found. Regression analyses with and without this value were conducted, and removing the extreme value in regression models did not significantly affect the final results. In stepwise regression modelling, after each step in which a variable was added, all candidate variables in the model are checked to see if their significance has been reduced below the specified tolerance level, and R^2 was reported in model selection. If a nonsignificant variable is found, it is removed from the model. Therefore, only the most significant variable is finally retained to the model, showing as the best predictor to the dependent variable. The following sections will present the results of the repeated measures ANOVAs and regression analyses sequentially.

6.2.3 Results

Performance in the picture-naming task

Reaction time

A 2×3 repeated-measures ANOVA was used to analyse the main effects of language (English, Chinese) and trial type (Single, Repeated, Switch) on participants' RTs. Table 6.5. below shows the mean reaction time (RT) and mean response accuracy for naming pictures in Chinese and English.

Table 6.5 Mean reaction time (RTs, milliseconds), correct response (ACC, %) for switch and non-switch trials by language. Costs for language switching are shown in both RT and ACC. Standard deviations are shown between parentheses.

	English		Chinese	
	RT (ms)	ACC (%)	RT (ms)	ACC (%)
Single	1158.81 (143.14)	86.33 (11.65)	1123.88 (156.25)	91.01 (10.11)
Repeated	1043.88 (130.12)	91.40 (10.30)	1094.51 (153.71)	89.86 (9.95)
Switch	1107.50 (28.04)	87.02 (11.73)	1180.66 (153.07)	86.79 (11.01)
Switch costs	63.63 (72.10)	4.38 (5.43)	86.14 (74.49)	3.07 (7.04)
Mixing costs	-114.93 (80.26)	-5.07 (8.99)	-29.36 (97.11)	1.15 (9.34)

The results showed a significant main effect for trial type on participants' language-switching performance, F (2, 60) = 23.55, p <.001, η_p^2 = .44. Specifically, RTs for switch trials were significantly longer than for repeated trials, while RTs for repeated and single-language trials were comparable. Moreover, participants were 30 ms faster in naming pictures in English than in Chinese (L1), F (1, 30) =5.03, p =.03, η_p^2 =.14, showing the effect of language on participants' RTs.

Analysis also revealed a significant language × trial type interaction in affecting participants' cued-language switching performance, F (2, 60) = 19.92, p < .001, η_p^2 = .40. RT asymmetry between switching to English and Chinese, p = .001, was found. Participants' RT switching costs to Chinese were about 73 ms greater than to English. Although participants' RT for Chinese and English single-language trials did not differ significantly, they responded faster in English repeated trials as compared to Chinese ones in the mixed language blocks, $p = .03$. This finding reflected the reversed language dominance effect in bilinguals' cued-language switching productions (e.g., Christoffels et al., 2007, 2016; Declerck et al., 2020; Gollan & Ferreira, 2009; Zhang et al., 2021). That is, bilingual speakers in the mixed language conditions would apply sustained and global inhibition on the dominant language to enable the efficient language production across two languages; and this process could finally result in facilitations on the retrieval time for the less dominant language than the dominant language.

Participants' RTs for different trials within each language were also compared. Participants' RTs for non-switch trials did not differ across Chinese repeated and single-language trials ($p = 1.00$). In contrast, participants responded fastest for English repeated trials ($p < .001$) in the mixed language blocks; however, their RTs for English switch and single-language trials were comparable ($p = .08$). Participants' improved RTs for English repeated trials in the mixed language blocks might be caused by the carry-over inhibition on L1 (Jylkkä et al., 2018). It is possible that the inhibition on L1 carries over to the following L2 repeated trials in the mixed language blocks, facilitating participants' L2 productions. Besides, the unpredictable trials for language switching and stay in the mixed language blocks increased the attentional demands, requiring participants to keep prepared all the time for accurate responses. Therefore, it is potential to increase participants' threshold of concentrations and efficiency for naming the pictures in accurate language in the mixed language blocks as compared to the single-language blocks. But, as this study was conducted online with small sample size, both the effects of carry-over reactive inhibition and mixed language condition on participants' L2 production need further investigations.

Participants' switch and mixing costs in the picture-naming task were analysed. Switch costs refer to differences in response time or accuracy between switching and repeated trials in the mixed language blocks, representing transit control processes; meanwhile, mixing costs represent the sustained and global control of interference, which compares differences between responses in repeated trials among the mixed language blocks and single-language trials (Barbu et al., 2018; Declerck & Philipp, 2015; Ma et al., 2016).

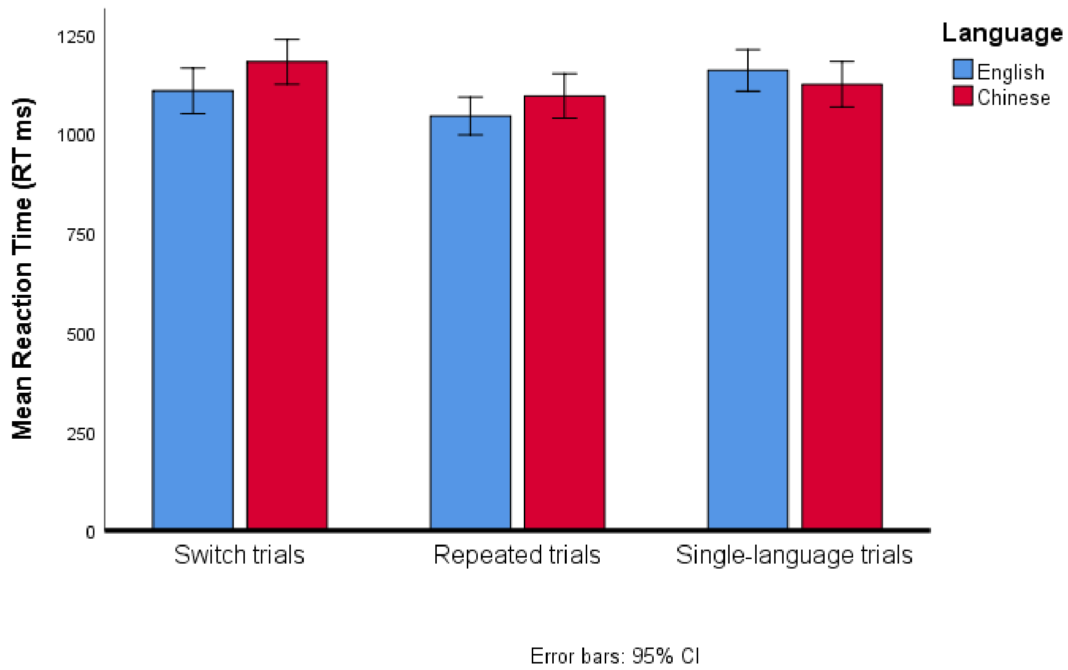

Figure 6.3 Mean RT (ms) for different trials in English and Chinese

Contrary to expectations, an asymmetrical pattern of RT switch costs was not found in this task, F (1, 30) = 1.60, p =.22, η_p^2 = .05. One possible reason for this finding could be that the less dominant language (L2) might be more easily and strongly primed by the language switching cues (Heikoop et al., 2016). However, as this study was based on limited sample size, the cue-priming effect on less dominant language on bilingual language switching still remained unclear, and it is a potential direction to explore in future studies.

Besides, participants' RT mixing costs to Chinese and English differed significantly, F (1, 30) = 21.07, p <.001, ηp^2 = .41, showing an asymmetrical pattern across participants' L1 and L2. Participants' RT mixing costs to English were about 86 ms smaller than to Chinese. Since participants' RTs in Chinese and English single-language trials were comparable (shown above), the smaller RTs mixing costs to English reflected their faster responses in L2 repeated trials, suggesting that the stronger global inhibition on L1 in the mixed language block significantly facilitated bilinguals' L2 production. This finding was consistent with the finding of reversed language dominance effect, i.e., shorter RTs for L2 repeated than L1 repeated trials in the mixed language blocks, and jointly reflected the higher level of proactive inhibition on L1 during bilingual language production in the mixed language blocks.

Response accuracy

Results showed the interactive effects of language context and trial type on participants' response accuracy, F (2, 60) = 5.06, p = .01, ηp^2 = .14. It can find that participants performed more accurately for English repeated trials in the mixed language blocks than for English single-language trials (p = .01). Additionally, significant higher response accuracy was found in English repeated trials as compared to switch trials in the mixed language blocks (p < .01). Furthermore, participants' accuracy in Chinese single-language trials was significantly higher than in English single-language trials, p = .03. Accuracy did not differ between trials switching to Chinese and those switching to English, p = 1.00.

Switch and mixing costs in response accuracy were also analysed. The results showed that switch costs were in a similar level no matter the different switching directions, F (1, 30) = .54, p = .47, η_p^2 =.02, and no asymmetry pattern was found. However, the response accuracy mixing costs in English were significantly smaller than in Chinese, F (1, 30) = 9.90, p=.004, η_p^2 = .25.

Performance in the nonverbal shifting task

Participants' RTs and response accuracy in the colour-shape switching task were analysed. Table 6.6 shows their performance in different trials of the task.

Table 6.6 Mean reaction time (RTs, milliseconds), correct response (ACC, %) for switch and non-switch trials. Standard deviations are shown between parentheses.

	RT (ms)	ACC (%)
Single	658.89(146.02)	97.20 (3.32)
Repeated	868.89 (181.33)	96.87 (3.07)
Switch	1059.48 (219.97)	95.32 (4.34)
Switch costs	190.58 (146.11)	1.54 (3.61)
Mixing costs	210.00 (120.30)	.33 (3.25)

Participants' RTs significantly varied across different trials, *F* (1.71, 51.41) = 108.28, $p < .001$, $\eta_p^2 = .78$. Longer RTs were found in switch trials as compared to non-switch trials (i.e., repeated and single trials), $p < .00$; furthermore, participants responded fastest in single-task trials, $p < .001$.

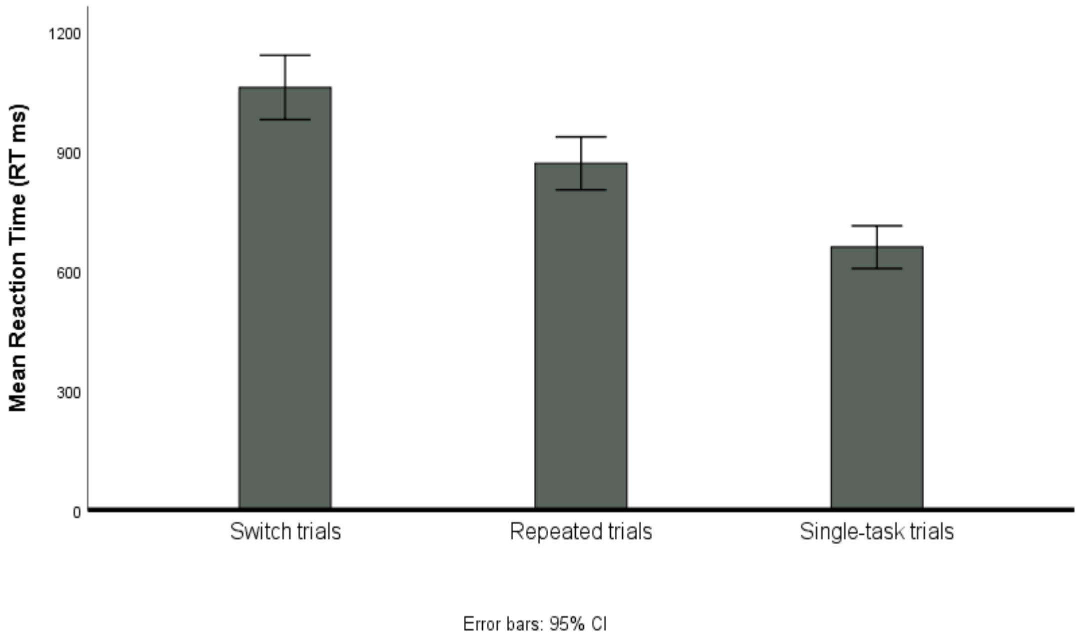

Figure 6.4 Reaction time (ms) for switch and nonswitch trials in the colour-shape switching task

As participants' response accuracy was not normally distributed, a nonparametric Friedman test was used, showing that participants performed with comparably high accuracy in switch and non-switch trials, χ^2 (2) = 5.31, $p = .07$.

Performance in the response inhibition task

Participants' performance in the whack-the-mole task was analysed. Besides RTs and response accuracy for go trials, participants' unsuccessful rates of withholding responses to no-go stimuli (i.e., percentages of false alarms) were also analysed.

Table 6.7 Participants' performance in Go and No-Go trials of the whack the mole task. Standard deviations are shown between parentheses.

	Go Trials	No-go Trials
Reaction Time (ms)	360.68 (41.15)	N/A
False Alarm (%)	N/A	13.31 (7.82)
Accuracy (%)	99.94 (.24)	86.80 (7.94)

In general, participants responded quickly and accurately in the go trials, though they tended to make more errors in the no-go trials than the go trials, F (1, 30) = 86.87, $p < .001$, $\eta_p^2 = .74$.

Regression analyses

How do participants' habitual code-switching and language proficiency affect their cued-language switching performance?

Variables related to participants' habitual code-switching and RTs in the picture-naming task were correlated in the multiple linear regression model using the stepwise method and the Bayesian regression model. Models for predicting the effects of habitual code-switching experience on bilinguals' RT switch costs to Chinese in the picture-naming task were shown in the two Tables below.

Table 6.8 The frequentist regression model: The role of bilingual's contextual switch frequency in predicting RT switch costs to Chinese

	Estimate	Std. error	t-value	Sig.
Intercept	-8.03	45.74	-.175	.84
Contextual Switch Frequency	10.81	5.00	2.159	.04

Table 6.9 The Best-fit Bayesian regression model: the associations between RT switch costs to Chinese in the picture-naming task and bilingual experience-based variables

						95% CI	
Coefficient	**Mean**	**SD**	**$P_{(incl)}$**	**$P_{(incl\|data)}$**	**BF $_{inclusion}$**	**Lower**	**Upper**
Intercept	86.14	11.21	1.00	1.000	1.00	63.66	109.02
Context Switch frequency	7.52	4.94	0.50	0.828	4.83	-0.44	15.15
Baseline switch costs	7.18	6.99	0.50	0.692	2.25	-1.97	19.46
L2OutsideHome	7.62	5.04	0.50	0.828	4.82	0.00	15.73
L1verbalFluency	-7.05	6.52	0.50	0.717	2.54	-18.08	0.51
L2inHome	-3.66	4.40	0.50	0.585	1.41	-13.10	1.48

As the Figure 6.5 below shows, participants' contextual switch frequency[2] positively associates with their RT switch costs to Chinese in the picture-naming task, *F* (1, 28) = 4.66, *p* = .04, adjusted R^2 = .112.

[2] It describes the patterns of language switching based on contextual cues; that is, instead of switching between languages in one situation, bilinguals use their two languages separately for different purposes or in different situations. This construct measured in BSWQ (Rodriguez-Fornells et al., 2012) corresponds with the term "bilinguals in single-language context" described in ACH (Green & Abutalebi, 2013) to some extends. The higher scores on contextual switch reflected the more intensively bilinguals switch their two languages across different contexts, or use languages separately in varied occasions.

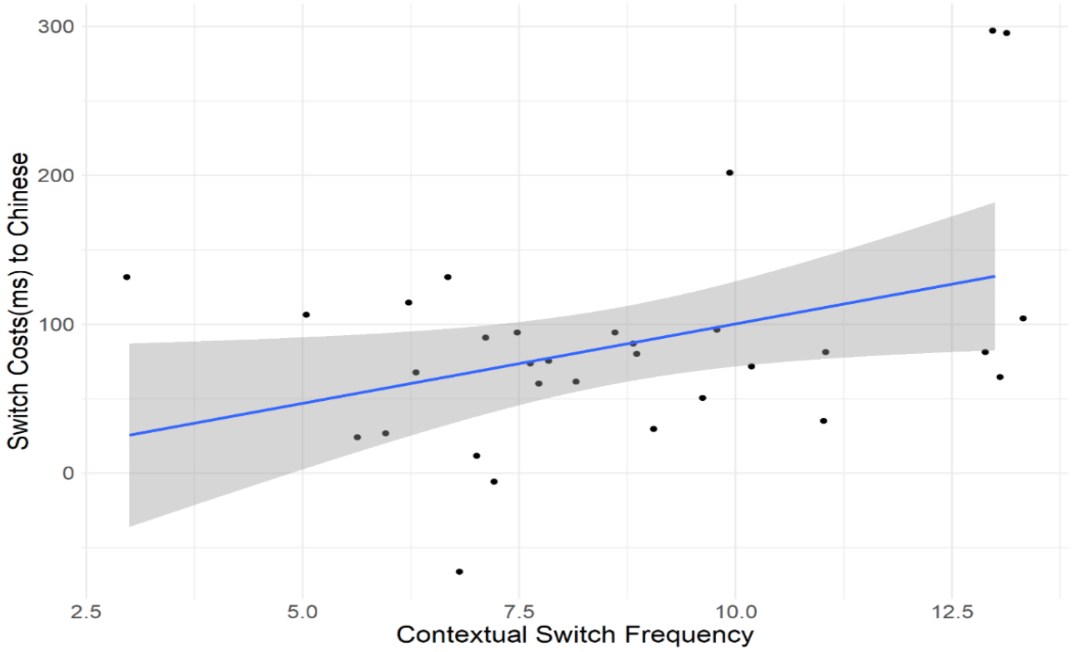

Figure 6.5 Correlation between bilinguals' frequency of contextual switching and their English to Chinese switch costs (ms) in the picture-naming task

It showed that bilinguals who habitually use languages separately in different contexts (i.e., single-language users) were more prone to produce greater RT switch costs to Chinese in the cued-language switching task. The result further indicated that the higher degree of single-language bilingualism (Hartanto & Yang, 2016) was associated with less-proficient language switching, and possible to exercise bilinguals' efficiency in language inhibition rather than switching. Consistently, the best-fit Bayesian model also indicated a positive correlation between participants' frequency of contextual switching and their English to Chinese switching proficiency in the picture-naming task (BF_{10} = 25.00, R^2 = .52). The models, in general, addressed the effects of intensive engagement in using language separately (single-language context) on bilingual speakers' cued-language switching performance.

Participants' switch costs to English were also analysed; however, a significant relationship (BF_{10} = 135.77, R^2 = .59) between participants' Chinese to English switching proficiency and their habitual code-switching practices was only found in the Bayesian regression model (shown in Table 6.10 below).

Table 6.10 The Best-fit Bayesian regression model: the associations between RT switch costs to English and bilingual experience-based variables

						95% CI	
Coefficient	**Mean**	**SD**	**P(incl)**	**P(incl|data)**	**BF inclusion**	**Lower**	**Upper**
Intercept	63.63	9.86	1.00	1.00	1.00	42.87	82.63
Context Switch	12.39	4.64	0.50	0.96	24.43	0.00	19.73
Baseline switch costs	1.67	1.76	0.50	0.63	1.70	0.00	5.38
Intrasentential Switching	-13.33	11.18	0.50	0.73	2.68	-33.87	0.00
L2dailyActivity	-3.88	1.82	0.50	0.92	11.49	-6.42	0.04
L1Switch tendencies	-12.52	7.30	0.50	0.86	6.35	-23.26	0.10

The model described the effects of bilinguals' habitual code-switching frequency and competence on their cued-language switching performance. Specifically, it indicated that participants with higher frequencies of using two languages concurrently and code-switching would perform smaller switch costs to English in the picture-naming task. As the model further shown, participant's L1 switch tendency negatively correlated with their switch costs to English. Participants' predominant use of L1 in bilingual communication indicated their high dependence on L1 in habitual language switching and unbalanced language proficiency. The smaller time costs of switching into

English reflected that participant were less effortful to reactivate L2 and efficiently inhibit L1 to realize fluent L2 production. In sum, this model explained that proficient bilingual switchers who habituate to use languages concurrently could be more efficient in switching to English and reactive inhibit Chinese in communication even their language proficiency were unbalanced.

As for participants' mixing costs to Chinese in the picture-naming task, both the frequentist (*F* (2, 27) = 5.95, p =.01, adjusted R2 = .25) (Table 6.11) and Bayesian regression (Table 6.12) model (BF10 = 7.16, R2 = .31) reflected that participants' L2 proficiency and their frequency of using L2 in occasions outside home were significant in affecting their mixing costs to Chinese in the language switching task.

Table 6.11 The frequentist regression model: The associations between bilinguals' RT mixing costs (ms) to Chinese in the picture-naming task and bilingual experience-based variables.

	Estimate	**Std. error**	**t-value**	**Sig.**
Intercept	-76.29	96.81	-0.79	0.44
L2outsideHome	-17.08	5.82	2.94	0.01
L2 Proficiency	3.58	1.42	2.52	0.02

Table 6.12 The Best-fit Bayesian regression model: the associations between RT mixing costs to Chinese and bilingual experience-based variables

						95% CI	
Coefficient	**Mean**	**SD**	**P(incl)**	**P(incl|data)**	**BF inclusion**	**Lower**	**Upper**
Intercept	-30.79	15.85	1.000	1.000	1.00	-66.33	-1.88
L2Proficiency	1.46	1.61	0.50	0.61	1.58	-0.19	4.68
L2outsideHome	-11.63	6.72	0.50	0.87	6.43	-22.13	0.00

Since participants in this study are Chinese Mandarin native speakers, and Chinese is the predominant language used by majority of them to communicate with their family members (e.g., parents, cousins, and relatives etc.), the higher frequency of using L2 outside home could indicate their higher frequency of using Chinese and English separately in different occasions (i.e., higher degree of single-language context bilingualism). Together with the variable of L2 proficiency, the models showed that the less proficient bilinguals habituated to use two languages separately in different occasions without frequent switching would perform reduced mixing costs to Chinese in the language switching task. The results revealed that controlling linguistics interferences from bilinguals' non-proficient language is less cognitive demanding, especially for those single-language context bilinguals who frequently select and control languages to use in distinct settings.

As for mixing costs to English, both regression models (Table 6.13 and Table 6.14)consistently found significant effects of participants' baseline code-switching proficiency on their mixing costs to English (*F* (1, 28) = 6.91, *p* = .01, adjusted R^2 = .17; BF_{10} = 34.50, R^2 = .44). Greater values of baseline switch costs indicated participants' less balanced proficiency across two languages and limited proficiency in code-switching.

Table 6.13 The Best-fit Bayesian regression model: the associations between RT mixing costs to English and bilingual experience-based variables

Coefficient	**Mean**	**SD**	**P(incl)**	**P(incl|data)**	**BF inclusion**	**95% CI Lower**	**95% CI Upper**
Intercept	-114.93	11.90	1.00	1.00	1.00	-138.45	-90.81
L2Switch tendencies	5.30	6.01	0.50	0.59	1.43	-0.62	17.79
Baseline switch costs	4.59	2.35	0.50	0.90	8.82	0.00	8.19

Coefficient	Mean	SD	$P_{(incl)}$	$P_{(incl\|data)}$	$BF_{inclusion}$	95% CI Lower	95% CI Upper
Age	6.69	3.11	0.50	0.92	11.93	0.00	11.41

Table 6.14 The frequentist regression model: the relationship between bilinguals' RT mixing costs (ms) to English in the picture-naming task and their baseline switch costs

	Estimate	Std. error	t-value	Sig.
Intercept	-188.79	29.39	-6.42	<.001
Baseline switch costs	5.69	2.16	2.63	0.01

The models showed that bilinguals who are less balanced in two languages and non-proficient in language switching tended to perform greater mixing costs to English, reflecting non-proficient bilingual switchers' greater cognitive efforts on L2 sustained control in language production. The Bayesian model further suggested that participants' mixing costs seemed to steadily increase after their age of 30. However, such age effect was not found in the multiple regression model. Therefore, it is hard to confirm whether bilinguals' age is a significant factor in affecting their language switching production, since the sample size is small and participants involved in this study are not so heterogeneous in age (mean age =28).

How do participants' habitual code-switching and language proficiency affect their performance in the colour-shape switching task?

The multiple linear regression model (Table 6.15, F (2, 27) = 7.82, p = .002, adjusted R^2 =.32) and Bayesian model (

Table 6.16, BF 1_0 =33.86, R^2 = .44) consistently reported the effects of participants' frequency of using L2 in occasions outside home and L2 verbal and their switch costs in the nonverbal colour-shape switching task.

Table 6.15 The frequentist Model: the roles of L2 use outside home and L2 verbal fluency in predicting nonverbal RT (ms) switch costs

	Estimate	Std. error	t-value	Sig.
Intercept	140.94	101.22	1.39	.18
L2 verbal fluency	-16.84	5.27	-3.19	.00
L2 use outside home	24.89	8.29	3.00	.01

Table 6.16 The Best-fit Model: the associations between nonverbal RT switch costs in reaction time and bilingual experience-based variables

						95% CI	
Coefficient	**Mean**	**SD**	**$P_{(incl)}$**	**$P_{(incl\|data)}$**	**$BF_{inclusion}$**	**Lower**	**Upper**
Intercept	190.58	21.61	1.00	1.00	1.00	145.05	228.72
L2OutsideHome	21.18	9.79	0.50	0.92	12.20	0.00	35.50
L2VerbalFluency	-12.92	5.79	0.50	0.93	13.86	-21.63	0.00
L2inHome	-7.44	8.84	0.50	0.57	1.33	-26.25	0.48

The models described a negative correlation between bilinguals' L2 verbal fluency and their switch costs in the cognitive shifting task, and such correlation was more salient among participants habituated to use two languages separately (i.e., intensive single-language context engagement). Specifically, single-language context bilinguals (higher frequency of using L2 outside home but predominantly use L1 at home) with less L2 verbal fluency could perform less efficiently in cognitive shifting task. The results showed the hindered efficiency of cognitive shifting attributed to the participants' habitual language use in single-language context and less proficiency in L2.

Participants' RT mixing costs were also analysed in regression models; however, no significant effects of their habitual bilingual language use experience on nonverbal mixing costs were found.

How do participants' habitual code-switching and language proficiency affect their performance in the Go/No-go task?

The percentage of false alarms in the Go/no-go task, calculating participants' unsuccessful rates of withholding their responses in no-go trials, was analysed in regression models (Table 6.17 and Table 6.18) as an indicator of participants' response inhibition performance. Higher percentages of false alarms indicate poorer response inhibition performance.

Table 6.17 The Frequentist regression model: the relationship between unintended bilingual switching frequency and participants' percentages of false alarm in the go/no-go task

	Estimate	**Std. error**	**t-value**	**Sig.**
Intercept	25.06	5.78	4.33	<.001
Frequency of unintended switch	-1.43	.69	-2.09	.046

Table 6.18 The Best-fit Bayesian regression model: the association between the percentages of false alarm in the go/no-go task and participants' bilingual experience-related variables

Coefficient	**Mean**	**SD**	**$P_{(incl)}$**	**$P_{(incl\|data)}$**	**BF inclusion**	**95% CI**	
						Lower	**Upper**
Intercept	13.31	1.10	1.00	1.00	1.00	11.06	15.60
L2switch tendency	1.72	0.82	0.50	0.93	12.34	-0.02	3.03
L1Switch tendency	-0.98	0.83	0.50	0.74	2.83	-2.60	0.01
Unintended Switch	-0.85	0.69	0.50	0.75	3.32	-3.92	0.00
Age	-0.24	0.26	0.50	0.64	1.76	-0.84	0.04
Intrasentential switching	-0.86	1.06	0.50	0.58	1.35	-3.30	0.28
Intersentential switching	-1.59	1.23	0.50	0.77	3.32	-3.92	0.00
L2OutsideHome	-0.87	0.54	0.50	0.86	5.88	-1.18	0.02

Both the Bayesian (BF_{10} = 106.96, R^2 = .66) and multiple linear regression (*F* (1, 28) = 4.36, *p* = .046, adjusted R^2 = .104) models indicated that unintended switch frequency negatively associated with participants' percentages false alarm.

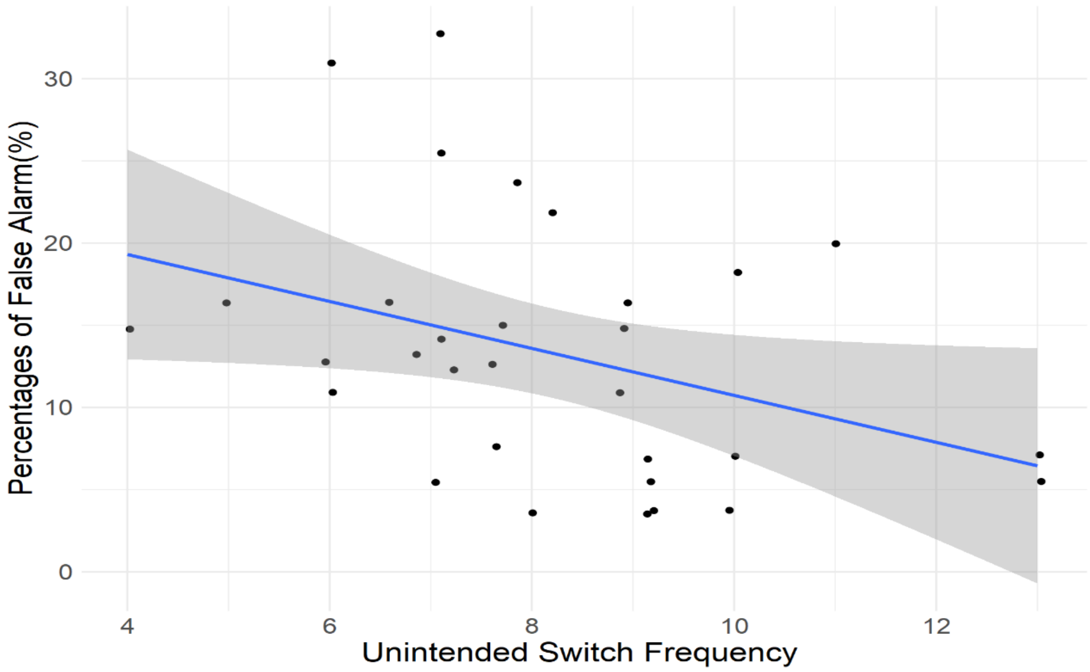

Figure 6.6 The relationship between bilingual's frequency of unintended switch in daily communications and their percentages of false alarm in the response inhibition task

Such finding was inconsistent with what previous studies reported (e.g., Festman & Münte, 2012; Soveri et al., 2011; Rodriguez-Fornells et al., 2012), where higher unintended switch frequency was broadly reported to reflect bilinguals' uncontrolled activation of non-target language during bilingual language production, and correlate with their worse performance in cognitive inhibition and attentional control.

To explore reasons of the finding, a correlation analysis between participants' unintended switch frequency and frequencies of inter-/intrasentential switching was conducted. It showed that participants' unintended switch frequency significantly correlated with their frequency of intrasentential switching (Pearson's r = .50, $p < .01$). That is, participants with intensive experience of intrasentential switching in daily communications are relatively weaker in bilingual language control, and tend to “loosely” control their co-activated languages in communications. Similarly, the Bayesian model further indicated that, besides unintended switch frequency, habitual code-switchers with highly frequency of inter- and intrasentential switching and intensive use of L2 in communications tended to have better response inhibition performance. Both the correlation analysis and Bayesian model reflected the relationship between bilinguals with dense code-switching experience and response inhibition performance.

Given that dense code-switchers cooperatively control their languages to realise efficient bilingual communications, and linguistic items from both languages are in “open control mode” during frequent language switching back and forth (Green & Li, 2014), they are relatively less cognitive demanding on language control and could be weaker in appropriately inhibition non-intended language in language production. Therefore, the models reflected that dense code-switchers executed relatively looser control on their two co-activated languages (i.e., open control mode) to produce efficient intensive code-switching in communications, and such dense code-switching experience further facilitated their nonverbal response inhibition efficiency.

Even the facilitation effect shown in the Bayesian model became more salient with participants’ age increasing, it is plausible to discuss that age is an important factor affecting bilinguals’ response inhibition efficiency as the limited number and relatively consistent age range of these participants in the study.

6.2.4 Study Discussion

This study aimed to investigate the effects of bilingual language use experience on domain-general cognitive control in a group of 31 Mandarin-English bilingual adults. Results revealed that participants' efficiency of cognitive shifting and response inhibition was associated with their habitual code-switching frequency. Contrary to previous studies (De Baene et al., 2015; Declerck et al., 2017; Prior & Gollan, 2011), this study did not find significant associations between bilinguals' language switching and nonverbal task switching performance (consistent with Branzi et al., 2016; Calabria et al., 2015; Gollan et al., 2014; Prior & Gollan, 2013). However, the findings showed the facilitations of participants' intensive practices of code-switching in daily communications on their performance in the cued-language switching task (e.g., Yim & Bialystok, 2012).

Cued-language production and relationship with habitual bilingual language experience

Results in the picture-naming task not only showed the significant mixing costs asymmetry between L1 and L2, but also reported the reversed language dominance effects on participants' language production, that is, their RTs for

L1 repeated trials were significantly longer than L2 in the mixed language blocks. Such findings reflected the consequence of the sustained inhibition on L1 in the mixed language condition to lower the proactive activation level of L1 for efficient switching to L2 production (Christoffels et al., 2007; Declerck, 2020). These findings further indicated that participants administered global and sustained inhibition to their dominant language during bilingual production, even in conditions requiring the use of both languages.

The finding of reversed language dominance effect on Chinese-English bilinguals' cued-language switching productions was consistent some previous studies on bilinguals with two closer-distanced languages (e.g., Dutch and German, German and English). For example, Christoffels et al. (2007) tested a group of Dutch-German bilinguals' language switching performance in the mixed language condition based on cues through the picture-naming task, and their results showed that participants in the mixed language block performed longer reaction time naming pictures in Dutch (L1) than in German (L2). The result was also consistent with Heikoop et al.'s (2016) study, in which they measured German (L1)-English (L2) bilinguals' reaction time for language and cue switches as well as cue repetitions conditions in the picture-naming task. They observed that bilinguals' less dominant language could be more strongly primed by the switching cues, showing shorter L2 RTs as compared to L1 RTs in these three conditions.

The current similar finding observed among Chinese-English bilinguals provided evidence for the facilitations of proactively inhibiting L1 in bilingual contexts on L2 production. Furthermore, it reflected such reversed language dominance effects in bilingual language production could occur in a broader scenario regardless of bilinguals' L1 and L2 patterns or distances; besides, it is reasonable to associate such effect with bilinguals' unbalanced proficiency in L1 and L2, rather than the language distance between them (Declerck, 2020).

The absence of switch costs asymmetry found among current participants with unbalanced proficiency in two languages was inconsistent with previous findings (e.g., Gollan & Ferreira, 2009; Peeters & Dijkstra, 2018; Slevc et al., 2016). Previous studies (e.g. Costa et al., 2006; Costa & Santesteban, 2004; Linck et al., 2012; Meuter & Allport, 1999) have discussed that the asymmetrical pattern of switch costs in L1 and L2 is associated with unbalanced bilinguals' different extents of transient control of two languages, while switch cost symmetry is assumed to associate with balanced-proficient bilinguals as their transient control of two languages during bilingual language processing is comparably strong.

However, Peeters and Dijkstra (2018) indicated that switch cost symmetry in cued-language switching production did not only exist to some extent among well-balanced bilinguals, but among less balanced bilinguals. They further addressed the facilitation of sustained dominant language inhibition on bilinguals' L2 production in bilingual co-occurrence contexts. Given that participants involved in current study are Chinese-English bilinguals residing in English-speaking countries, and most of them are university students who have intensive experience of using L1 and L2 separately in different contexts (e.g., predominantly use L2 in the classroom and read in L2 English, but speak in Chinese with family members or friends), their intensive experience of using languages in single-language contexts has equipped them relatively stronger capacities of maintaining the targeted language with controlling and inhibiting the interferences of the competing others (Green & Abutalebi, 2013). Therefore, they performed efficiently to sustained control their dominant language over competing co-activated linguistic items to facilitate L2 production in the mixed language conditions.

As for the relationship between participants' habitual and cued language switching performance, the study showed that bilinguals who are more frequently engaged in language switching practices or contexts (dual-language or dense code-switching contexts), rather than single-language contexts, were more efficient in reactive inhibition on linguistic interferences in the cued-language switching task, which was in line with current study's hypothesis and previous findings (e.g., Barbu et al., 2018; Prior & Gollan, 2011).

In contrast, the smaller mixing costs to L1 were closely related to unbalanced- proficient bilinguals' intensive engagement in single-language contexts, reflecting their enhanced efficiency of sustained language control during language production in the single-language context. As languages are not co-used in a single-language context, bilinguals' long-term experience of sustained control of nontargeted language to distinctively use two languages, in turn, brings them advantages in their proactive control mechanism. Therefore, single-language context bilingual speakers could perform proficiently in targeted language maintenance, especially their dominant language, which was driven by their efficiently sustained inhibition mechanism.

However, the modulation of single-language context on the efficiency of non-dominant language sustained inhibition was not observed. Bayesian model showed the interconnection between increasing mixing costs to L2 and participants' less proficiency in code-switching. Code-switching proficiency, discussed in this study, indicates bilinguals' verbal fluency level between L1 and L2, and their familiarity level with code-switching in daily interactions. It seemed that single-language context bilinguals with limited code-switching frequency and proficiency did not show advantages in efficiently controlling their non-dominant language in communication.

Relationship between habitual bilingual language experience and cognitive shifting

Switch costs in the task-set switching task reflected the costs of switching between different tasks driven by participants' local control mechanisms (Kiesel et al., 2010; Yang et al., 2016). Regression analyses revealed that bilinguals' higher frequency of engagement in a single-language context was related with greater switch costs in the nonverbal cognitive shifting task, showing that habitually using languages separately hindered bilinguals' cognitive shifting efficiency. According to the ACH (Green & Abutalebi, 2013), bilinguals engaged in a single-language context always keep their languages apart and do not mix them up during communication, leading to further exercising of their abilities in goal maintenance and interference control rather than cognitive shifting. Higher frequency of code-switching (e.g., Barbu et al., 2018; Prior & Gollan, 2011) and engagement in code-switching contexts (e.g., Green & Abutalebi, 2013; Hartanto & Yang, 2016; Lai & O'Brien, 2020) has been assumed to boost bilinguals' efficiency in shifting between different mental sets. Besides, the results further indicated that bilinguals' L2 fluency was also an important factor in affecting their cognitive shifting performance. Therefore, bilinguals who are fluent in L2 and have intensive practices of code-switching are expected to be efficient in cognitive monitoring and shifting.

Although results showed the modulations of bilinguals' habitual language switching frequency on their cognitive shifting, similar association was not found between their cued-language switching and cognitive shifting performance. This finding was in line with those studies showing little evidence for an overlap between the mechanisms of cued-language switching and cognitive shifting (e.g., Calabria et al., 2015; Klecha, 2013; Prior & Gollan, 2013). Bilinguals in cued-language switching tasks are guided by language selection cues or pictures, which is a bottom-up cognitive mechanism; however, a top-down cognitive mechanism is assumed to direct bilingual language selection when bilinguals are allowed to switch between languages voluntarily or freely (Declerck & Philipp, 2015). The modulation of frequent habitual language switching, rather than cued-language switching, on task-switching efficiency addressed the necessity of discussing the role of bilingual habitual language experience on bilingual cognitive control. Another reason, as Klecha (2013) mentioned, is that switching between languages is a complex process in nature, involving multifaceted factors related to bilingual language experience as well as executive functions; furthermore, it requires many more cognitive challenges than switching between non-linguistic schemas.

In general, the result reflected ACH's prediction that bilinguals with intensive experience of using language in single-language contexts are less efficient in switching between mental-set tasks. In addition, consistent with this study's hypothesis, the results showed the intercorrelations between improved cognitive shifting efficiency and participants with more balanced bilingual proficiency and higher frequency of using both languages concurrently in communications. Using and switching two languages concurrently requires bilinguals efficiently to distinguish stimuli from a certain abstract category (i.e., either linguistic or non-linguistic categories), which are able to boost their language-set shifting efficiency in communications. These efficient skills could further extend to advantages in non-linguistic shifting, contributing to behavioural outcomes in cognitive shifting.

Relationship between habitual language switching and response inhibition

In this current study, a fast-paced go/no-go task was administered to examine the association between bilinguals' frequency of code-switching and their response inhibition efficiency. Results showed that bilinguals highly engaged in dense code-switching tended to perform more successfully in withholding their habitual responses to no-go stimuli, which suggested dense code-switchers' advantages in both avoiding habitual but erroneous responses and resolving response conflicts (Blackburn, 2013; Bunge et al., 2002). It could be that global inhibition of untargeted language, at least in the articulatory stage (i.e., the motor level), is also employed to facilitate code-switching production, besides the process of interference suppression

(Hofweber et al., 2020). The intensive dense code-switching practices trained bilinguals' efficiency in response inhibition because they have to constantly control their ongoing language before articulation and switching to appropriate language to produce.

Although the results were not strictly in line with the predictions of ACH, where inhibitory advantages are not supposed to associate with bilinguals' dense code-switching practices, there are relevant studies showed similar intercorrelations between dense code-switching practices and enhanced performance in response inhibition task (e.g., Hofweber et al., 2016, 2020). It was argued that, besides the inhibitory skills, participants in the Go/No-go task also have to constantly monitor the no-go signals among go-trials, which led to the activations of proactive monitoring. These participants, who are intensively engaged in dense code-switching practices, are relatively proficient in monitoring cross-linguistic competitions, and their feasible control of two languages further modulated their efficiency in monitoring and inhibit conflicting responses. Therefore, the outperformance in response inhibition task among dense code-switchers reflected the proficiency in monitoring and managing the co-activations of languages during intensive code-switching practices could further contribute benefits to efficient conflict-monitoring and inhibition performance beyond language domains. In sum, the findings provided novel insights into the overlap between code-switching production and response inhibition processes, implying the involvement of motor control of prepotent response to globally inhibit the ongoing predominant language in bilingual code-switching production.

6.2.5 Study Limitations and Conclusion

There are limitations of this study. The outbreak of COVID-19 had severely affected participants' recruitment for this study, leading to only 31 participants finally being included in this study. The associations between bilinguals' habitual language use experience and cognitive control found in this study may only reflected the characters of the limited number of participants involved, and need to be tested with more bilingual participants involved in the future. Besides, participants in this study have great variations in their self-reported L2 AoA (Mean = 10, SD = 4.81). Although these participants shared the similar L2 learning context, that is, learning English from mainstream schools in China, the variations in L2 AoA could lead to different language experiences with regard to length of L2 exposure, language proficiency and cognitive control abilities (Gullifer & Titone, 2021; Gullifer et al., 2018; Luk et al., 2011). Participants' L2 AoA was measured through their self-reported responses to the question, asking participants to indicate at what age they learned English in the LSBQ (Anderson et al., 2018). Since this is not an objective measure and participants might have different understandings on "learned from birth", their self-rated age for L2 acquisition might not perfectly reflect their actual L2 learning experience. Objective measures or calculations to quantify variables related to bilinguals' language use experience, such as language entropy (Gullifer & Titone, 2020b), are needed in future research.

In addition, conducting behavioural tasks and collecting data online meant that it was not possible to control individual participants' experiment equipment and test environment. Participants from different countries completed the tasks on different computers with different qualities of internet connections, and distractions (e.g., noises) during their study participations were hard to control. These factors may affect the study results. However, this is one significant attempt in bilingualism research to conduct behavioural experiments and collect human participants' data fully online during the pandemic period.

In conclusion, the study reflects the facilitation of cognitive shifting and inhibition derived from bilinguals' high frequency of code-switching production in daily life. It provided evidence for the predictions of the ACH and CPM that bilinguals habituated in a single-language context without high frequency of code-switching practices excel in goal maintenance and interference control. However, bilinguals with high frequency of dense code-switching and engaging in cooperative control of their languages are more efficient in cognitive shifting and response inhibition. In addition, this study indicates cooperation between interference control and response inhibition during code-switching production, and points out that the efficiency of response inhibition could be enhanced through intensive experience of code-switching production in life. Although the study used a small sample size, it confirms that bilingual code-switching habits, including switching frequency and context, are crucial in shaping and modulating bilinguals’ skills in cognitive flexibility and inhibition.

The study, in general, is an attempt to conduct bilingualism research and test Chinese-English bilingual participants remotely. As compared to the traditional lab-based studies, running studies online could be a new trend for future research in post-pandemic era, since it offers a more efficient and economically approach to test participants from more diverse cultural and language communities. More studies conducting online are expected in future to help improve the validity and reliability of online data collection platforms; in addition, to contribute more data collected online to make cross-comparisons and evaluations.

In the next section of Chapter 6, I will investigate how bilinguals’ habitual language use experience affect their cognitive control in un-cued language switching production in the naturalistic communicative condition.

6.3 Empirical Study 2: Modulating bilingual language production and cognitive control: how bilingual language experience matters

6.3.1 Study introduction

This study aims to take more comprehensive approaches to measure bilingual participants' habitual language use practices, and explore how individual differences in bilinguals' language use habits affect their spontaneous bilingual language production and efficiency in cognitive control. It investigated how habitual bilingual language use modulates cognitive shifting and inhibition efficiency in Chinese-English bilinguals living in an L2 environment. In addition to quantifying bilinguals' habitual language use patterns via self-reported questionnaires (Hartanto & Yang, 2016; Rodriguez-Fornells et al., 2012) and language entropy computation (Gullifer & Titone, 2020), this study further examined these patterns through two spontaneous bilingual language production tasks (i.e., the naturalistic conversation task and narrative task). Participants' language proficiency levels were also assessed. Furthermore, their efficiency in controlling and inhibiting linguistic and non-linguistic resources was measured through a verbal and a spatial Stroop task, respectively. A well-established colour-shape switching task was also used to examine participants' nonverbal cognitive shifting performance.

In sum, this study intends to explore how bilingual language use habits affect bilinguals' spontaneous language production and domain-general cognitive control performance. Specifically, it addressed the following research questions: i) what is the relationship between bilinguals' performance in spontaneous language production tasks and cognitive control tasks? ii) how do differences in habitual bilingual language use experience affect bilingual language production and efficiency in cognitive control of these bilinguals? iii) can bilinguals' performance in spontaneous language production tasks reflect their habitual bilingual language use patterns (e.g., habitual code-switching frequency, habitual code-switching patterns)?

6.3.2 Methods

Participants for this online study were recruited from among Chinese-English bilingual adults living in English-speaking countries (including the USA, Canada, Ireland and the UK). Only individuals residing in these English-speaking countries at the time of the study and making regular use of Chinese and English every day were invited to join the study. An information sheet and consent form were provided to individuals who expressed an interest in this study so that they could decide whether to participate or not. Prior to data collection, the researcher briefly introduced the participants to the goals of the study, and all consenting participants took part in it.

Participants

Forty-one (9 males; Mean age = 26, SD = 2.92, range: 21-33 years old) right-handed healthy Chinese-English bilingual adults living in English-speaking countries took part in this study. These participants are late bilinguals, who have English learned as their second language (L2) after their native language Chinese Mandarin has well-acquired (Mean L2 AoA = 6.7 years old). At the time of this study, participants on average had lived in English dominant communities (e.g., the UK, the USA) for 3.5 years. The LexTALE test (Lemhöfer & Broersma, 2012) was used to objectively measure participants' L2 proficiency, and it showed that participants, in general, are moderately-high proficiency in English (Mean = 63.75).

In addition, participants' self-reported language proficiency levels and their habitual bilingual language use patterns were measured through the LEAP-Q (Marian et al., 2007) and the code-switching and interactional context questionnaire (Hartanto & Yang, 2016), respectively. The Chinese-translated bilingual switching questionnaire (BSWQ) (Rodriguez-Fornells et al., 2012) was used to measure participants' habitual code-switching practices. To quantify participants' individual differences in bilingual language use and overcome some limitations of self-reported language experience questionnaires, this study also computed participants' language entropy (Gullifer & Titone, 2020) in four different communicative contexts: home, workplaces, school and social activities. More introduction on language entropy and how it is computed can be found in Chapter 5. Table 6.19 below shows information related to bilingual participants' language use experience.

Table 6.19 Demographic, language history and bilingual language use information of the Chinese-English bilingual participants

	Sample (N = 41)	
	Mean	SD
Basic demographics		
Age (years)	26.17	2.92
L2 AoA (years)	6.68	3.66
LexTALE score	63.75	9.52
L2 exposure (years)	3.49	2.29
Chinese use in bilingual conversations (%)	67.32	20.86
English use in bilingual conversations (%)	32.68	20.86
Proportion of reading in Chinese (%)	61.34	23.37
Proportion of reading in English (%)	38.66	23.37
Accent perception in L2		
Self-perceived (1-10)	4.17	2.18
Other-recognised (1-10)	5.22	3.37
Self-reported L2 proficiency		
Reading (1-7)	5.71	0.98
Comprehension (1-7)	5.54	0.93
Writing (1-7)	4.93	1.01
Speaking (1-7)	5.22	1.01
Bilingual switching habits		
L1 switch tendencies	7.98	2.22
L2 switching tendencies	8.32	1.96
Contextual switch	8.71	2.73
Unintended switch	7.88	2.35
Habitual code-switching and interactional context		
Single-language score	69.49	20.91
Dual-language score	4.83	1.86
Intersentential switching index	2.16	0.75
Intrasentential switching index	2.78	0.95
Language entropy		
Home	0.49	0.33
School	0.54	0.34
Work	0.31	0.40
Social activities	0.91	0.31

Materials and task design

Due to the influences of pandemic, this study was administrated remotely. All behavioural tasks in this study were created using PsychoPy (Pierce et al., 2019) and hosted by the online platform Pavlovia (http://pavlovia.org/). Language production tasks were conducted through online one-to-one meeting between the researcher and participant.

Spontaneous language production tasks

Two tasks, a naturalistic conversation task and a story narration task, which require participants to spontaneously produce languages, were included in this study to capture participants' bilingual language use characteristics in both naturalistic and controlled language productions. The conversation task is considered as an un-cued language switching task, in which participants are allowed to use their languages and switch between Chinese and English as what they habitually do in naturalistic bilingual conversations. While the story narration task is designed as a semi-cued language switching task, which requires participants to control their languages and produce code-switching utterances based on instructions. For both tasks, pauses, monolingual utterances, and frequencies of different code-switching utterances (i.e., intersentential switching and intrasentential switching) produced by participants were counted.

Naturalistic conversation task

This task is designed as a semi-structured conversation in which participants discussed with a Chinese-English bilingual experimenter on topics of their weekend plans and favourite weekend activities. The experimenter acted as a facilitator in the conversation to communicate with participants one-to-one through online Zoom meetings.

Initially, the experimenter gave each participant 5 minutes to have a monologue on the topic of “what did you do last weekend”. During this monologue, participants were free to use both Chinese and English, and allowed to switch in their habitual ways. To maximize language switching in an artificial lab setting within an English dominant context, the instructions of this task were communicated in Chinese Mandarin. After that, the experimenter would propose three questions to prompt participants’ language productions in interactive settings and assess whether they would use two languages differently in response to questions asked monolingually and bilingually. Also, participants were told to freely use or combine two languages to respond to these questions, as they were in a daily bilingual discussion with their friends.

Two questions were asked in Chinese and English single-language respectively, and the other question was asked with two languages combined. The order of these three questions was counterbalanced across participants.

The Table 6.20 below showed the three questions followed to participants' five-minute monologue.

Table 6.20 Questions asked in the naturalistic conversation task. English translations for non-English questions are shown in brackets.

	Questions
Chinese single-language	如果不考虑一些限制条件，就是理想状态下，让你好好规划一次你的周末，你打算怎样安排呢？ (What will you do for your weekends if you were given a chance to plan your weekends ideally?)
English single-language	What kind of activities you love to do most on weekend? With friends? Or just alone? Why?
Code-switching	那你觉得你目前的 activities on weekend，还有对 weekend 的 expectations 啊,相比 COVID-19 之前，have any changes 或者说 differences 吗？ (Compared to weekends before the outbreaks of COVID-19, do you think you have experienced some differences on your weekend plans and activities, or your expectations to holidays?)

The frequencies of intersentential and intrasentential switching were counted in both participants' monologue and question answering parts. Frequency and mean duration of pauses in participants' speech were also measured. As the topics used for this task involves past events or experience recalling, participants' pausing at the very beginning of their monologues were not counted as an indicator of code-switching and bilingual language control behaviours. Adopting Gardner-Chloros et al.'s (2013) and Zantout (2019) measurement of bilinguals' pausing in speech, pauses were discussed as indicators of language processing in code-switching. Both silent and filled pauses, which are over 250ms, in bilinguals' speech were counted and included in analysis (Huensch & Tracy-Ventura, 2017; Zantout, 2019). The details of language production data analysis are further explained in later sections.

Story narration task

This is a self-designed semi-naturalistic bilingual speech production task, which is an adaption of the story recounting task and picture descriptive task used by Toribio (2001) and Lloyd-Smith et al. (2019). It intends to engage participants in bilingual speech production, and measure their code-switching and language control performance through monological narrations of a series of well-known fairy tales. Both this task and the naturalistic conversation task introduced above aim to elicit bilingual participants' spontaneous language production and code-switching. Different from the conversation task, this narration task controls the dysfluency in participants' speech caused by the memory demands on recalling and redescribing their past experience. Another advantage of this task is that it constrains the variations of topics participants might produce in their speeches, reducing the confounds in narrative data analysis caused by the different familiarity and variations in speech topics (Zantout, 2019).

This task was administered in single-language contexts which one specified language was instructed to use or a bilingual context which instructed participants to produce code-switching in a voluntary manner. Two sets of pictures on the stories of Hua Mulan (Chinese traditional story) and the little match girl (western fairy tale) were designed for participants' narrations in single-language contexts, while one set of pictures of three little pigs (non-culture related story) was included for elicit participants' bilingual language speech.

In the narration task, participants were given a set of well-ordered pictures (story pictures shown in Appendix IV: Picture sets for story narrations in single-language and bilingual language conditions) without any linguistic cues. Then, they were instructed to describe what happened in each picture and recount the story illustrated by these pictures in five minutes. Each set of pictures, printed together on one PowerPoint slide, were shared to the participant in the online one-to-one meeting session. A set of 13 pictures was used for bilingual narration, while two sets of 12 pictures were included in the single-language condition.

Given that bilinguals' language production in naturalistic interactions is influenced by interlocutors and social contexts they immersed in, this task requires participants to imitate that they were telling the story based on provided pictures to one of their monolingual or Chinese-English bilingual friends. Participants were verbally instructed to tell stories based on provided pictures in the language assigned by the researcher. Specifically, they were required to produce two monolingual narrations (i.e., Chinese-only and English-only) for each set of pictures designed for single-language production (i.e., Hua Mulan and the little match girl); while they were allowed to produce a bilingual narration which combines two languages and code-switching based on a set of pictures of three little pigs. To prompt participants' language production in naturalistic interactive settings, the researcher, in the single-language narration condition, uses Chinese and English accordingly to assign a specified language for participants to tell a story in. Bilingual utterances were included in researcher's instructions in the bilingual language condition, requiring participants to tell a story in two languages. The detailed prompts for this task were presented in Appendix V: Prompts for the story narration task.The order of the single-language story narrations was counterbalanced across participants, and the bilingual story narration was always conducted at last. Short breaks were offered after participants completed each narration, and their narrative speeches in this task were recorded. Audio-recorded data was transcribed to measure the types of code-switching and switching directionality produced by participants. Pause frequency and duration in participants' story narrations were also measured and analysed using the Praat software.

Verbal Stroop task

This task was adapted from the computerised version of the Stroop (1935) colour-naming task, and used to measure participants' verbal cognitive control performance. Verbal stimuli were designed in Chinese characters as participants' native language is Chinese. There were four types of trials based on four different colours: red, blue, yellow and green, in this task. Participants in this task would see

In this task, participants would see four colour words in Chinese (i.e., 红(red), 绿(green), 蓝(blue) and 黄(yellow)) printed in the four ink colours. Their task was to respond to the “ink” colour of the Chinese word they saw on the screen through pressing the corresponding keys. For example, if participants see the word “绿” on the screen, they need to press the corresponding key (i.e., the right arrow) on their keyboard for the ink colour blue and ignore the meaning of this Chinese word (i.e., green). The other three keys, “left arrow”, “up arrow” and “down arrow”, correspond to the ink colours of red, yellow and green respectively.

In the congruent trials, the meaning of the colour word matches with its ink colour in which the word is printed on screen (e.g., ‘红’ printed in red). In the incongruent trials, the meaning of the colour word mismatches with its ink colour in which the word is printed (e.g., ‘黄’ printed in green). There are also 24 neutral trials, which include four Chinese non-colour words: 吃(eat), 忙(busy), 路(road), 富(rich), printed in four different ink colours. At the beginning of this task, there was a practice session consisting of 12 trials with response feedback; after that, a total of 120 trials were included in five formal experimental blocks. Each trial began with a centred fixation cross (+) presented on a black background for 500ms, followed by the verbal stimulus that remained on the screen for 3500ms or until a response. A blank black sheet presented for 300ms immediately after a response or the stimulus disappeared.

Initially, participants needed to complete a neutral block with 24 trials. Then, they were instructed to complete a congruent and an incongruent block respectively, each of them including 24 trials. The order of these two blocks were counterbalanced across participants. The mixed block of 48 trials with an equal number of congruent and incongruent trials was required to be completed at last. Trials in the mixed block were presented in a fixed pseudo-random order. Participants' reaction time (RT) and response accuracy in this task were automatically recorded and collected for data analysis. The general procedure and design of this verbal Stroop task could be found in the Figure 6.7 below.

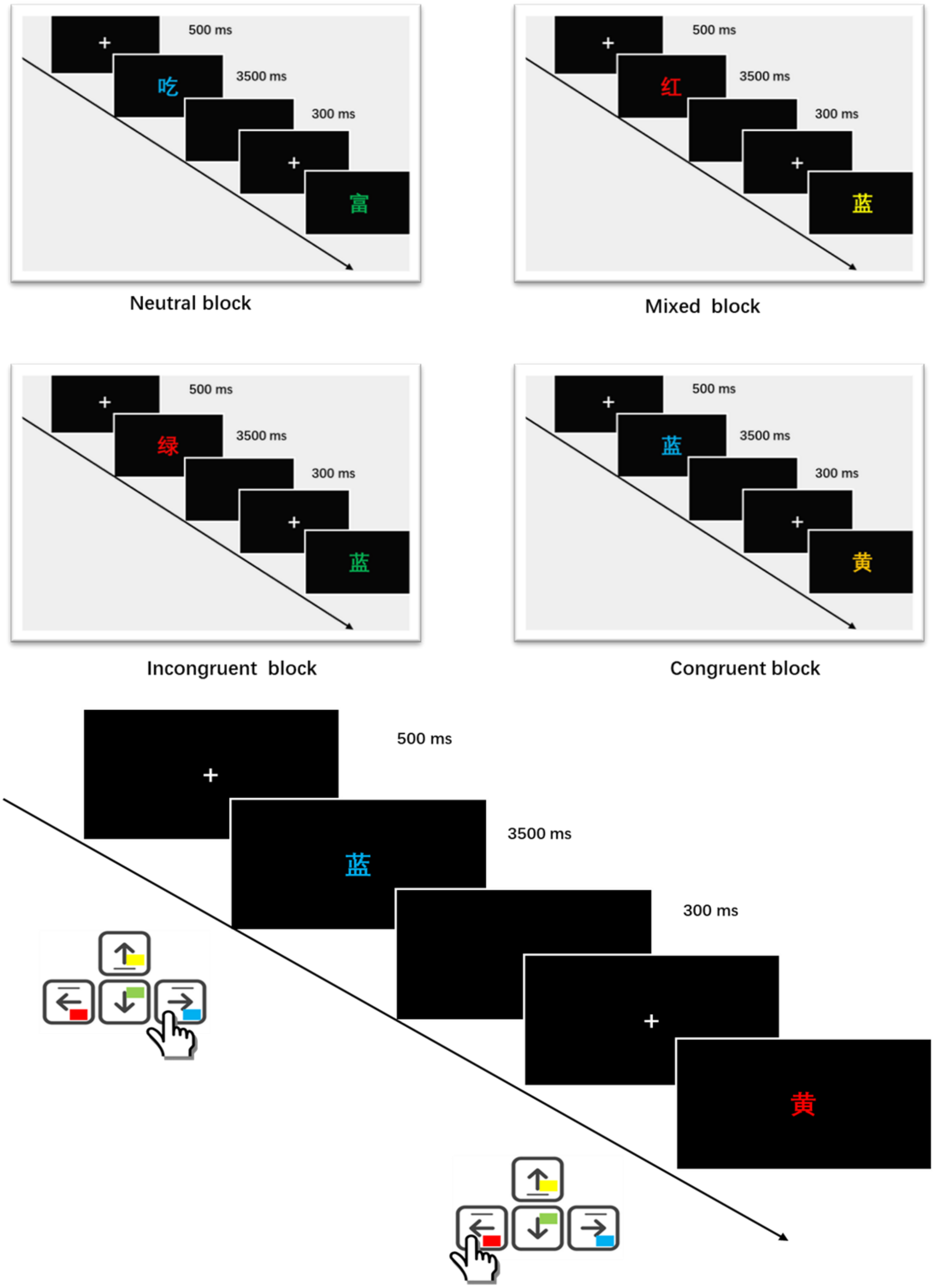

Figure 6.7 General procedure and block design of the verbal Stroop task

Spatial Stroop task

The spatial Stroop task, adapted from Blumenfeld and Marian (2011, 2013), aims to measure participants' nonverbal inhibitory control performance. Participants in this task were instructed to judge the arrow's direction with ignoring the location of the arrow as quickly and accurately as possible. For example, they need to press the left arrow on their keyboard immediately as they see a left-pointing arrow presented on the screen no matter it presented on the left or right side of the screen. Trials are congruent when the arrow's pointing direction matches with its location on the screen (e.g., left-pointing arrow presented on the left side of the screen); otherwise, when the arrow's pointing direction is inconsistent with its location, it is an incongruent trial (e.g., up-pointing arrow presented at the bottom of the screen). Each trial began with the presence of a fixation cross at the centre of the screen for 500ms, followed by a 3500ms presentation of the stimulus. After that, a blank sheet immediately appeared for 300ms.

Besides the congruent and incongruent blocks, the task also consists of one neutral block, in which a circle rather than a direction-pointing arrow presented as visual stimulus on the screen. The mixed block, containing equal numbers of congruent and incongruent trials, was presented at the end of this task. All visual stimuli, both the arrow and the neural circle, can appear at any of the four locations (top, bottom, left and right side) on the screen. The design of each block and general procedure of this task were shown in the Figure 6.8 below.

After completed 12 practice trials with response feedback at the beginning of this task, participants were instructed to complete 24 neutral trials in the neutral block. The congruent and incongruent block with 24 trials respectively was followed, and the order of the two blocks were counterbalanced across participants. The mixed block, containing 48 trials with an equal number of congruent and incongruent trials, was required to be completed at last. Trials in the mixed block were presented in a fixed pseudo-random order. In total, participants in this task needed to complete 120 formal experimental trials.

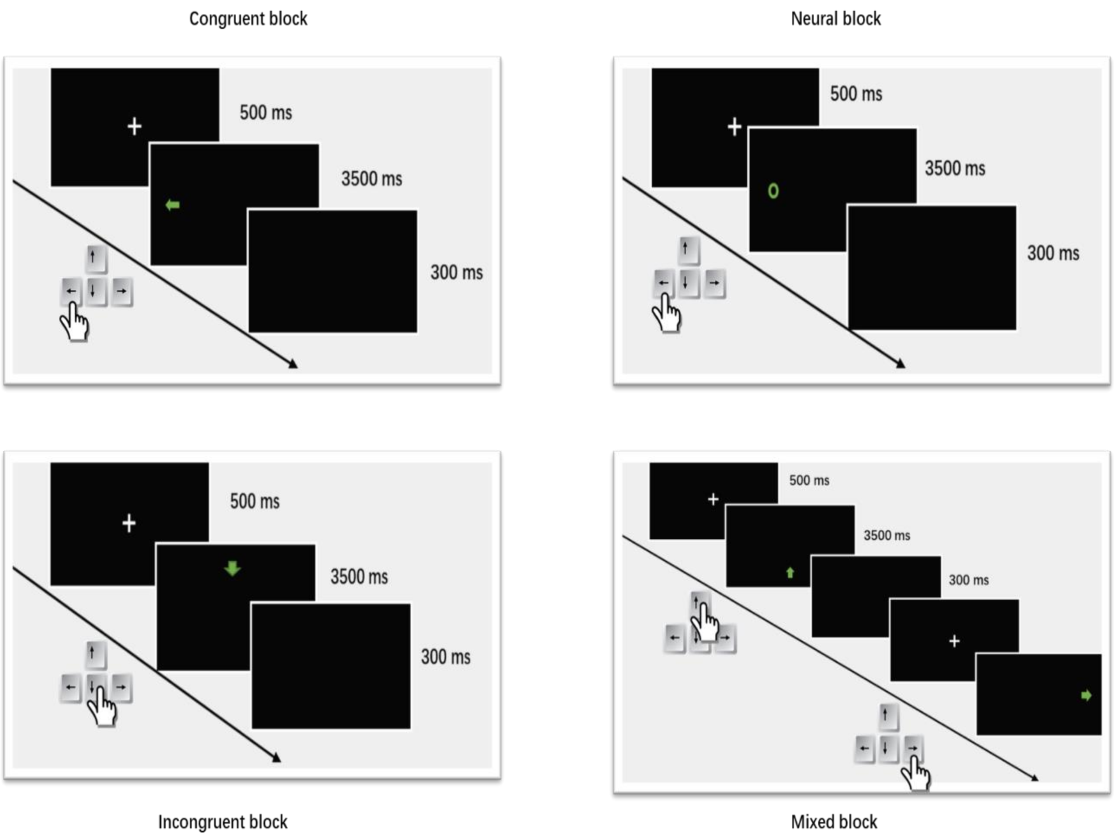

Figure 6.8 General procedure and presentation of each block of the spatial Stroop task

Colour-Shape switching task

The colour-shape switching task used in this study was based on Barac and Bialystok (2012), and was adapted from the task design in Yim and Bialystok's (2012) to measure participants' domain-general cognitive shifting abilities. Participants in this task saw three pictures presented on the screen at a time. Two target pictures of orange rabbit and green duck presented at the top of the screen while one stimulus picture, either orange duck or green rabbit, appeared below the two targets. Participants were instructed to match the stimulus picture (orange duck or green rabbit) to one of the target pictures (orange rabbit and green duck), according to a cue that appeared together with the stimulus picture. An icon of jigsaw is the cue for matching the stimulus picture with the target pictures according to its shape, while a palette icon indicates to match stimulus with targets based on its colour. If the stimulus matches with the left side target picture, participants should press left arrow on their keyboard to respond, otherwise, they should press the right arrow.

Each trial start with a 250ms fixation cross at the centre of screen, followed by the pictures stimuli that remained for 3000ms on the screen or until a response was made. Following the response, the next trial started after a delay of 1000ms. Figure 6.9 below showed the procedure of this nonverbal cognitive shifting task, and illustrated the stimulus and target pictures in each trial.

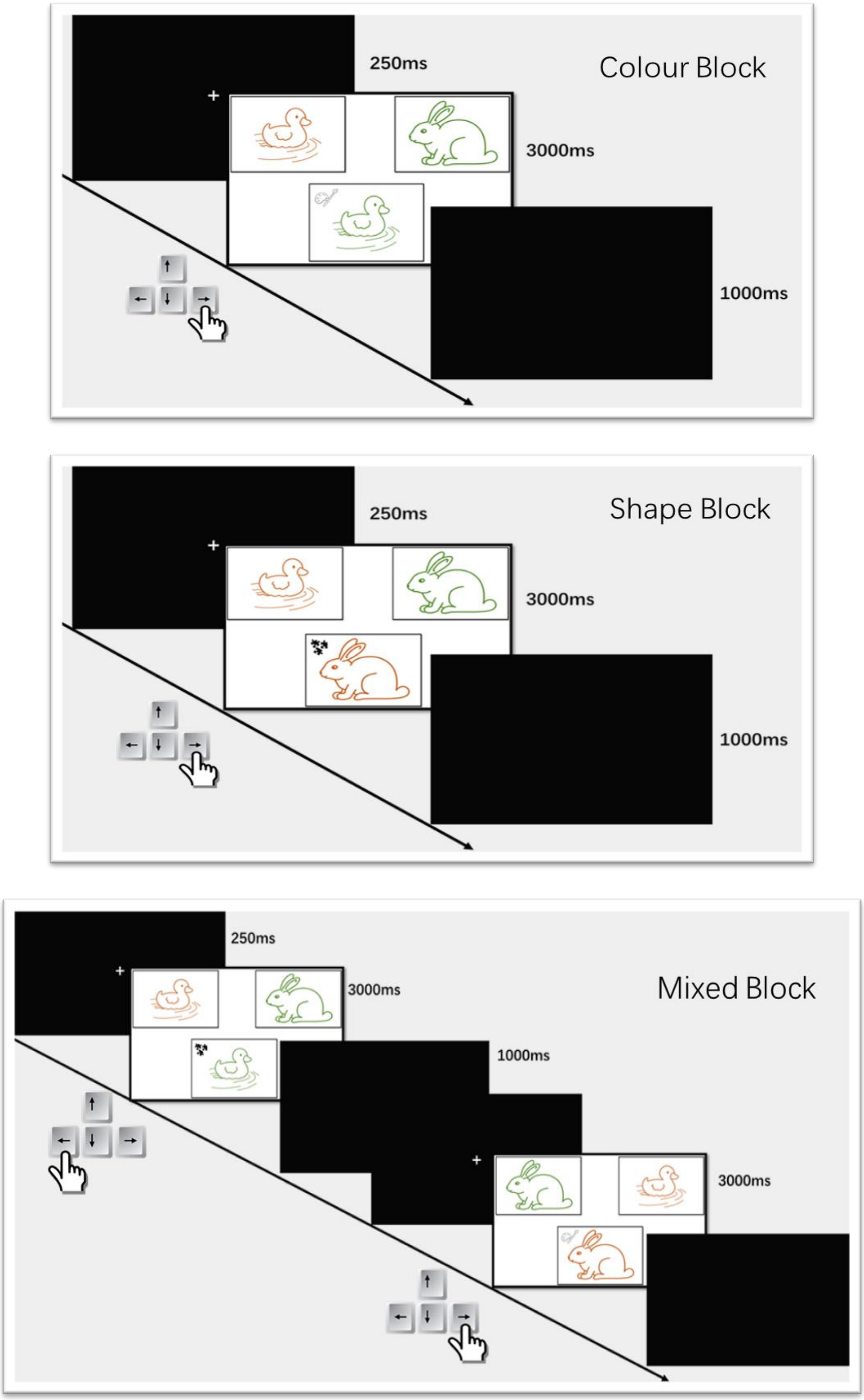

Figure 6.9 Illustrations of trial design and procedure of the colour-shape switching task

There were 200 trials across two single task blocks (i.e., 25 colour trials and 25 shape trials) and three mixed blocks (50 trials each). In the single-task blocks, participants were required to match stimulus and target pictures consistently based on either the criterion of shape or colour. However, in the mixed blocks, successive trials could either have the same matching criterion (repeated trials) or different matching criteria (switch trials). The proportion of switch and repeated trials in each mixed block was 1:1. The formal blocks, after the practice block with 8 trials, were administered in a fixed order starting with the two single-task blocks and continuing with the three mixed blocks. The order of single-task blocks and the order of three mixed blocks were counterbalanced across participants. Participants are instructed to perform as quickly and accurately as possible throughout this task. Both their RTs and response accuracy in this task were measured.

Procedure

After providing informed consent, all participants were suggested to take part in this study remotely in their own quiet rooms. Before online tasks started, participants were instructed to complete questionnaires, BSWQ (Rodriguez-Fornells et al., 2012) and the code-switching and interactional context questionnaire (Hartanto & Yang, 2016), to measure their habitual bilingual language use experience. The online LEAP-Q (Marian et al., 2007) and LexTALE (Lemhöfer & Broersma, 2012) test followed to measure participants' language proficiency and dominance levels. After they completed these measures on their language history and bilingual experience, they were invited to a one-to-one online meeting with the researcher, in which two spontaneous language production tasks, the naturalistic conversation task and the story narration task, were conducted. Afterwards, links for the three online behavioural tasks, verbal Stroop task, spatial Stroop task and the colour-shape switching task, were emailed to participants for they could complete these tasks remotely. They were allowed to completed these behavioural tasks in their own pace and preferred order, but these behavioural tasks were always completed after participants finished the two language production tasks in the online meeting.

6.3.3 Statistics

Data collected

For each participant, output from the naturalistic conversation task was obtained from the four conditions: 5-minute monologue (free to use both languages), answering question asked in Mandarin, answering question asked in English and answering question asked with code-switching. In the story narration task, participants' language output from English-only, Chinese-only and code-switching conditions were obtained. The audio-recordings of these language production tasks and transcriptions were analysed using the Praat phonetic software (version 6.1.14, Boersma & Weenink, 2018). An internal *textgrid* (*silences*) script in the software allows slicing each audio into "*sounding*" segments (speeches) and "*silent*" segments (pauses). Noticeably, pauses in participants' language productions comprised both silent pauses and filled pauses which contained a series of meaningless lexicalisations like 'uh', 'eh' or 'um'. As these filled pauses were prone to be recognised as sounding segments by Praat, all sounding segments were also manually checked to make sure all pauses were correctly and appropriately counted. Any kind of pauses over 250ms were identified for pause frequency calculations. Therefore, for each participant, pause frequency was calculated by measuring the total number of pauses (i.e., silent and filled pauses) during language production in both the conversation and narration task. However, the number of pauses in participants' language production was associated with the total length of the speech each participant produced. Participants producing longer speeches in these two tasks are supposed to have higher number of pauses (Zantout, 2019). Therefore, ratios of their pause frequency in these two tasks were computed as index to analyses participants' pauses and control the extraneous effects of participants' inconsistent speech lengths on pauses frequency. The computation of pause frequency ratio followed Zantout's (2019:272) study, that is, the total number of pauses over 250ms for each participant was divided by the total speaking duration of his/her in a speech sample measured by seconds. The speaking duration in one speech sample was also regarded as the total phonation duration, which is computed as participants' total speech length minuses their total duration of pauses in the speech. The lower pause frequency ratio indicated that there were few pauses throughout participant's speech, while a higher ratio indicated that participants produced relatively higher number of pauses during the overall speech. Pause frequency ratios were computed in both participants' language production during the naturalistic conversation task and their speeches in the story narration task, and these ratios were then used in all subsequent analyses.

Besides, the duration of each pause was also identified through Praat and measured. The total duration of pauses in every participant's speech was calculated. In the two language production tasks, every participant's mean pause duration was also computed by dividing the total length of pauses in the speech by the total number of pauses one has produced in the speech. For example, if an individual produced pauses for 4 times, 800ms, 670ms, 1200ms, and 900ms, in a speech, then the mean pause duration was computed as (800+650+1200+900)/4 =887.5ms.

In addition to calculating pauses incurred in participants' speech, code-switching produced by participants in these two tasks were also measured and computed. Audio for every participant's speech in the two tasks was transcribed for counting the total number of utterances he/she has produced in the speech. Then, the numbers of utterances containing intersentential switch and intrasentential switching were calculated respectively as the frequency of their intersential/intrasentential switching in the conversation task. The number of utterances which contains only English or Chinese were also calculated as the frequency of English/Chinese in participants' speech sample. However, participants were only allowed to freely switch between languages in narrating the story of three little pigs, therefore, code-switching frequency in their speeches was only calculated in this story narration. Consistently, their frequency of producing monolingual utterances (i.e., Chinese or English) was also measured in the story narration task.

Noticeably, participants' frequency of code-switching is associated with the entire number of utterances they have produced in these tasks. To controlling the bias in code-switching frequency calculation which might arose due to the variety in utterances number across participants, the percentages of code-switching and monolingual utterances for every participant in each speech sample were computed. For example, the number of intersentential switching utterances divided by the total number of utterances in the conversation task is the participant's percentage of intersentenial switching. Same computation also applies to percentages of monolingual utterances in speech samples. Percentages of code-switching and monolingual utterances in the monologue part, the three question answering parts and the overall conversation during the naturalistic conversation task, and these percentages in the bilingual story narration session were collected for subsequent analyses.

Table 6.21below showed the variables in the two spontaneous language production tasks which are measured through Praat, and relevant indexes computed for subsequent analyses.

Table 6.21 Data collected in the spontaneous language production tasks

	Description
A. Pauses data	
Pause frequency	Total number of pauses over 250ms
Pause duration	Length of each pause in milliseconds
Total pause duration	Total length of all pauses in a speech in seconds
Mean pause duration	Total duration of all pauses over 250ms divided by the total number of pauses in a given speech sample
Total Speech duration	Overall length (including pauses) of the entire language production.
Total phonation duration	Total speaking time in a speech sample, calculated as total speech duration – total pause duration
Pause frequency ratio	Total number of pauses divided by the total phonation duration in a speech sample
B. Code-switching data	
Intersentential switching frequency	Total number of utterances containing intersentential switching in the speech.
Intrasentential switching frequency	Total number of utterances containing intrasentential switching in the speech.
English frequency	Total number of English monolingual utterances in the speech.
Chinese frequency	Total number of Chinese monolingual utterances in the speech.
Total utterances	Total number of utterances in a speech sample
Percentage of intersentential switching	Total number of intersentential switching utterances divided by total number of utterances in a speech sample
Percentage of intrasentential switching	Total number of intrasentential switching utterances divided by total number of utterances in a speech sample
Percentage of English utterances	Total number of English monolingual utterances divided by total number of utterances in a speech sample

Percentage of Chinese utterances	Total number of Chinese monolingual utterances divided by total number of utterances in a speech sample

Participants' reaction time (RTs) measured in milliseconds and their response accuracy in the three cognitive tasks were collected and calculated for subsequent analyses. In addition, the self-reported data which was collected from participants' responses in the bilingual language experience-related questionnaires was also included in subsequent correlational and regression analyses.

Data preparation and analysis

As mentioned above, a manual check of the number of pauses was conducted in data processing to ensure the correct number of pauses was reported and to adjust any overcounting pauses identified automatically by Praat. Besides including both filled and silent pauses into total number of pauses counting, some pauses which were not caused by difficulties in speech productions were removed. In the story narration task, pauses which were incurred when participants transferred their gazes from one picture to another or scrolled down pictures were excluded from analyses. These pauses varied in duration but were stemmed from processing visual information rather than disfluency or difficulties in planning their languages during story narrations. Researcher can notice these pauses through observe participants' facial expressions and eye gazing during the story narration session. Furthermore, since the naturalistic conversation task asked participants to recall the activities they did in last week, the silences or any meaningless filled lexicalisations produced by participants before their speaking started were marked as “recalling period”, and removed from data collection.

In the verbal Stroop task, RTs and response accuracy were collected for a total of 4,920 trials (41 participants, 24 trials in a neutral block, 48 trials in two single blocks and 48 trials in a mixed block). 17 missing values (0.35% of trials) were excluded from subsequent data analyses. Any values in RTs below 200ms and over 3500ms were also removed from the dataset. Besides, any values above 2.5 standard deviations of participants’ individual mean RTs (n =153) were also excluded. Therefore, after this wave of data pre-processing, 4,750 data points were left. Since only corrected responded trials were analysed in discussing participants’ RTs in this task, values for incorrect responses (n = 1002) were removed, leaving 3,816 trials for subsequent participants’ RTs analyses.

Similarly, participants’ responses to a total of 4,920 trials (41 participants, 120 trials per person) in the Spatial Stroop task were stored. There were no missing data observed in the dataset. Three values below 200ms were removed, and 13 values above 2.5 standard deviations of participants’ individual mean RTs were also excluded from further analyses. Finally, 4,676 data points left for participants’ RTs analyses after removing 127 trials which were wrongly responded.

In total, 7,872 responses (41 participants, 2 single task blocks and 3 mixed blocks) in the colour-shape switching task were collected. Firstly, 99 missing values (1.26%) were removed from the dataset. The following responses were also excluded: correct responses with RTs below 200ms (n=2), and values above 2.5 standard deviations of participants' individual mean RTs (n =211). Incorrect responded trials (n =493) were also excluded from participants' RTs analyses, finally leaving 7,067 trials included.

Linear mixed effect models in R (Version 4.0.2; R Studio Team, 2020) were used to analyse participants' task performance in the three cognitive tasks. For the analysis of RTs, a mixed model was run, using the lmer function as implemented in the lme4 package for R (Version, 1.1 - 26; Bates et al., 2015). Participants' response accuracy in these tasks was analysed through the generalised linear mixed effects model with a logistic link function. The model was run with a glmer function as implemented in the lme4 package for R (1.1.21; Bates et al., 2015). The random effect of subject was included in the analyses to account for variability across participants. Reported *p*-values were calculated based on Satterthwaite's method as implemented in the lmerTest package in R (Kuznetsova et al., 2017).

The interactions between participants' language production and their domain-general cognitive control performance were also investigated in this study. To address this question, associations among participants' cognitive task performance and their z-scored bilingual language use habits (collected from self-reported bilingual language experience questionnaires), language entropy in four different contexts (i.e., home, work, school and social) as well as their language production task performance were analysed through linear mixed effect models.

6.3.4 Results

The following sections present results for both spontaneous language production tasks and cognitive tasks respectively. Results of the linear mixed effect models among the interactions between bilingual language use and cognitive control performance are also followed.

Performance in the spontaneous language production task

Pauses and code-switching are two focused aspects in participants' language production. Their mean pause duration, pause frequency ratio and percentages of code-switching in naturalistic conversation task and story narration task were analysed. Descriptives of participants' performance in the naturalistic conversation task and story narration task are presented in Table 6.22 below.

Table 6.22 Descriptives of pauses and code-switching information among bilinguals' speech samples in the two language production tasks

Naturalistic Conversation Task	**Mean**	**SD**
Pause frequency ratios		
in monologue part	0.06	0.04
in answering Chinese question	0.05	0.05
in answering English question	0.06	0.06
in answering mixed-language question	0.05	0.05
in entire conversation	0.05	0.04
Mean pause duration (in seconds)		
in monologue part	1.28	0.51
in answering Chinese question	0.74	0.60
in answering English question	1.01	0.91
in answering mixed-language question	0.90	0.69
in entire conversation	1.37	0.92
Percentages of code-switching		
Intersentential switching in conversation	0.04	0.05
Intrasentential switching in conversation	0.30	0.14
English in conversation	0.15	0.20
Chinese in conversation	0.51	0.21
Intersentential switching in answering Chinese question	0.04	0.12
Intrasentential switching in answering Chinese question	0.23	0.20
English in answering Chinese question	0.06	0.17
Chinese in answering Chinese question	0.68	0.27
Intersentential switching in answering English question	0.06	0.11
Intrasentential switching in answering English question	0.23	0.29
English in answering English question	0.29	0.39
Chinese in answering English question	0.42	0.36
Intersentential switching in answering mixed-language question	0.03	0.07
Intrasentential switching in answering mixed-language question	0.36	0.25
English in answering mixed-language question	0.10	0.26
Chinese in answering mixed-language question	0.51	0.29
Story Narration Task	**Mean**	**SD**
Pause frequency ratios		
English narration of Hua Mulan story	0.19	0.05
Chinese narration of Hua Mulan story	0.13	0.06
English narration of the little match girl story	0.19	0.05
Chinese narration of the little match girl story	0.13	0.05
Bilingual narration of three little pigs' story	0.14	0.06
Mean pause duration (in seconds)		

English narration of Hua Mulan story	1.62	0.58
Chinese narration of Hua Mulan story	1.51	0.36
English narration of the little match girl story	1.56	0.35
Chinese narration of the little match girl story	1.47	0.50
Bilingual narration of three little pigs' story	1.50	0.40
Percentages of code-switching		
Intersentential switching in bilingual narration	0.06	0.08
Intrasentential switching in bilingual narration	0.15	0.14
English in bilingual narration	0.14	0.28
Chinese in bilingual narration	0.65	0.32

Pause frequency analysis

In order to analyse participants' pauses produced in the naturalistic conversation task and compare their pause frequency in bilingual conversation and bilingual story narration, ANOVAs were conducted to analyses participants' pause frequency ratios in the two tasks.

The results showed that participants' pause frequency in bilingual speeches significantly varied across the conversation and narration conditions, F (5, 240) = 15.99, $p < .001$, $\eta^2 = .25$. Table 6.23 summarised the ANOVA post hoc contrasts of pause frequency ratio in bilingual's narrative and conversative speeches. Specifically, pause frequency ratio in bilingual narration was significantly higher as compared to bilinguals' speeches in the conversation task (t = 7.16, Cohen's d = 1.60, p <.001). Moreover, participants produced more pauses and showed relatively higher level of disfluency during bilingual narration than answering different questions asked by the researcher in the conversation task (p <.001).

Table 6.23 Summary of ANOVA post hoc contrasts of pause frequency ratio in bilingual narration and conversation tasks

		t-value	Cohen's *d*	p_{bonf}
Bilingual narration	CN question answers	6.98	1.39	<.001
	EN question answers	6.12	1.13	<.001
	Mixed-language question answers	7.14	1.49	<.001
	Monologue speeches	6.91	1.49	<.001

However, participants' frequency of pauses produced in the naturalistic conversation task was comparable between the monologue part and three question answering parts, $F(4, 200) = 15.99$, $p = .81$, $\eta^2 = .01$ (see Figure 6.10 below).

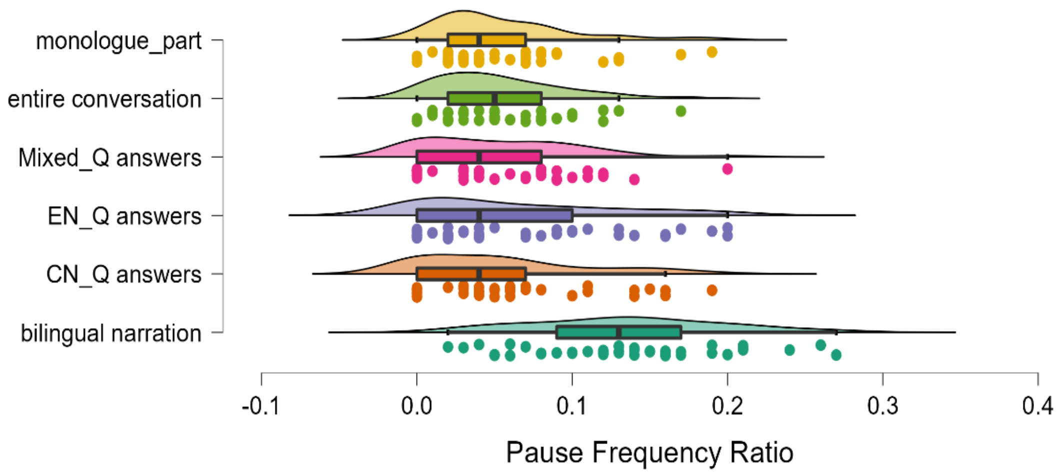

Figure 6.10 Pause frequency ratio comparison across bilingual narration and conversational speeches

These results, in general, reflected that different language production settings (i.e., un-cued and semi-cued bilingual production) are influential to bilingual individuals' speech production fluency. Since participants were allowed to use two languages in their habitual ways without giving them any cues to produce specific patterns of bilingual utterances during the conversation, they were prone to perform more fluently in their speeches. In addition, participants' comparable pause frequency ratios in speeches across answering the three different types of questions further reflected that the interlocutors, rather than the language used by the interlocutors, could be an essential factor in affecting bilinguals' language production and fluency of their speeches. As these three questions were asked by a Chinese-English bilingual speaker, these bilingual participants were not necessary to use only one language in their speech to answer questions asked monolingually. Therefore, the bilingual interlocutor shared the same repertoire with these participants made their language selection and speech production more flexible, which further ensured their equal fluency in answering the three different questions. In addition, more cognitive loads required to process visual information in bilingual narrations could be a potential reason that led to participants' disfluency in speeches.

Apart from analysing pause frequency across two tasks, participants pause frequency within the story narration task was also analysed through ANOVAs (see Figure 6.11 below).

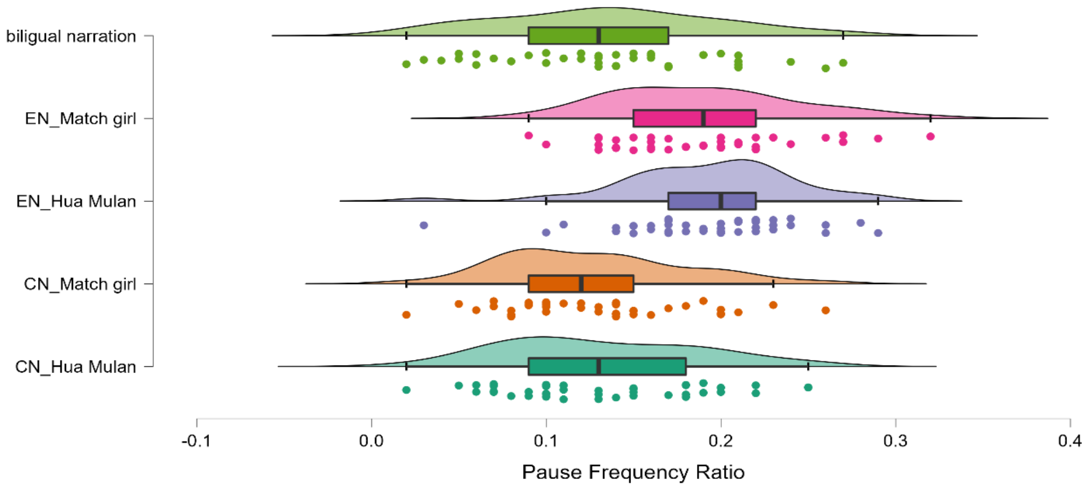

Figure 6.11 Pause frequency ratio comparison within different narrative speeches

Significant differences in pause frequency ratios across participants' speeches of narrating stories monolingually (i.e., Chinese-only and English-only) and bilingually were found, F (4, 200) = 14.38, p < .001, η^2 =.22. As expected, participants' pause frequency was found to associate with their language proficiency levels. They were prone to pause more frequently when they were narrating the story in English as compared to narrating the same story in Chinese. Specifically, participants produced significantly less pauses in retelling the story of Hua Mulan in Chinese as compared to retelling this story in English (t = -4.97, Cohen's d = -1.13, p <.001). Same situation was also found in narrating the story of the little match girl, that is, participants' narrations of this story in Chinese contains less pauses than their narrations in English (t = -5.11, Cohen's d = -1.18, p <.001).

Even in different story narrations, participants performed relatively higher fluency with less pauses during narrating the story in Chinese than in English. Although the story of Hua Mulan and the little match girl have different cultural background, these participants were still more proficient in narrating either of the stories in Chinese than in English. Their Chinese narrations on the story of Hua Mulan had significantly smaller pause frequency ratios than their English narrations of the little match girl story (t = -4.71, Cohen's d = -1.04, p <.001). Similarly, narrating the little match girl story in Chinese seemed to be easier and less pause-caused for them as compared to telling the Hua Mulan story in English (t = -5.37, Cohen's d = -1.28, p <.001).

Interestingly, when these bilingual participants were allowed to use both of their languages to retell a story based a set of given pictures, they produced less pauses during their narrations as compared to retelling stories (either the story of Hua Mulan or the little match girl) in English. However, pause frequency ratios in their bilingual narrations were comparable with the ratios in their Chinese narrations. Table below summarised the contrast results of pause frequency ratios between participants' bilingual narrations and monolingual narrations.

Table 6.24 Summary of ANOVA post hoc contrasts of pause frequency ratio in bilingual and monolingual story narrations

		t-value	**Cohen's *d***	p_{bonf}
EN_Hua Mulan	Bilingual narration	4.67	1.01	<.001
EN_Match girl	Bilingual narration	4.41	0.93	<.001
CN_Hua Mulan	Bilingual narration	-0.30	-0.06	1.00
CN_Match girl	Bilingual narration	-0.70	-0.15	1.00

The results revealed that language proficiency plays an essential role in shaping bilingual speakers' language production; besides, the assumed effects of cultural background in facilitating their language production were not observed in the story narration task.

Pause Duration Analysis

Mean pause duration in participants' speeches in naturalistic conversation and story narration tsks were also analysed. Results showed that mean pause duration in participants' speeches varied across the two tasks, $F(5, 240) = 7.45$, $p < .001$, $\eta^2 = .13$. The significant differences in pause duration mainly laid between speeches in bilingual narration and speeches for three questions' answers in the conversation task. Specifically, longer duration of mean pauses produced in participants' bilingual narration than in their speeches of answering Chinese question ($t = 4.97$, Cohen's $d = 1.51$, $p < .001$), English question ($t = 3.23$, Cohen's $d = 0.71$, $p = .02$) as well as answering questions asked with two languages mixed-up ($t = 3.93$, Cohen's $d = 1.07$, $p = .002$). However, participants' mean pause duration did not differ across their speeches of answering three different questions. Furthermore, in participants' speeches for bilingual narration and conversational monologue, they performed comparable duration of pauses on average ($t = 1.44$, Cohen's $d = 0.48$, $p = 1.00$).

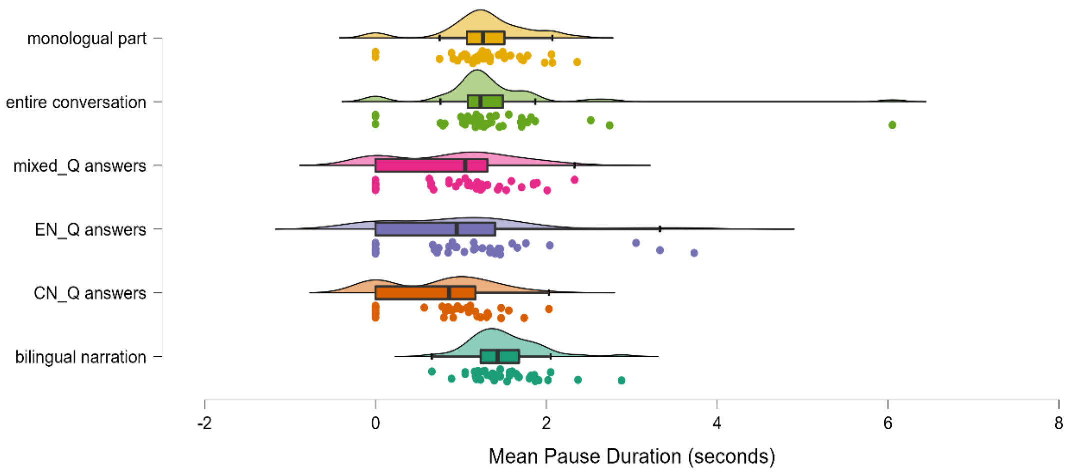

Figure 6.12 Comparison of mean pause duration in conversational speeches and bilingual narration

In order to analyse the differences in mean pause duration across participants in the story narration task, ANOVAs were conducted to compare their speeches for monolingual and bilingual story narrations (see Figure 6.13 below). However, there was no significant differences in their mean pause duration across their different types of story narrations in this task, F (4, 200) = 0.69, p = .60, η^2 =.01. It seemed that they produced pauses in similar length on average, no matter they were required to retelling the story in Chinese/English monolingually or narrating the story with language switching.

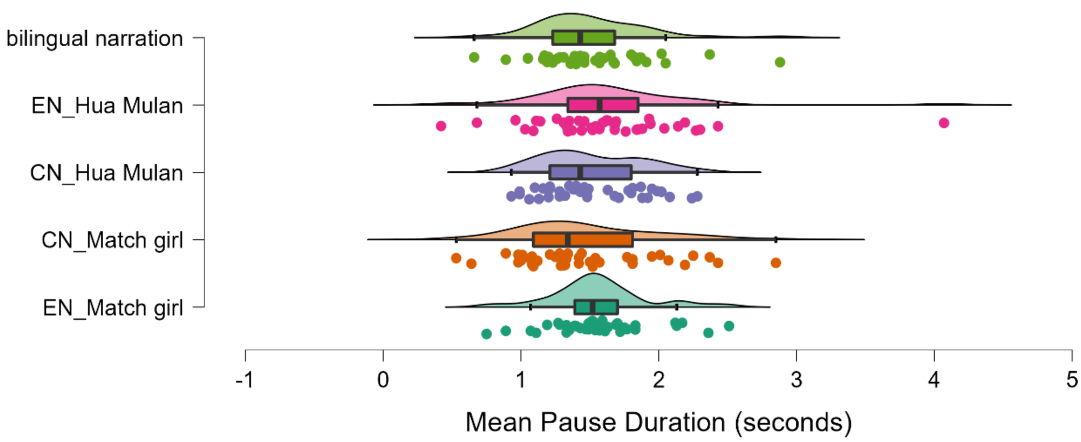

Figure 6.13 Comparison of mean pause duration in different story narrations.

Code-switching frequency analysis

Participants' frequency of different type of code-switching in their conversational speeches and bilingual narrations were analysed and compared. In general, there was a significant difference in participants' percentages of code-switching frequency across their different speech samples in conversation and bilingual narration, $F\ (19, 800) = 33.58$, $p < .001$, $\eta^2 = .44$. Table 7 below summarized the contrasts of participants' percentages of different type of utterances produced in each kind of speech sample across the two tasks.

It can find that participants produced significantly more Chinese monolingual utterances as compared to any other types of utterances (i.e., English monolingual, intersentential switching and intrasentential switching) in both their conversational speeches and bilingual narrations ($p < .001$). As for English monolingual utterances in speeches, participants had significantly less frequent use of English in answering all three different questions asked during the conversation task, as compared to producing English monolingual utterances in their conversational speeches ($p < .001$) or bilingual narrations ($p < .001$).

Besides, participants produced intrasentential switching more frequently than intersentential switching in their conversational speeches ($t = -5.12$, cohen's $d = -2.45$, $p < .001$); similar patterns were also found when comparing their intersentential switching frequency in bilingual narrations with their intrasentential switching in conversational speeches (t = -4.80, cohen's d = -2.12, $p < .001$), that is, participants were more prone to switch intrasententially during language production. Table 6.25 below summarised ANOVA post hoc contrasts of bilingual participants' code-switching frequency in narrative and conversative speeches.

Table 6.25 Summary of ANOVA post hoc contrasts of percentages of code-switching frequency in participants' conversational speeches and bilingual narrations.

		t-value	Cohen's *d*	p_{bonf}
CN freq_bilingual narration	EN freq_conversation	9.81	1.88	<.001
	interSw freq_conversation	11.94	2.69	<.001
	intraSw freq_conversation	6.81	1.41	<.001
	EN freq_bilingual narration	9.93	1.69	<.001
	interSw freq_ bilingual narration	11.61	2.57	<.001
	intraSw freq_ bilingual narration	9.72	2.02	<.001
CN freq_conversation	EN freq_conversation	7.13	1.77	<.001
	EN freq_bilingual narration	7.25	1.49	<.001
	interSw freq_conversation	9.25	3.14	<.001
	intraSw freq_conversation	4.13	1.18	.008
	interSw freq_ bilingual narration	8.93	2.91	<.001
	intraSw freq_ bilingual narration	7.03	2.01	<.001
EN freq_bilingual narration	CN freq_CN question answer	-10.49	-1.92	<.001
	CN freq_EN question answer	-5.50	-0.86	<.001
	CN freq_mixed language question answer	-7.23	-1.29	<.001
	intraSw freq_ mixed language question answer	-4.32	-0.83	.003
EN freq_conversation	CN freq_CN question answer	-10.37	-2.19	<.001
	CN freq_EN question answer	-5.38	-0.93	<.001
	CN freq_mixed language question answer	-7.11	-1.46	<.001

	intraSw freq_ mixed language question answer	-4.20	-0.95	.006
interSw freq_bilingual narration	intraSw freq_conversation	-4.80	-2.12	<.001
interSw freq_conversation	intraSw freq_conversation	-5.12	-2.45	<.001

The results reflected that the interlocutor in a communication is important in shaping these bilingual speakers' language production. Since the interlocutor and the speakers shared the same language repertoire, Chinese is intensively used for their communicative convenience. Besides, as these participants are dominantly proficient in Chinese, they are more prone to produce utterances containing with Chinese more frequently than English.

Performance in cognitive control tasks

RT(s) and Response accuracy in the verbal Stroop task

Participants' RTs and response accuracy in the verbal Stroop task were analysed through the linear mixed effect models. Table 6.26 below presents their performance across three different blocks in this task.

Table 6.26 Participants' RTs and response accuracy in the verbal Stroop task

		RTs (ms)		**Accuracy (%)**	
Block	**Trial**	**Mean**	**SD**	**Mean**	**SD**
Neural (Ne)	neural	823.53	135.24	94.97	11.59
Single	congruent	712.83	122.91	72.52	8.72
	incongruent	895.45	173.99	71.12	9.26
Mix	congruent	787.72	146.22	88.39	9.55
	incongruent	899.51	159.04	73.20	9.52

Results showed that participants' RTs varied across different blocks, F (1, 39.82) =11.55, p = .002. Besides, congruency also showed significant effects on participants' RTs in this task, F (1, 39.45) =111.76, p < .001. An interactive effect of block*congruency was also found to affect participants' RTs, F (1, 37.13) =6.65, p = .01. Figure 6.14 below illustrated participants' RTs for congruent and incongruent trials across different blocks.

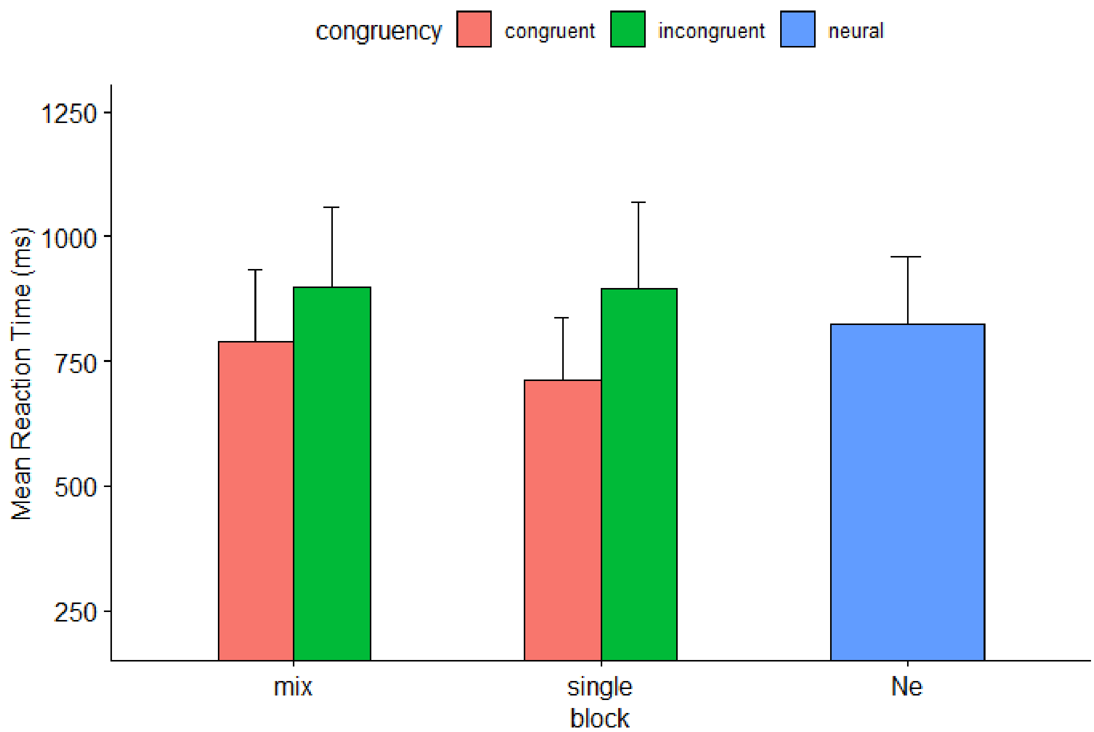

Figure 6.14 Mean RTs differences across single-task, mix-task and neural blocks

As expected, participants performed longer RTs for incongruent trials than congruent trials in the mix block (t (39.7) = -6.67, p <.0001); similar patterns were also found in single blocks, where participants performed faster in the congruent than incongruent block, t (39.6) = -9.45, p <.0001. moreover, participants also tended to perform faster for congruent trials in the mix block as compared to their performance in single incongruent block, t (39.5) = -6.07, *p* <.0001. Comparing participants' RTs in congruent trials across mix and single blocks, participants' congruent RTs in the mix block were significantly greater than in single block, *t* (39.6) = 4.92, *p* =.0001. However, incongruent RTs in both single and mix block were comparable without significant differences, *t* (39.6) = 0.71, *p* =1.00.

In the same vein, both congruency (β = -0.54, SE=0.08, *z*=-6.65, *p*<.0001) and block (β = -0.58, SE=0.08, *z* = -7.08 *p* <.0001) showed main effects on participants' response accuracy in this task. The interactive effects of congruency and block (β =0.98, SE=0.16, *z*=5.98, *p*<.0001) were also found to affect participants' response accuracy. Figure 6.15 below presented the verbal Stroop task response accuracy for congruent and incongruent trials across different blocks.

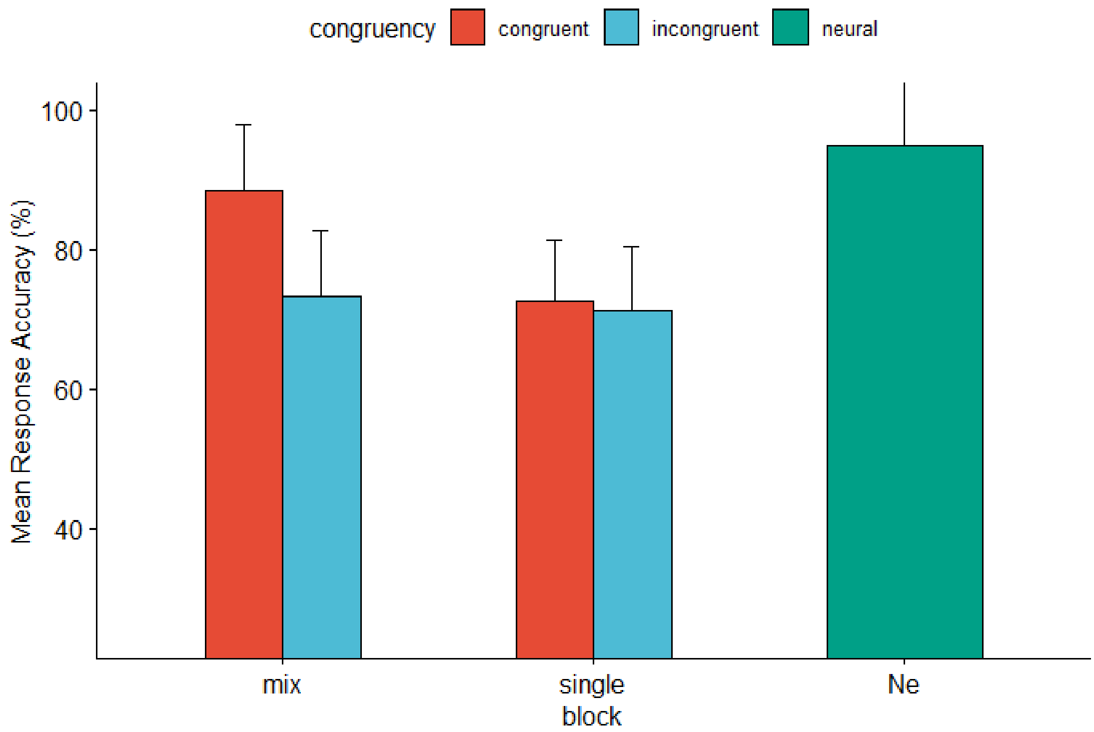

Figure 6.15 Mean response accuracy differences across mix-task, single-task and neural blocks

In the mix block, participants were prone to have higher response accuracy for congruent than incongruent trials (β =1.03, SE=0.13, z=8.19, p<.0001). Higher response accuracy for congruent trials in the mix block was found as compare to trials in single congruent block (β =1.07, SE=0.13, z=8.54, p<.0001) and single incongruent block (β =1.12, SE=0.13, z=8.92, p<.0001). However, participants' response accuracy for single congruent and incongruent blocks was comparable (β =0.06, SE=0.10, z=0.53, p =1.00). No significant differences in response accuracy for incongruent trials between mix and single blocks were also found (β = 0.09, SE = 0.11, z = 0.86, p =1.00). Although slightly more correct responses were found for congruent trials in the single block than incongruent trials in the mix block, there was no significantly statistical differences between them (β = -0.03, SE = 0.11, z = -0.33, p =1.00).

RT(s) and Response accuracy in the Spatial Stroop task

Participants' RTs and response accuracy in the spatial Stroop task were also analysed through the linear mixed models. Table 6.27 below showed their performance across different blocks in this task.

Table 6.27 Participants' RTs and response accuracy in the spatial Stroop task

		RTs (ms)		Accuracy (%)	
Block	**Trial**	**Mean**	**SD**	**Mean**	**SD**
Neural (Ne)	neural	465.88	90.93	99.49	1.38
Single	congruent	452.45	76.88	99.49	1.67
	incongruent	557.41	97.09	94.83	13.20
Mix	congruent	498.24	78.16	99.69	1.11
	incongruent	535.59	83.22	92.81	20.22

The linear mixed effect model showed that participants' RTs varied across blocks (F (1, 40.06) =4.23, p = .046) and also significantly differed based on congruency (F (1, 36.35) =159.02, p < .001.). A main effect of block*congruency was also found to affect participants' RTs in this task, F (1, 38.57) = 47.83, p < .001. Figure 6.16 Mean RTs differences across mix-task, single-task and neural blocks below showed RTs in incongruent and congruent trials across different block in the spatial Stroop task.

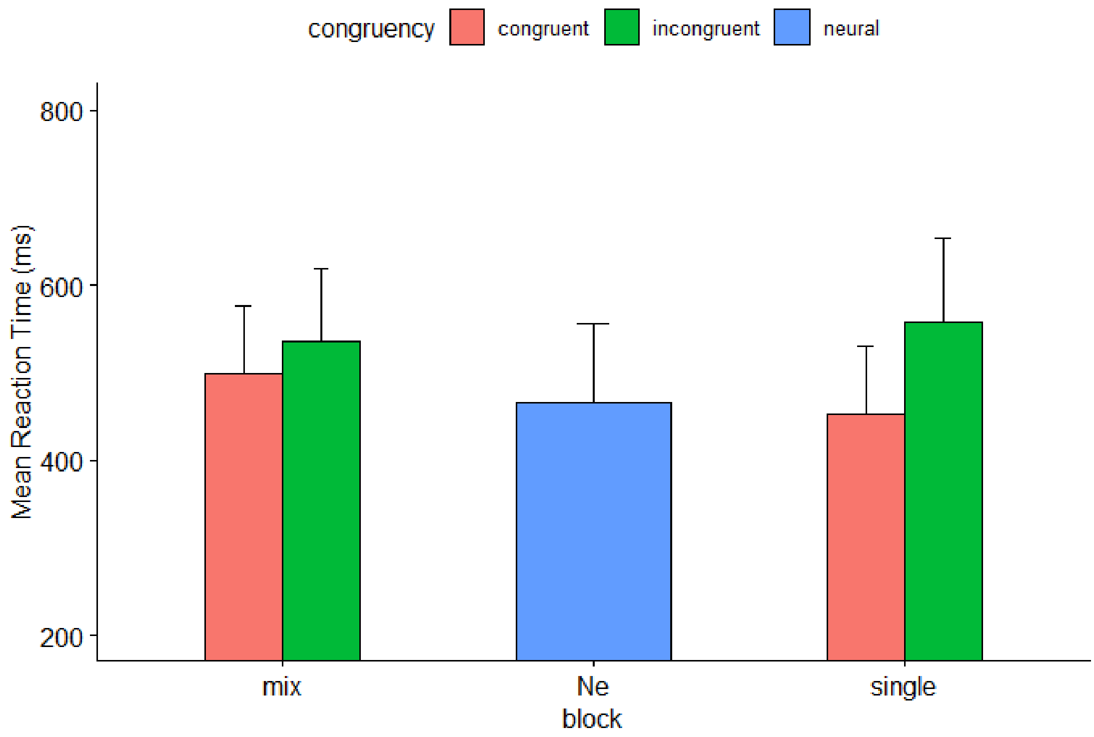

Figure 6.16 Mean RTs differences across mix-task, single-task and neural blocks

Pairwise contrasts showed that RTs for congruent trials in either single (*t* (39.7) = -11.09, *p* <.0001) or mix (*t* (39.3) = -5.71, *p* <.0001) block were significantly reduced than incongruent trials RTs in mix block. Moreover, participants’ RTs for single congruent block were significantly smaller than RTs for single incongruent block (*t* (39.9) = -11.86, *p* <.0001). Comparing participants’ performance between mix and single blocks, it found that participants’ performed more significantly smaller RTs for incongruent trials in the mix block than RTs in incongruent single block (*t* (39.4) = -3.36, *p* = .01). However, there were greater congruent RTs for mix block than congruent RTs for single block (*t* (40) = 6.42, *p* <.0001). Reduced RTs were also found for congruent trials in the mix block when comparing with incongruent RTs in the single block, *t* (39.8) = -7.46, *p* <.0001.

Figure 6.17 below showed participants' response accuracy across different blocks. GLMM analysis results revealed that participants' response accuracy might slightly differ between congruency (β =-2.87, SE=1.35, z=-2.13, p =.03). However, the followed pair-wise contrasts did not show significantly statistical differences on response accuracy for congruent and incongruent trials across blocks. That is, participants in general performed comparable levels in response accuracy for different trials and in different blocks.

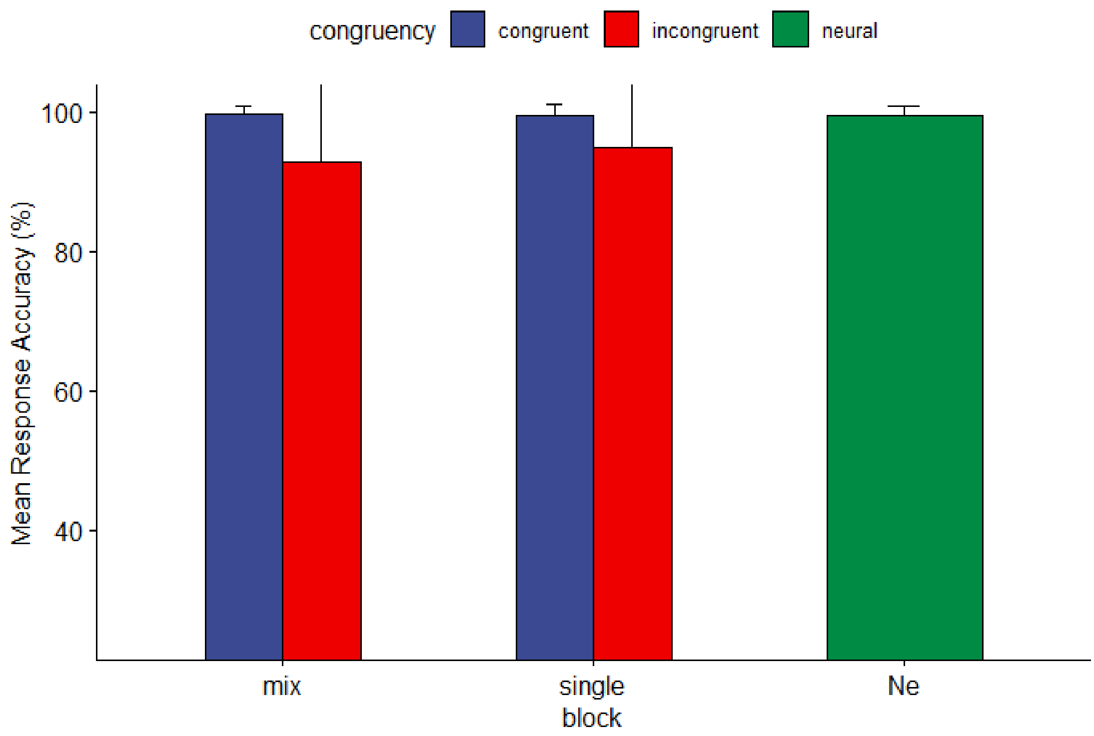

Figure 6.17 Mean response accuracy differences across mix-task, single-task and neural blocks

RT(s) and Response accuracy in the Colour-shape switching task

Participants' performance in the colour-shape switching task was analysed, and their switch and mixing costs in RTs and response accuracy were calculated for subsequent analyses. Table 6.28 below presented participants'

RTs and response accuracy, including their switch and mixing costs in both RTs and accuracy, in this task.

Table 6.28 Participants' RTs and response accuracy performance with switch and mixing costs calculated in the colour-shape switching task

		RTs (ms)		**Accuracy (%)**	
Block	**Trial**	**Mean**	**SD**	**Mean**	**SD**
Mix	Repeated	1218.70	191.00	90.68	11.31
	Switch	1225.70	193.65	91.87	11.60
Single	Single	1051.71	179.94	95.48	10.63
	Switch costs	7.00	85.40	2.27	2.46
	Mixing costs	167.00	181.57	8.43	11.23

Linear mixed effect model showed that participants' RTs on average significantly differed across mix and single blocks, F (1, 38.65) = 36.66, $p < .001$. However, no significant effect of trial types on their RTs in this task was found, F (1, 34.41) = 0.20, $p = .66$.

Subsequent pairwise contrasts showed that participants' RTs for single task trials were significantly smaller than RTs for repeated (t (40.0) = 6.05, $p <.0001$) and switch trials (t (40.0) = 5.96, $p <.0001$) in the mix task block. However, their switch and repeated trials' RTs were comparable within the mix task block, t (39.6) = -0.45, $p =1.00$. Figure below illustrated participants' mean RTs for three different trials.

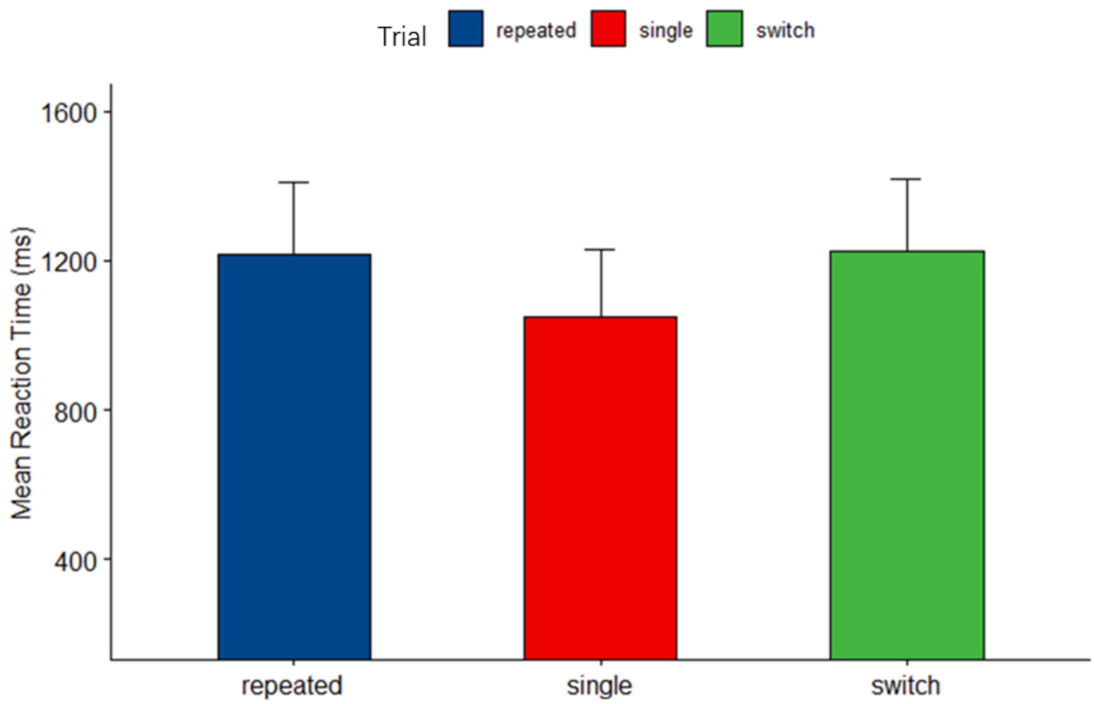

Figure 6.18 Participants' RTs differences in repeated, switch and single trials in the colour-shape switching task

Participants' response accuracy for different trials in mix and single task blocks were also analysed. The results showed that participants' response accuracy significantly differed across single and mix task blocks (β =0.89, SE=0.14, z=6.19, p <.001); while no significant within block differences were found in the mix task block (β =0.17, SE=0.11, z=1.56, p =.12). Specifically, participants' response accuracy was comparable between repeated and switch trials in the mix task block (β =-0.17, SE=0.11, z=-1.56, p =.36), but their response accuracy in repeated trials was smaller than in single task trials (β =-0.89, SE=0.14, z=-6.19, p <.0001). Similarly, participants were found to perform more accurately in the single task trials as compared to in the switch trials (β = 0.72, SE=0.15, z = 4.96, p <.0001). Figure 6.19 below showed participants' mean response accuracy in three different types of trials.

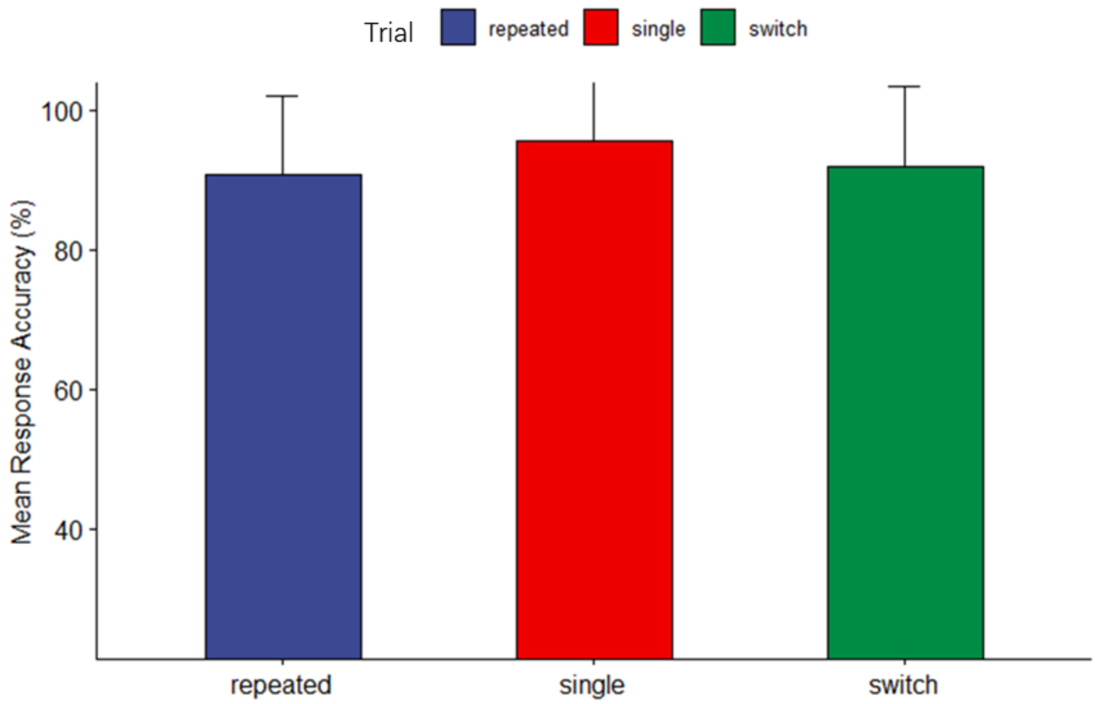

Figure 6.19 Participants' response accuracy differences in repeated, switch and single trials in the colour-shape switching task

Regression analyses of habitual bilingual language use on verbal and nonverbal cognitive control

The effects of habitual bilingual language use on participants' verbal and nonverbal cognitive control processes were analysed through the linear mixed effect regression models. Regression analyses were conducted on participants' verbal and nonverbal cognitive control task performance with predictors of their different language use experience factors, including L2 proficiency, L2 exposure, language entropy in different contexts, habitual language use contexts and language switching habits, and their different bilingual language production behaviours measured in the two spontaneous language production tasks. The following parts presented analyses results respectively.

Effects of habitual bilingual language use on participants' verbal Stroop task performance

A random intercept for subject was added to the linear mixed effect model for analysing RTs in the verbal Stroop task, and it reached convergence after a by-subject random slope for the additives of congruency and block was added. When z-scored English proficiency and habitual bilingual language use factors which were collected from questionnaires and language entropy computations, as well as factors related to participants' performance in the language production tasks: pause frequency ratios, code-switching frequency and pause duration, were fitted into the model, it reached best-fit convergence. Table 6.29 below showed the significant factors which influence participants' RTs in the verbal Stroop task (the whole best-fit model was show in Appendix VI).

Table 6.29 Fixed effects of the linear mixed effect model for RT (ms) in the verbal Stroop task with congruency*block and z-scored factors related to habitual bilingual language use and participants' spontaneous language production performance as reference levels. Formula: RT ~ 1 + block * congruency + *[factors related to habitual bilingual language use]* + *[spontaneous bilingual language production performance]* + (1 + congruency + block | subject)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	-1161.3893	8332.75	-0.14	
block (single task)	-119.24	36.85	-3.24	**.003**
congruency (incongruent)	138.99	163.67	0.85	
block: congruency	7.22	60.31	0.12	
single-language index	9.49	3.39	2.80	**.02**
intersentential switching index	-274.95	68.79	-4.00	**.003**
Bilingual narration P.ratio	3506.57	949.66	3.69	**.005**
En_MulanP.ratio	-2866.56	1085.99	-2.64	**.03**
Conversation P.ratio	-3689.72	1255.10	-2.94	**.02**
MeanEn_match_P.dur	-497.61	212.94	-2.34	**.04**
Congruency: Yrs_in_EN	-16.28	5.84	-2.79	**.009**
block: home_entropy	80.08	36.75	2.18	**.04**
block: congruency: School_entropy	149.89	69.56	2.16	**.03**

The model showed that participants' single-language index and intersentential switching index were significantly influential in their incongruent verbal Stroop trials RTs. The two factors were collected and computed from participants' responses to the code-switching and interactional context questionnaire (Hartanto & Yang, 2016). The single-language index measures the degree of bilingual individuals using two languages separately or immersing into single-language contexts; while higher values in intersentential switching index reflects bilinguals' higher frequency or more intensive degree of switching languages intersententially during daily communications. The two factors in the model reflected that participants who habitually use two languages together and switch intersententially, rather than frequently using languages separately in single-language contexts, were prone to perform reduced RTs for incongruent RTs in this task, showing their higher efficiency in verbal inhibitory control process. In addition, participants' smaller pause frequency ratio in bilingual story narrations was positively associated with their RTs for incongruent trials in this task. This indicated that participants who were more fluent in narrating a story bilingually were more efficient in verbal inhibitory control.

There was also an interactive effect of congruency*L2 exposure on participants' verbal inhibitory control performance. Longer L2 exposure duration was found to associate with bilinguals' overall reduced incongruent trials RTs. Besides higher efficiency in verbal inhibitory control of these habitual bilingual language co-users, this model further revealed that those habitual single-language bilingual users would perform better to trials in the single-task blocks during this task. Both the interactive effect of block * language entropy in home settings and the effect of block*congruency*language entropy in school settings were found to positively associate with participants' RTs in this task. That is, participants with lower language entropy values in home and school settings would have better performance in the single task blocks, especially in the incongruent single task block. Lower language entropy value indicates the language use in one context is highly predictable and two languages are less mixed in using.

Therefore, the model revealed that those individuals using English and Chinese separately in home and school settings were proficient in inhibiting and controlling verbal interferences in low cognitive monitoring conditions (i.e., single task blocks).

In addition to the above-mentioned factors, participants' spontaneous bilingual language production performance seemed also impose effects on their verbal inhibitory control process. The model showed that participants' pause ratio in conversational and Mulan story English narrative speeches, as well as their mean pause duration of little match girl story English narrative speeches, were all negatively correlated with their incongruent trials RTs. One potential reason could be that narrating a story using English only would be difficult for bilingual speakers, especially for these unbalanced Chinese-English bilingual individuals. Therefore, they all tended to produce more pauses and longer pausing durations during English story narrations. These factors in the model portrayed participants' language production pattern, and reflected its interactions with these bilingual individuals' verbal inhibitory control performance.

In sum, the results indicated the higher frequency of using two languages alternatively and increasing L2 exposure were able to facilitate bilingual participants' verbal inhibitory control efficiency. Furthermore, habitual single-language users could be more proficient in dealing with verbal interferences in low cognitive monitoring conditions, showing heightened proactive verbal cognitive control efficiency.

Participants' response accuracy in this task was analysed using a generalized linear mixed effects model. A random intercept for subject was included in the model. No random slopes were included in order to keep model convergence. The model converged and wad significantly improved after adding the factor of L2 environment exposure. Therefore, the final best-fitted model was shown in Table 6.30 below.

Table 6.30 Fixed effects of the general linear mixed effect model for response accuracy in the verbal Stroop task with congruency*block and L2 environment exposure as reference levels. Formula: response accuracy ~ 1 + block * congruency + Yrs_in_EN + (1|subject)

Variable	Estimate	*SE*	z-value	*Pr* (>|z|)
Response accuracy				
(Intercept)	1.53	0.12	13.03	**<.0001**
block (single task)	-0.58	0.08	-7.08	**<.0001**
congruency (incongruent)	-0.54	0.08	-6.65	**<.0001**
block: congruency	0.98	0.16	5.97	**<.0001**
Yrs_in_EN	-0.08	0.03	-2.73	**<.001**

Apart from what have been discussed above that participants' response accuracy varied across congruency and blocks, their duration in L2 environment was also influential to their response accuracy in this task. That is, longer duration of L2 exposure negatively associated with participants' response accuracy for incongruent verbal Stroop trials. It reflected that with increasing L2 environment duration, bilingual individuals' accuracy in dealing with verbal interference control might not be significantly improved although their efficiency in verbal cognitive control got enhanced (see model for RTs discussed above).

Effects of habitual bilingual language use on participants' spatial Stroop task performance

A random intercept for subject was added to the linear mixed effect model for analysing RTs in the verbal Stroop task, and it reached convergence after a by-subject random slope for the interactives of congruency and block was added. When z-scored English proficiency and habitual bilingual language use factors which were collected from questionnaires and language entropy computations, as well as pause frequency ratios and code-switching frequency in bilinguals' narrative and conversational speeches, were fitted into the model, it reached best-fit convergence. Table 6.31below showed the factors which significantly interact with participants' RTs in the spatial Stroop task (the whole best-fit model was show in Appendix VII).

Table 6.31 Fixed effects of the linear mixed effect model for RT (ms) in the spatial Stroop task with congruency*block and z-scored factors related to habitual bilingual language use and participants' spontaneous language production performance as reference levels. Formula: RT ~ 1 + block * congruency + *[factors related to habitual bilingual language use]* + *[spontaneous bilingual language production performance]* + (1 + congruency *block | subject)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	468.31	131.95	3.55	**.002**
block (single task)	-15.51	13.73	-1.12	
congruency (incongruent)	88.13	8.67	10.16	**<.0001**
block:congruency	70.14	10.26	6.84	**<.0001**
z_scored LexTALE score	-36.38	12.54	-2.90	**.008**
intersentential switching index	-83.30	21.71	-3.84	**.001**
Home_entropy	107.21	42.45	2.53	**.02**
Cn_match P.ratio	869.79	308.48	2.82	**.01**
Conversation P.ratio	-950.86	335.16	-2.84	**.009**
interSw_freq_bilingual narration	427.17	160.58	2.66	**.01**
IntraSw_freq_ bilingual narration	-222.55	90.93	-2.45	**.02**
Congruency:Yrs_in_EN	-5.49	1.98	-2.77	**.009**
block: home_entropy	54.38	13.99	3.89	**.0004**
block: School_entropy	-37.22	15.55	-2.39	**.02**

The model indicated that increasing L2 proficiency and intersentential switching index in daily communications interconnected with participants' reduced RTs for incongruent nonverbal Stroop trials, which reflected their facilitations on bilinguals' nonverbal inhibitory control efficiency. Moreover, the interactive effect of congruency and the duration of L2 exposure on participants' RTs was also revealed in this model. That is, participants with longer duration of immersing into L2 environment were more prone to perform more efficiently for trials requiring more cognitive loads (i.e., incongruent trials). This finding was consistent with the RTs model results in the verbal

Stroop task, reflecting that more intensive exposure into L2 environment was possible to modulate bilingual individuals' both verbal and nonverbal inhibitory control efficiency.

Similar to model for verbal Stroop task RTs, participants' language entropy in home and school settings were also found to paly influential roles in participants' nonverbal Stroop task performance. Specifically, participants' lower language entropy value in home settings associated with their smaller incongruent RTs, specifically in the single task block. Their higher language entropy values at school settings, however, were found to associate with their faster responses in the incongruent single task block. These findings illustrated that these bilingual participants habitually form their language use in different patterns based on interactional contexts, and they prefer to communicate in the single language at home settings while switch between languages when they are at school settings. In this vein, this model revealed that these bilinguals who habitually use languages in different patterns in distinct contexts would be more efficient in proactive nonverbal inhibitory control.

Interconnecting with participants spontaneous bilingual language production performance, the model showed that these unbalanced bilinguals with higher fluency in Chinese narrative speeches and higher intensity of intrasentential switching in bilingual story narrations tended to have improved incongruent RTs in this task. However, their higher intersentential switching frequency in narrative speeches and higher fluency in bilingual conversational speeches did not show significant modulations on their nonverbal inhibitory control performance.

To sum up, participants' nonverbal inhibitory control efficiency was found to be modulated by their higher L2 proficiency, intensive L2 exposure, and more frequently intersentential switching in daily communications. Moreover, habitual single-language users were found to be more proficient in inhibiting and controlling both verbal and nonverbal interferences in low cognitive monitoring conditions.

The interactions between participants' habitual language use and response accuracy in the spatial Stroop task was also analysed using a generalized linear mixed effects model. The model included a random intercept for subject. It reached convergence after a by-subject random slope for the interactives of congruency and block was added. The model failed to converge after adding factors related to bilingual habitual language use and participants' spontaneous bilingual language production performance. Therefore, with only an interactive congruency*block effect included the mode reached best-fitted convergence. Table 6.32 below showed this model for describing participants' response accuracy in the nonverbal inhibitory control task.

Table 6.32 Fixed effects of the generalized linear mixed effect model for response accuracy with congruency*block. Formula: accuracy ~ 1 + congruency*block + (1 + congruency*block | subject)

Variable	Estimate	*SE*	*z*-value	*Pr* (>|z|)
Accuracy				
(Intercept)	5.63	0.67	8.47	**<.0001**
block (single task)	-0.14	1.35	-0.10	.92
congruency (incongruent)	-2.87	1.35	-2.13	**.03**
block: congruency	-0.66	2.69	-0.25	.81

As the model revealed, participants' habitual language use patterns and their performance in spontanuous bilingual language production tasks did not affect their response accuracy in the nonverbal inhibitory control task. Besides, in general, they all performed with comparable accuracy levels across different blocks and congruency in this task.

Effects of habitual bilingual language use on participants' colour-shape switching task performance

Participants' switch and mixing costs of RTs in the colour-shape switching task were analysed in linear mixed effect models. Switch costs indicated the differences in RTs between repeated and switch trials within the mix task block; while mixing costs calculated the RTs differences between repeated trials in the mix task block and single trials in the single task block.

In constructing the linear mixed effect model, a random intercept for subject was added to the linear mixed effect model, and the model reached convergence after z-scored English proficiency and habitual bilingual language use factors and language entropy in different contexts were added. As including participants' performance in two bilingual spontaneous language production tasks did not lead to convergence and improvement of the model, factors related to their language production performance were removed from the model. Table 6.33 below showed the factors which significantly influence participants' switch and mixing costs of RTs in the colour-shape switching task (the whole best-fit model was show in

Appendix VIII).

Table 6.33 Fixed effects of the linear mixed effect model for mixing and switch costs in RT (ms) in the colour-shape switching task with interactives of RTs cost type and factors related to habitual bilingual language use and language entropy as reference levels. Formula: RT ~ 1 + costs type + z_scored_LexTALE test score*costs type + L2 AoA* costs type + *[factors related to habitual bilingual language use]* + Home_entropy * costs type + School_entropy * costs type + Work_entropy * costs type + social_entropy* costs type + (1 | subject)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	953.58	350.58	2.72	**.01**
Mixing costs ($RT_{repeated} – RT_{single}$)	-553.98	147.20	-3.76	**.0002**
Switch costs ($RT_{switch} – RT_{repeated}$)	-15.70	134.04	-0.12	.91
Switch costs: z_scored LexTALE score	24.37	10.78	2.26	**.02**
Mixing costs: L2 AoA	16.03	3.69	4.35	**<.0001**
Mixing costs: dual-language score	45.04	6.69	6.74	**<.0001**
Mixing costs: intersentential switching index	88.11	21.11	4.17	**<.0001**
Mixing costs: intrasentential switching index	-57.37	16.74	-3.43	**.0006**
Mixing costs: School_entropy	-143.41	54.12	-2.65	**.008**
Mixing costs: work_entropy	115.70	38.27	3.02	**.003**

The results showed that higher proficiency in L2 English did not associate with smaller switch costs of RTs in the nonverbal cognitive shifting task as expected; that is, L2 proficiency was not found to have significant facilitations on bilinguals’ nonverbal reactive control and cognitive shifting efficiency. However, the model indicated a significant relationship between less frequency of using and switching languages alternatively in the dual-language contexts during daily communication and smaller mixing costs of RTs. Besides, it further revealed that participants with smaller language entropy value in work setting but greater language entropy value in school settings were prone to have smaller mixing costs of RTs in this task. These results, one the one hand, reflected participants' different language use patterns in different interactional contexts; that is, they prefer to intensively produce utterances witch code-switching in one context (i.e., school) but produce monolingual utterances in another setting (i.e., during work). On the other hand, these bilinguals habituated to use languages separately in distinct contexts (i.e., single-language users) were prone to produce smaller mixing costs in this task, showing their heightened proactive inhibition efficiency. Noticeably, such association between habitual single-language using and enhanced proactive inhibition efficiency would be more salient among participants with relatively earlier L2 acquisition age.

Switch and mixing costs for response accuracy in this task were also analysed in the generalized linear mixed effect model. Since participants' habitual language use experience and performance in language production tasks did not improve the model, the final model keeps only participants' language entropy in different contexts as reference levels. A random intercept for subject was added, and the model reached best-fit convergence. Table 6.34 below showed the final model for describing participants switch and mixing costs of response accuracy in the colour-shape switching task.

Table 6.34 Fixed effects of the generalized linear mixed effect model for switch and mixing costs in response accuracy in the colour-shape switching task with interactives of trial type and language entropy in different contexts. Formula: accuracy ~ 1 + costs type + Home_entropy * costs type + Work_entropy * costs type + social_entropy * costs type + (1 | subject)

Variable	Estimate	*SE*	z-value	*Pr* (>|z|)
Accuracy (Intercept)	3.99	0.50	7.91	**<.0001**
Mixing costs ($RT_{repeated} - RT_{single}$)	-0.18	0.55	-0.33	.74
Switch costs ($RT_{switch} - RT_{repeated}$)	0.81	0.40	2.04	**.04**
Home_entropy	0.01	0.50	0.02	.98
Work_entropy	0.08	0.42	0.20	.84
Social_entropy	-1.00	0.55	-1.82	.07
Mixing costs: home_entropy	2.24	0.47	4.77	**<.0001**
Switch costs: home_entropy	-0.39	0.35	-1.12	.26
Mixing costs: work_entropy	1.95	0.40	4.88	**<.0001**
Switch costs: work_entropy	0.05	0.25	0.21	.83
Mixing costs: social_entropy	-0.73	0.57	-1.29	.20
Switch costs: social_entropy	-0.56	0.42	-1.33	.18

Consistent with above discussed results, the model for response accuracy model also showed that smaller language entropy values in both home and work settings were related to smaller mixing costs, reflecting the significant facilitatory effects of using two languages separately in different contexts on domain-general proactive inhibition efficiency. However, participants' switch costs of response accuracy did not show significant interactions neither with their habitual language use experience nor with their language entropy in different contexts.

6.3.5 Study discussion

In this study, individual differences of habitual bilingual language use and spontaneous bilingual language production patterns in affecting bilinguals' domain-general cognitive control performance were investigated. The association between participants' habitual language switching patterns and cognitive control was also examined according to predictions proposed in the ACH and CPM. Apart from assessing bilinguals' language experience and habitual use patterns through a series of self-reported questionnaires, including: BSWQ (Rodriguez-Fornells et al., 2012), LEAP-Q (Marian et al., 2007) and code-switching and interactional context questionnaire (Hartanto & Yang, 2016b), this current study further computed participants' language entropy (Gullifer & Titone, 2020) in four different contexts: school, work, social and home, to quantify how they habitually use two languages or produce code-switching in different communicative settings. Two spontaneous bilingual language production tasks (i.e., the naturalistic conversation task and the story narration task) were also used to observe and measure participants' bilingual language switching behaviours, to gain a fuller picture of their bilingual language control and production performance. To understand the interactions between bilingual language use habitus and their cognitive inhibition and shifting in both verbal and nonverbal control processes, a verbal and a spatial Stroop task were included in this study. A colour-shape switching task was used to assess participants' cognitive shifting performance.

Participants' performance in each spontaneous language production task was analysed to find out how their conversational and narrative speeches associated with their bilingual language experience. Besides, the relation of individual differences in bilingual habitual language use and cognitive control was examined. Also, the study discussed the effects of participants' spontaneous language production performance on cognitive control in regression analyses.

As expected, participants' speech fluency in the two spontaneous language production tasks was closely associated with their language proficiency levels. Furthermore, higher intersentential switching frequency in communications showed significant facilitatory effects on both participants' verbal and nonverbal inhibitory control efficiency, which supported the prediction proposed by the ACH and CPM. Besides, longer duration of L2 exposure also showed modulations on participants' inhibitory control efficiency.

In analysing the interactives between participants' bilingual language production and verbal control performance, regression models indicated that those who performed more fluently in bilingual narrative speeches and produced less pauses during bilingual narrations were prone to perform faster to incongruent verbal Stroop trials. This reflected the modulations of habitually higher frequency of co-using or switching between languages on bilingual individuals' verbal control efficiency.

As for the colour-shape switching task, the analysis indicated that bilingual individuals habitually using their languages in different patterns in distinct communicative contexts tended to produce smaller mixing costs of RTs, reflecting these habitually contextual code-switchers or single-language users' heightened strength in proactive inhibition. However, participants with higher

L2 proficiency were found to perform greater switch costs in this task. Moreover, the model also revealed that less frequency of intersentential switching and using languages in dual-language contexts was related to smaller RTs mixing costs; and such interaction was more salient among bilinguals with younger age of L2 acquisition. However, participants with higher L2 proficiency were found to perform greater RTs switch costs in this task.

Relationship between bilinguals' language use experience with verbal and nonverbal inhibitory control

In this current study, regression analyses pointed out that after accounting for bilinguals' L2 proficiency, participants reported intersentential switching frequency showed a significant tendency to predict bilingual individuals' higher efficiency in both verbal and nonverbal inhibitory control (smaller RTs for incongruent trials in these two tasks). Besides, participants who reported that they had smaller degree of engagement into single-language contexts in daily interactions were found to have higher efficiency in verbal inhibitory control processes. These findings provided evidence for the predictions proposed by the ACH and CPM that increasing engagement in dual-language contexts or higher frequency of switching between languages alternatively would enhance bilinguals' efficiency in controlling verbal and nonverbal interferences. Such results indicated that bilinguals' cognitive control abilities in bilingual language control depended on how they use their languages in different patterns (i.e., interchangeably or separately); and further reflected frequent co-using and switching between languages in daily communications trained bilinguals' efficiency not only in controlling verbal-related but nonverbal-related interferences (e.g., Beatty-Martínez et al., 2020; Lai & O'Brien, 2020).

Smaller degree of engagement in single-language contexts and higher frequency of intersentential switching indexed that bilingual individuals habitually use two languages in the same environment and switch between languages interchangeably at sentence levels during daily communications. During bilingual communications, bilinguals have to constantly monitor the co-activated languages, inhibit lexical resources from the non-target language, and switch to the target one interchangeably (Green, 1998; Green & Abutalebi, 2013). Bilinguals' such habitual practices of using languages in dual-language contexts that imposes them higher cognitive demands on constantly monitoring cross-linguistic competitions, inhibiting non-targeted lexical resources, and efficiently engaging and disengaging between two languages. Therefore, their heightened cognitive demands on managing the competition between co-activated languages in the same linguistic context trained up bilinguals' abilities of verbal interference control and language switching, and further exercised their efficiency in nonverbal interferences control.

Interestingly, regression analyses also pointed out the positive association between bilinguals' L2 exposure and their efficiency in both verbal and nonverbal inhibitory control processes. This finding addressed the effects of bilingualism experience on modulating bilinguals' cognitive control. As bilingualism is a dynamic continuum, multifaceted factors in bilingualism development are interconnected (Gullifer, Kousaie, Gilbert, Grant, Giroud, Coulter, …& Titone, 2021; Luk & Bialystok, 2013; Surrain & Luk, 2019). According to ICM (Green, 1998), the degree of language inhibition during bilingual language management is determined by the extent of activation of the languages. More intensive engagements in L2 environment conferred bilingual individuals' higher proficiency levels of L2, which further increased the extents of activation of L2 and linguistic competitions between L1 and L2. Therefore, intensive practices of managing the co-activated languages, controlling and inhibiting verbal interferences from relatively proficient languages further contributed to bilinguals' enhanced efficiency in interference and attentional control (Mishra, Hilchey, Singh & Klein, 2012; Singh & Kar, 2018). There are studies (e.g., Rosselli, Ardila, Lalwani & Vélez-Uribe, 2016; Singh & Mishra, 2012; Yow & Li, 2015) showed the positive associations between bilinguals' language proficiency and inhibitory control efficiency.

In addition to L2 proficiency, increasing engagements in L2 environment could also be interrelated with bilinguals' efficiency in bilingual language control. According to previous studies (e.g., Beatty-Martínez et al., 2020;

Woumans et al., 2016; Zhang, Diaz, Guo & Kroll, 2021), bilingual individuals who have intensively immersed in L2 environment could vary in how well they regulate their native languages (i.e., proactive inhibitory control on L1), and in more general cognitive control performance. Participants were living in English speaking countries at the time of this experiment, and they had to use English frequently in most of their daily activities, like attending seminars, communicating with colleagues or shopping. As more daily L2 exposure reduced these bilinguals' frequency of L1 use and lightened their L1 dominance, they would perform relatively easier to access to L2 and control L1 interferences during communicative interactions (Xie & Dong, 2021). Longer L2 exposure has equipped bilinguals' stronger abilities to control their native language to facilitate L2 processing, which further strengthened their efficiency in inhibitory control on L1. The current results reflected what Zhang et al. (2021) discussed, that bilinguals' L2 exposure modulated their proactive control efficiency, and such control efficiency goes beyond language domain.

Apart from communicating in English in majority of daily activities, participants in this current study also reported that they tended to rely on L1 in conversations with their Chinese-English bilingual peers or family members, which enriched their experience of switching between languages. Therefore, their heighted bilingual language management demands conferred in the more intensive L2 exposure further modulated their efficiency in inhibitory control, leading to their better performance in both incongruent verbal and spatial Stroop trials.

Noticeably, results of the model also showed a positive association between participants' language entropy in home and school contexts and their inhibitory control task performance. Specifically, bilinguals with smaller language entropy values at home and school contexts would perform more efficiently in the incongruent single task blocks in both verbal and spatial Stroop tasks. In fact, it illustrated that those habitual single-language context bilinguals were more expert in interference inhibition and control in the condition requiring relatively lower cognitive monitoring. This result was also in line with the predictions referred in the ACH, where habitually using languages in separate contexts would exercise bilinguals' abilities in goal maintenance and inhibitory control rather than task engagement and disengagement.

Relationship between bilinguals' spontaneous language production performance with verbal and nonverbal inhibitory control

In examining bilinguals' conversational and narrative speeches in the bilingual spontaneous language production tasks, a more nuanced relationship with cognitive control was revealed. With including factors related to bilingual language production performance, regression analyses indicated the associations between bilinguals' naturalistic language switching behaviours and their verbal and nonverbal inhibitory control performance. In this study, higher frequency of intrasentential switching in these Chinese-English bilinguals’ narrative speeches was found to interconnect with their nonverbal inhibitory control efficiency. Besides, higher fluency of narrating a story bilingually (i.e., less pauses frequency in their bilingual narrative speeches) were found to significantly predict these bilinguals’ verbal inhibitory control efficiency. The expected positive relationship between intersentential switching frequency in bilingual narrative speeches and bilinguals’ domain-general inhibitory control efficiency was not observed in the analyses.

In the spontaneous bilingual story narration, these bilingual individuals were able to produce language switching utterances voluntarily, without being cued, to complete telling a story in two languages. The patterns of their bilingual language use in the narrative speeches are internally driven, rather than cued by any external factors (de Bruin et al., 2018a; Lai & O’Brien, 2020b). Therefore, bilinguals choose the way to narrate the story or produce their code-switching utterances based on the accessibility of lexical items across two languages and for the ease of communications (de Bruin, Samuel & Duñabeitia, 2018). The current finding revealed that intersentential switching frequency in bilingual narrative speeches did not predict bilinguals’ outcomes in interference control and inhibition was contrary to the ACH (Green & Abutalebi, 2013) and CPM (Green & Li, 2014), which suggested frequent language alternations and switching in the dual-language contexts would benefit bilinguals' efficiency in salient cue detection and interference control. However, the finding was consistent with Hartanto and Yang's study (2019), in which they failed to find the modulations of dual-language context on bilingual individuals' interference control performance. Similarly, Kałamała et al.(2020) reported that bilinguals' intensity of using languages in dual-language context was unrelated with their response inhibition. Apart from these studies, bilinguals' intensive practices of dense code-switching, rather than intersentential switching, in daily communications, were found to train up their proactive inhibition and constant conflict monitoring abilities (Hofweber et al., 2016, 2020).

Noticeably, as compared to intersentential switching, participants largely depended on intrasentential switching when they were allowed to voluntarily produce code-switching utterances during bilingual narrations (see Table 7 above). Since bilinguals' code-switching production was for the ease of communication and reflected their bilingual language use habits in naturalistic settings, the finding, in fact, predominantly stressed the general effects of bilinguals' naturalistic language switching behaviours, rather than specifying how different types of code-switching produced by bilinguals affect their inhibitory control. It pointed out fluent bilingual language users habituated to manage two languages in communications would produce less pauses when narrating a story with two languages and would be more efficient in dealing with verbal and nonverbal conflicts through suppressing interferences in cognitive control processes. These fluent code-switchers are more frequently immersed in contexts where require them to constantly monitor and manage their co-activated languages. Such intensive bilingual language control experience, on the one hand, accumulated their proficiency in producing bilingual speeches; on the other hand, their feasible control and switch between languages trained their abilities to monitoring and controlling linguistic interferences appeared in bilingual communications, and such outcomes in verbal cognitive control process could further extend to non-linguistic domains, contributing to their higher efficiency in domain-general cognitive control processes. In addition, the analyses also showed the positive interactions between bilinguals' fluency in Chinese monolingual narrations and their nonverbal inhibitory control efficiency. Together with the above-discussed findings, these results jointly reflected the effects of habitually frequent code-switching on inhibitory control modulation although bilingual individuals were relatively unbalanced across two languages, with higher proficiency in their dominant language and heightened efficiency in controlling L2 interferences in their dominant language production. Furthermore, the model indicated that participants were influent in narrating stories in English monolingually, which also reflected that staying in one language during story narration could be more effortful and pause-caused for these bilinguals as compared to freely switching across languages (de Bruin et al., 2018a).

Although the relationship between bilinguals' naturalistic language switching behaviours and cognitive control did not fully support the ACH and CPM, the current results emphasised the modulations on cognitive control varied across bilinguals' language switching practices in cued and voluntary conditions. Specifically, intensive experience of language switching in naturalistic settings would enhance bilingual individuals' inhibitory control efficiency, contributing to their higher fluency in bilingual language management and efficiency in interferences control. Moreover, it should not be ignored that existing robust evidence on associations between code-switching and cognitive control efficiency identified during bilinguals' cued code-switching practices(e.g., Bonfieni et al., 2019b; Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009; Linck, Schwieter & Sunderman, 2012) might not be consistently applicable to bilinguals' voluntary switching practices (e.g., Gollan et al., 2014; Gollan & Ferreira, 2009; Gross & Kaushanskaya, 2015).

In general, most of studies examining the ACH and CPM were based on cued-language switching practices, although investigating bilinguals' voluntary switching practices would be more helpful in understanding how language switching in naturalistic settings interact with their cognitive control. So, more empirical evidence from bilingual naturalistic language switching practices is needed to have a fuller picture on cognitive control mechanism underlying bilingual language production.

Relationship between bilinguals' language use experience and cognitive shifting

Participants' mixing and switch costs were assessed in the colour-shape switching task as two essential indexes of their cognitive shifting abilities, since the two task-switching costs were regarded to indicated different cognitive control mechanisms (Yang et al., 2016). Mixing costs in the task measure participants' response differences on task-repeated trials in the mix-task blocks and on trials in the single-task blocks. It is regarded as the cognitive costs of monitoring and maintain two competing tasks in the global control mechanisms (Tse & Altarriba, 2014). Differently, switch costs indicate slower responses on task-switch trials than task-repeated trials in the mix-task blocks, reflecting the cognitive costs of switching between different tasks (Declerck & Philipp, 2015; Rogers & Monsell, 1995; Yang et al., 2016). It connects with the local control mechanisms with involvement of individuals' abilities in task set reactivation, task reconfiguration and irrelevant task suppression over time (Tse & Alt Arriba, 2014; Yang et al., 2016).

Regression analyses revealed that bilingual individuals' higher L2 proficiency levels were significantly interconnected with their increasing RTs switch costs in this task. It seemed that bilingual participants in this study did not have their task-switching performance improved as their L2 proficiency increased. This finding failed to observe the facilitatory effects of bilingual L2 proficiency on their switch costs, which was inconsistent with previous evidence showing the positive relationship between L2 proficiency and cognitive shifting performance (e.g., Prior & Gollan, 2011; Tse & Alt Arriba, 2015; Wu, Wang, Wu, Ji & Yan, 2022). One possible reason for this finding could be that participants in this study might be so well-functioning at task-switching that they were at the ceiling level, and therefore, their task-switching performance was not sensitive to the variations in L2 proficiency. As above-discussed Table showed, both participants' RTs and response accuracy in switch and repeated trials within mix-task blocks were comparable without significant differences. This further indicated that these participants (Mean age = 26) were at their peak proficiency in dealing with the task requiring constant task-set switching.

However, things are different when it comes to participants' mixing costs in this task. Results revealed a significant relationship between intensive experience of using languages in the single-language contexts and bilinguals' smaller RTs mixing costs. Besides, participants' smaller dual-language context scores and intersentential switching frequency were also found to associate with their reduced RTs mixing costs. Similarly, analyses of participants' response accuracy mixing costs in this task also showed that smaller language entropy values at home and work settings (i.e., using English at work but speaking in Chinese at home) predicted participants' smaller mixing costs.

These findings, in general, reflected habitual single-language context bilinguals' heightened efficiency of proactive control mechanisms for successful task-set maintenance and constant monitoring switching demands in this task. Consistent with the adaptive control hypothesis (D. W. Green & Abutalebi, 2013a), bilinguals habituated in single-language contexts have intensive experience of keeping their languages separately or formatting their bilingual language use patterns according to the variations of contexts, which exercised their abilities in task-set goal maintenance and interference control (including constant conflict monitoring and interference suppression) rather than cognitive shifting (Han et al., 2022). The targeted language is supposed to be proactively activated while the non-targeted one is sustained controlled during bilingual individuals' speeches in single-language contexts (Grosjean, 2013). Thus, long-term experience of sustained language control and constant conflict monitoring to inhibit irrelevant linguistic resources in their single-language use further enhanced these single-language bilinguals' domain-general proactive control mechanisms. Participants' smaller RTs mixing costs observed in this task implied that they could efficiently sustain monitoring the immediate required switching demands and maintain the competing task in the mix-task blocks as their performance in the single-task blocks. Combining with the above-mentioned null findings on these participants' switch costs, evidence becomes clearer to show that, instead of facilitations on cognitive shifting efficiency, habitually using languages in single-language contexts is essential to bring bilinguals outcomes to their sustained inhibition and global cognitive control efficiency.

Moreover, the model further stressed that such effects were more salient among habitual code-switchers with relatively earlier acquisition of L2 acquisition (L2 AoA). Specifically, bilinguals' L2 AoA was found to negatively correlate with their RTs mixing costs in the colour-shape switching task. This is due to the impacts of L2 AoA on bilingual language dominance and use patterns. It has been suggested that L2 AoA is an essential factor in bilingualism development which strongly interconnects with bilingual individual's language dominance and influences their language control (Birdsong, 2014; Bonfieni et al., 2019a; Luk, De Sa & Bialystok, 2011). Earlier age of L2 acquisition indicated that individuals had relatively earlier experience of L2 learning, which further resulted in their longer and more intensive experience of managing more than one language in daily lives as a bilingual. Therefore, longer experience of L2 learning enhanced their abilities of L2 lexical access, making L2 more dominant through the development of bilingualism. Moreover, in naturalistic bilingual communications, bilinguals with more balanced levels in language dominance would produce language switching more often than unbalanced bilinguals (Gollan & Ferreira, 2009; Prior & Gollan, 2011). This is the possible reason for the significantly improved mixing costs in this task among these frequent code-switchers with earlier L2 AoA revealed in the model.

As previous studies have shown (e.g., Abutalebi & Green, 2007; Meuter & Allport, 1999; Ng & Yang, 2021), bilinguals need to recruit domain-general cognitive control networks in monitoring and controlling their two languages, and such constant involvement of cognitive control networks in bilingual language managements fortified the networks, leading to more efficient in cognitive functioning. In terms of bilingual participants with earlier L2 AoA, linguistic competitions between two languages were more competitive due to their enhance dominance in L2, and heightened competitions required more cognitive demands on conflict monitoring and inhibitory control to realise efficient bilingual language management in communication. Furthermore, since these bilinguals were habituated to use language in single-language contexts, their long-term experience of selecting one language to use via sustained control of the other one between the two co-activated languages with comparable proficiency levels has equipped them stronger abilities in sustained conflict monitoring and interference control in both language and non-language domains. In general, the finding was in line with existing studies, which reported that earlier L2 AoA was associated with bilinguals' better performance in inhibiting prepotent responses (e.g., Soveri et al., 2011; Yow & Li, 2015) and suppressing interferences (e.g., Luk et al., 2011).

Although the current finding failed to find the effects of L2 AoA on bilinguals' task-set shifting performance, it provided new evidence from participants' nonverbal cognitive shifting task performance to complement the role of L2

AoA in affecting bilinguals' language dominance and cognitive control. Noticeably, regression analyses did not show interplays between participants' spontaneous language production performance and their colour-shape switching task performance, remaining the question of how bilinguals' naturalistic language production affect nonverbal cognitive shifting performance to be examined in future research.

6.3.6 Study Conclusion

To conclude, this current study provided new evidence for the importance of bilingual language use experience in modulating bilingual individuals' language production and their strategies of cognitive control deployments during language processing. It partially supported the predictions proposed by the ACH and CPM that frequent practices of switching languages in dual-language contexts during daily communications can fortify bilinguals' efficiency in domain-general inhibitory control. In contrast, habitual single-language context bilinguals in this study were found to be expert in goal maintenance, sustained conflict monitoring and control rather than task disengagement and engagement. The interactive effects of L2 AoA, language proficiency and L2 exposure on bilinguals' language and cognitive control performance were also discussed. Results addressed the close interconnections among these multifaceted factors in complementing the continuum-like bilingualism, and revealed the different magnitudes of effects on bilinguals' cognitive control derived from their individual differences in language use experience.

In addition, apart from the broadly-used self-reported bilingualism questionnaires, this study also adopted diverse approaches to measure and quantify bilingual individual's language use patterns in naturalistic contexts, which included language entropy computation and spontaneous bilingual language production. These approaches aim to minimise the bias of understanding the effects of bilingualism on cognitive control due to the difficulty in measuring bilinguals' habitual language use patterns, and attempt to capture the characteristics of bilingual participants in a more ecological way. Although participants' task-set shifting performance was not found to associate with their naturalistic language use patterns, this study suggested the necessity to take their bilingualism development experience-related factors (e.g., L2 environment exposure, L2 AoA) into account when characterising the effects of bilingual language experience on cognitive control. Since bilinguals seldomly switch languages based on specific cues in their daily communication, their cognitive control deployments in un-cued language switching await more investigations. In future research, more attentions on bilinguals' language switching in naturalistic setting (i.e., un-cued/voluntary switching), and explorations for more well-designed measurements to describe participants' bilingualism from a dynamic perspective are needed.

6.4 Summary of this chapter

The two studies in this chapter discussed the associations between bilingual habitual language use experience and their cognitive inhibition and shifting efficiency in the processes of cued and voluntary language switching production, respectively. Participants' verbal and nonverbal inhibitory control performance were measured in these two studies. Furthermore, both of the studies used the colour-shape switching task to measure participants' nonverbal cognitive shifting efficiency.

In general, the facilitatory effects of single-language contexts on bilinguals' efficiency in proactive inhibition and goal-maintenance were found in both of the two studies. That is, bilinguals habituated to use languages in the single-language contexts without intensive experience of code-switching are proficient in controlling competing linguistic interferences and maintaining the targeted language in either cued- and voluntary bilingual language production processes. Furthermore, it found that their such proficiency in language control could also contribute benefits to their nonverbal proactive inhibition performance.

Using the cued-language switching paradigm, the study 1 evidence to support the modulations of frequent code-switching on bilinguals' nonverbal cognitive shifting and inhibition performance. Bilinguals' proficiency in cognitive shifting, controlling nonverbal interferences and resolving response conflicts is suggested to be trained through their constant language conflicts monitoring and resolution during intensive code-switching practices. However, this study did not find evidence to support the interconnections between bilinguals' cued-language switching performance and their nonverbal cognitive shifting performance.

Similarly, the study 2, testing bilinguals' voluntary language switching in spontaneous language production tasks, further revealed the modulations of bilinguals' higher frequency of code-switching on their verbal inhibitory control efficiency. More importantly, the study 2 indicated the significant facilitatory effects of high frequency of intersentential switching in naturalistic communications on bilingual speakers' verbal and nonverbal inhibitory control efficiency. This finding is in line with the predictions proposed in the ACH and CPM, addressing the dynamical interactions between bilinguals' cognitive control and different code-switching productions.

To sum, bilinguals' habitual interactional contexts and code-switching practices were found as influential factors in affecting their cognitive control efficiency in both cued and voluntary language switching production processes. In the following chapter 7, associations between bilingual individuals' habitual language use experience and their cognitive control underlying language comprehension processes will be discussed.

Chapter 7 Investigating effects of bilingualism on cognitive control in bilingual language comprehension

7.1 General Introduction

As we have already discussed, bilingual speakers have to select an appropriate word from the target language to use and inhibit competing linguistics from non-target language in a given context during their language production. When a speech listener is comprehending a sentence, meanings for each word or phrase are rapidly allocated in the syntactic unfolding order and the individual can make an early prediction of meanings at the sentence level. In some cases, such early meaning interpretations based on syntactic structure can lead to incompatible or erroneous comprehension of sentence meaning; therefore, cognitive control is also hypothesised to be involved in language comprehension processes, facilitating linguistic conflict monitoring and resolution as well as revision of meaning interpretation (Novick, Trueswell & Thompson-Schill, 2005; Teubner-Rhodes, Mishler, Corbett, Andreu, Sanz-Torrent, Trueswell & Novick, 2016; Ye & Zhou, 2009). Therefore, constant practice in selecting and using appropriate language without interference from the co-activated language in bilingual language processing has been regarded as a way training bilinguals’ cognitive control efficiency.

Numerous studies have shown that cognitive control external to the lexicon, especially conflict monitoring and inhibition, plays an important role in both code-switching production (e.g., Costa et al., 2008; Costa & Santesteban, 2004; Filippi et al., 2014; Finkbeiner et al., 2006; Meuter & Allport, 1999) and comprehension (e.g. Adler et al., 2020; Bosma & Pablos, 2020; Bultena et al., 2015; Hsu & Novick, 2016).

In the previous chapter, bilingual speakers' habitual language switching patterns and interactional contexts were found as essential factors in affecting their cognitive control in bilingual language production. However, as compared to studies on language production, relative fewer studies focusing on cognitive control underlying bilingual language comprehension processes and how bilinguals' language experience affects their deployments of cognitive during language comprehension. Additionally, ample empirical evidence (e.g., Adler et al., 2020; Bosma & Pablos, 2020; Wu & Thierry, 2013) has acknowledged the adaptive engagements of cognitive control in comprehending bilingual utterances in different induced interactional contexts, but more understandings on whether comprehending bilingual utterances in habitual (i.e., naturalistic) and induced (i.e., lab-based) language interaction conditions imposes different effects on cognitive control are needed.

In this chapter, two empirical studies are included, investigating the effects of habitual language use experience on bilinguals' cognitive control in language switching comprehension processes. Bilinguals' cognitive control mechanism underlying bilingual language comprehension in naturalistic and induced language interactive conditions were investigated and compared. Consistent with the studies on bilingual language production introduced in the prior chapters, Chinese-English bilingual adults, residing in English-speaking countries, took part in these two studies in this chapter, and the effects of their habitual language use experience on their inhibitory control efficiency were discussed.

In the study 3, different dialogue-listening conditions were created to induce participants' cognitive control in speech comprehension; and how interactional contexts interact dynamically with cognitive control during bilingual individuals' speech comprehension was explored. However, the study 4 focused on bilingual utterance reading comprehension, in which participants' inhibitory control in reading utterances containing different patterns of code-switching was investigated. The different impacts of habitual language use experience on inhibitory control underlying bilingual utterances comprehension in naturalistic and induced communicative conditions were further compared in this study. In general, the two studies shed some light on bilinguals' adaptive deployment of cognitive control in bilingual language comprehension with accounting for their bilingualism-related factors. Self-reported questionnaires (introduced in Chapter 5) were used to understand participants' bilingual language use habits, including L2 proficiency, habitual code-switching frequency and interactional contexts, for subsequent regression analyses in these studies.

7.2 Empirical Study 3: Facilitatory effects of dual language contexts on bilinguals' cognitive control: evidence for the Adaptive Control Hypothesis

7.2.1 Study introduction

Prior studies reported the co-activation of linguistic resources from two languages during bilingual switch and non-switch speech comprehension. For example, Spivey and Marian (1999) tested Russian-English bilingual adults and English monolinguals using an auditory processing paradigm in which competing lexical items were presented. Competition from English lexical items was found in both monolingual and bilingual speakers. However, only the bilingual speakers also experienced competition from Russian, indicating cross-linguistic competition between two languages and, therefore, suggesting a parallel activation of both in speech comprehension.

Other studies (e.g., Weber & Cutler, 2004; Curler, Weber & Otake, 2006) replicated Spivey and Marian's findings even when participants processed non-native language without code-switching. Besides word comprehension, Hsu and Novick (2016) found that cross-linguistic competition occurs also at sentence level. They also found that executive function plays a critical role in controlling interference from co-activated linguistic resources in sentence comprehension.

Although some studies (e.g., Bultena et al., 2015; Wang, 2015) argued that differences in cognitive control paradigms (top-down control vs bottom-up control) might be employed in code-switching production and comprehension, the involvement of cognitive control beyond language domain in bilingual language comprehension has been broadly examined and supported. Specifically, studies on both syntactic complex or ambiguous sentences (e.g., Hsu & Novick, 2016; Navarro-Torres, Garcia, Chidambaram& Kroll, 2019; Teubner-Rhodes, Bolger & Novick, 2019) and bilingual sentences with code-switches (e.g., Adler, Valdés Kroff & Novick, 2020; Bosma & Pablos, 2020; Wang, 2015) indicated the role of cognitive control in facilitating successful comprehension.

The influence of individual differences like second language age of acquisition, proficiency and language usage has been also studied to investigate cross-linguistic activation and competition in language processing (e.g., Blumenfeld & Marian, 2007, 2011; Canseco-Gonzalez, Brehm, Brick, Brown-Schmidt, Fischer & Wagner, 2010; Olson, 2017). Canseco-Gonzalez and colleagues (2010), for example, highlighted the roles of second language age of acquisition and language usage in modulating bilinguals' language processing. Specifically, the earlier a second language was acquired, the higher was the degree of lexical activation in this language. Additionally, they found that bilinguals controlled their languages more efficiently as a function of language usage, that is, bilinguals performed significantly faster when matching the visual targets with their corresponding name presented auditorily in the monolingual mode than in the bilingual mode.

This study further investigates the relationship between cognitive control and speech comprehension with particular focus on the bilingual participants' language experience and how they use their languages in everyday life. We specifically address the question whether different interactional contexts interact dynamically with cognitive control in language comprehension. In this vein, this study intends to explore the bilinguals' adaptive deployment of cognitive control in comprehending different patterns of bilingual dialogues, aiming to provide more evidence on the effects of bilingual experience-related factors and informing theory and practice.

The current study explored how bilinguals coordinate their cognitive control during language comprehension in three interactional contexts (i.e., single-language, dual-language and dense code-switching contexts) by investigating a group of Chinese-English bilingual adults.

Two main questions were addressed in this study:

1) To what extent can different interactional contexts modulate inhibitory control processes in bilingual speakers?

2) How do different interactional contexts affect bilinguals' speech comprehension performance?

It was predicted that participants manipulated in a dual-language context will perform better on both inhibitory control and dialogue comprehension tasks. As participants in the current study were all Chinese-English bilinguals with Chinese as their native language, it was also predicted that they will exhibit best performance in the single-language Chinese comprehension condition.

7.2.2 Methods

The study met the requirements and gained the approval of the Ethics Committee of the Institute of Education, University College London, concerning empirical studies with human participants. Chinese-English bilinguals were recruited from university students in London. Only individuals residing in London at the time of the study and regularly using Chinese and English on daily basis were invited to join the study. The information sheet and consent form were provided to individuals who expressed an interest to this study so that they could decide whether to participate or not. No data were collected until participants signed an informed consent form. Prior to the experiment, the researcher briefly introduced participants the goals of the study and all consenting participants took part in the study as volunteers without remuneration.

Participants

Thirty-six (12 males, 24 females; age range 19–30 years) right-handed healthy Chinese-English bilinguals took part in this study. All participants are

Chinese Mandarin native speakers, raised in Chinese Mandarin-speaking families. At the time of this study, participants had resided in London for 1.90 years on average. They all reported that they use both Chinese and English nearly every day on a regular basis. Besides, even they engaged in code-switching practices quite frequently in daily communications (Mean language switching frequency = 4.44), they habitually switch between their two languages based on sociolinguistic cues, like using English at work with English-speaking partners but communicate in Chinese with Chinese interlocutors and at home settings. All the participants learned English as a second language in mainstream school classroom settings after Chinese was well acquired, and they reported that English and Chinese were used together as instruction languages in their English classes (average English usage: 39.43%; average Chinese usage: 60.57%), indicating that they had considerable experience of switching or translation between the two languages during English learning.

Participants were instructed to complete the language history and background information questionnaire (LHQ; Li et al., 2006), and a forward and backward digit span test (Hoosain, 1979) as well as the Raven's Advanced Progressive Matrices Set 1 (Raven et al.,1998) to understand their bilingual language experience and baseline cognitive skills. The LexTALE test (Lemhöfer & Broersma, 2012) was administered to objectively measure their English (L2) proficiency. Table 7.1below shows that participants, in general, are bilinguals with relatively high proficiency in English (average LexTALE score = 64.79%), and have regular practices of language switching between Chinese and English in daily life (average switching frequency = 4.44).

Table 7.1 Demographic, language background information and cognitive background information for adult Chinese-English bilingual participants

	Mean	SD
Age	24.25	2.90
Raven's non-verbal IQ (%)	76.16%	0.15
Working Memory (%)	83.43%	0.12
English proficiency (LexTALE %)	64.79%	0.10
Years of English learning	15.25	3.51
Years resided in London	1.90	1.52
English Reading (Max: 7)	5.25	1.13
English Speaking (Max: 7)	4.69	1.06
English Writing (Max: 7)	4.50	1.13
English Comprehension (Max: 7)	5.11	1.06
Bilingual language switching frequency (Max: 7)	4.44	1.78

Materials, design and study procedure

Dialogue-listening materials for interactional context manipulation

Four three-minute dialogues, in the forms of Chinese only, English only, Chinese-English dual-language and dense code-switching, were created as listening materials to manipulate participants' language and cognitive processing statuses in the three interactional contexts referred to in the ACH. Chinese and English word frequency in each dialogue was also calculated through the index of word frequency per million and Zipf value based on the free online linguistic corpora: SUBTLEXus corpus (Brysbaert & New, 2009) and SUBTLEXch corpus (Cai & Brysbaert, 2010). The word frequency summary in each dialogue is shown in Appendix X. The different code-switching patterns involved in the bilingual dialogues were designed with adoptions of the classifications on code-switching proposed by Muysken (2000). In the dual-language dialogue, Chinese and English are alternatively used at clause/sentence level without mixing up in a single sentence. However, sentences in the dense code-switching dialogue involve the joint activation of linguistic resources from Chinese and English at both the grammatical and lexical levels. Two languages intensively switch back and forth, and have their lexical items densely mixed in one sentence. The dialogue with Chinese and English alternative switching is used for the dual-language context manipulation, while the dense code-switching dialogue is used for manipulating participants in the dense code-switching context (examples of dialogue materials see Appendix X). Ten dialogue content-related comprehension questions were asked orally by the researcher after participants listened the dialogue and completed the flanker task. Introducing these comprehension questions was to ensure that participants were paying attention during each session (Adler et al., 2020; Bosma & Pablos, 2020a), and to index how well they comprehend or process information conveyed monolingually and bilingually with different code-switching involved. To keep the consistency of interactional context manipulation, comprehension questions in each session were formed in the same linguistic structure as sentences in the dialogue. For instance, questions in the English monolingual dialogue session were asked in English, while questions were designed to similarly involve intensive code-switching between Chinese and English in the dense code-switching dialogue listening session. It is noticeable that questions in the dual-language context were asked in either Chinese or English; specifically, alternatively asking five questions in Chinese and five in English. Correct answers for each comprehension question were straightforward, which participants could directly match the answer with one word/utterance appeared in the dialogue. If participants used a different word/expression but indicated the same meaning with what was used in the dialogue, their answers were also marked as correct. The total number of participants' correct answers for comprehension questions in each session were calculated and compared. Examples for yes/no comprehension questions were presented in Appendix X.

Two native English speakers and two proficient Chinese-English bilingual speakers are involved in dialogues recording, and the recordings are presented as daily conversations between a female and a male.

Flanker Task

A simplified flanker task (Fan et al., 2002) with 50:50 congruent and incongruent trials was used to test participants' inhibitory control performance. In this task, an array of five direction-pointing stimuli presented at the centre of the screen. Participants were instructed to respond as quickly and accurately to indicate the direction of the central visual stimulus (target) by pressing the corresponding key while ignoring other surrounding stimuli (flankers). When the target points left, participants have to press “Q” on the keyboard, while it points right, immediate pressing of “P” is required (for the stimuli used in flanker task see Appendix XI). The task embedded in each dialogue-listening session contains 40 congruent (i.e., flankers point in the same direction as the target) and 40 incongruent (i.e., flankers point in the opposite direction to the target) trials. Each trial began with a fixation cross for 500ms, followed by an array of visual stimuli for 1500ms. A short practice session (4 trials) was administered before the formal task to make sure participants fully understood the instructions.

Study Procedure

Visual and audio stimuli in this study were presented using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Dialogue-listening materials were recorded through Microsoft recorder and stored in mp3. format. Auditory stimuli were presented to participants through a headphone. All participants completed this study on the same equipment in a sound-proof room.

After completing the language history questionnaire and baseline cognitive skills measures, participants were instructed to perform a baseline flanker task initially. Then, they were invited to the dialogue-listening sessions, in which they had to complete a flanker task immediately after listening to a 3-minute dialogue. On completing the flanker task, they had to orally answer ten comprehension questions related to the dialogue asked by the researcher. The four dialogue-listening sessions were counterbalanced across participants. Figure 7.1below is an illustration of the study procedure.

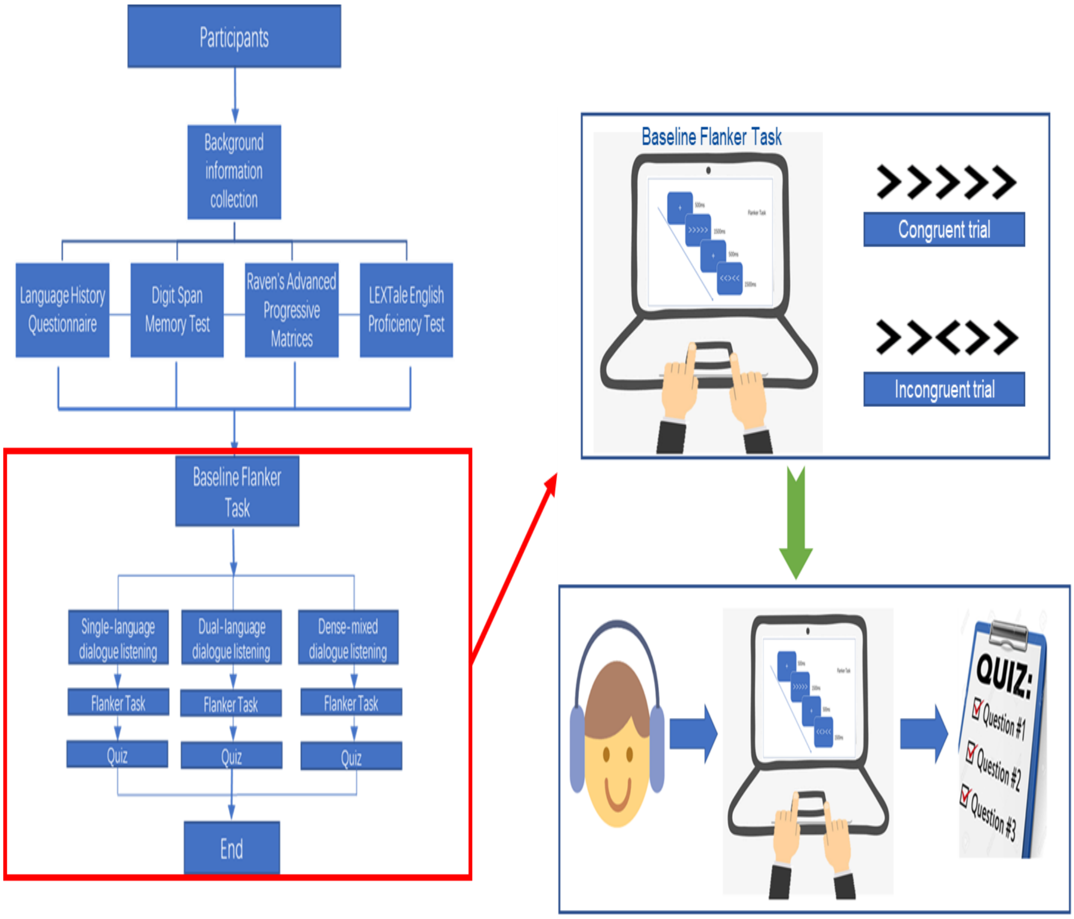

Figure 7.1 Illustration of the experimental procedure.

7.2.3 Results

Participants' performance in flanker tasks and comprehension questions are presented in the following parts. Paired sample t-tests and repeated-measures ANOVA were carried out with JASP (JASP Team, 2020 version

0.14.1) to analyse the differences in participants' performance in flanker tasks across different dialogue-listening sessions.

Results for baseline flanker task

A paired sample t-test was conducted to compare Reaction Time (RT) in congruent and incongruent conditions, and there was a significant difference in the RT for congruent (Mean = 455.17, SD = 68.41) and incongruent (Mean = 501.42, SD = 76.69) conditions; t (35) = -9.51, p < .001, r = -.62, Cohen's d = -1.59, displaying a typical flanker interference effect (Eriksen & Eriksen, 1974). Besides, participants' response accuracy for congruent trials was significantly higher than incongruent trials, t (35) = 4.65, p < .001, r = .36, Cohen's d = .78. Table 7.2 and Figure 7.2 below illustrate the typical flanker interference effect in participants' baseline flanker task performance.

Table 7.2 Mean RT (ms) and accuracy (%) of congruent and incongruent trials in the baseline Flanker task with SD

	RT		Accuracy	
	Mean	SD	Mean	SD
Congruent	455.17	68.41	96.86	0.15
Incongruent	501.42	76.69	92.78	0.16

Flanker task performance in different interactional contexts

Participants' flanker task performance in different interactional contexts were analysed through the repeated-measures ANOVA. Table 7.3 shows participants' mean RTs and response accuracy in flanker tasks after being manipulated in the single-language, English-Chinese dual-language and dense code-switching contexts.

Table 7.3 Mean RT (ms) and accuracy (%) of congruent and incongruent trials in the flanker tasks in the three interactional contexts

	RT (ms)				Accuracy (%)			
	Congruent		Incongruent		Congruent		Incongruent	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Baseline	455.17	68.41	501.42	76.69	96.86	0.15	92.78	0.16
English	411.73	56.10	444.35	62.35	98.75	0.02	95.08	0.05
Chinese	412.09	54.75	421.70	57.90	97.94	0.04	95.94	0.05
Dual-language	400.79	51.64	424.66	63.55	97.92	0.03	95.89	0.06
Dense code-switching	420.46	56.00	448.43	57.43	98.75	0.03	94.36	0.05

A main effect of congruency on participants' RTs across different contexts was found, F (1, 35) = 171.79, p < .001, partial η^2 = .83. It indicated that participants, in general, performed longer RTs for incongruent than congruent trials (see Figure 7.2 below).

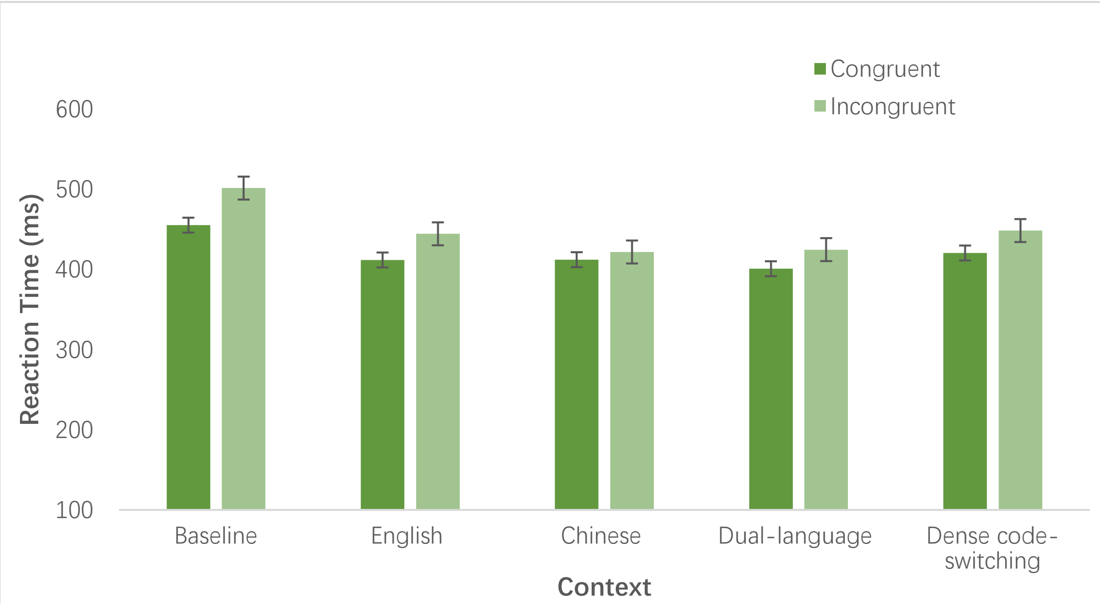

Figure 7.2 Participants' flanker task RTs (ms) and standard errors in different language contexts

Besides, participants' RTs varied significantly across different interactional contexts, *F* (1.98, 69.29) = 29.51, $p < .001$, partial $\eta^2 = .46$. Specifically, participants' RTs for both congruent and incongruent trials in different interactional contexts, as compared to their baseline RTs, were significantly improved.

In addition, there was also an interactive effect of context * congruency on participants' RTs, *F* (3.67, 128.42) = 14.80, $p < .001$, partial $\eta^2 = .30$. As for incongruent RTs, participants performed significantly faster in the Chinese single-language context than in the English single-language ($t = 2.90$, Cohen's $d = .48$, $p = .04$) and dense code-switching contexts ($t = -3.42$, Cohen's $d = -.57$, $p = .01$). No significant differences in RTs were found between Chinese single-language and dual-language contexts.

The results further showed that participants' incongruent RTs in the dual-language context were significantly reduced as compared to the dense code-switching context ($t = -3.04$, Cohen's $d = -.51$, $p = .03$). Similarly, RTs for congruent trials in the dual-language context were also smaller than in the dense code-switching context ($t = 2.97$, Cohen's $d = -.50$, $p = .04$).

It seems that cognitive demands, even in language comprehension processes, also vary across different interactional contexts, leading to different degree of modulation of cognitive control. The findings revealed the facilitatory effects of interactional contexts on participants' RTs in the flanker task, in particular, supporting the study hypothesis on the significant effects of both dominant language and dual-language contexts on domain-general inhibitory control modulation.

Response accuracy in flanker tasks across different sessions was also analysed. Although a main effect of context on participants' response accuracy (F (1.11, 38.68) = .60, p = .46, partial η^2 = .02) was not found, the typical flanker interference effect in response accuracy was revealed. In general, participants performed more accurately for congruent than incongruent trials, F (1, 35) = 53.70, p < .001, partial η^2 = .61.

The analysis further revealed that participants' response accuracy for both congruent trials (F (1.13, 39.65) = .45, p = .53, partial η^2 = .01) and incongruent trials (F (1.29, 45.28) = 1.02, p =.34, partial η^2=.03) did not vary significantly across the baseline and four different language contexts. Figure 7.3 showed the response accuracy for flanker tasks across different contexts.

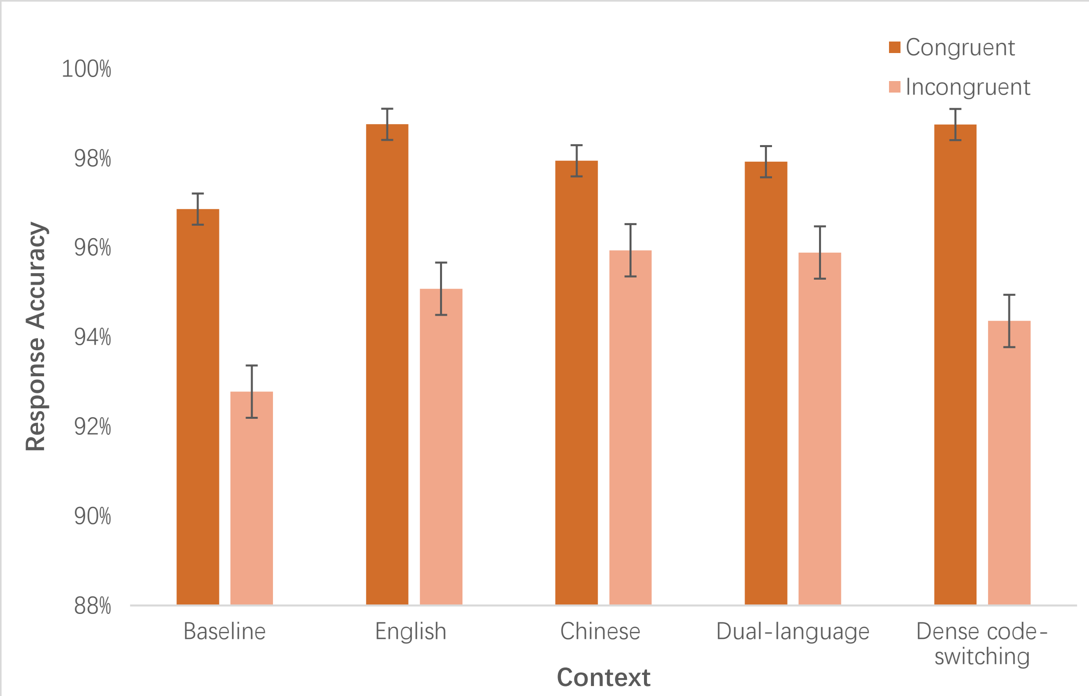

Figure 7.3 Comparisons of mean response accuracy and standard error in flanker tasks across different interactional context

Language comprehension performance in different language contexts

Participants' performance in answering comprehension questions after the flanker task in each interactional context was analysed through the one-way ANOVA. Table 7.4 summarised participants' language comprehension performance in three interactional contexts.

Table 7.4 Participants' response accuracy in comprehension questions in different language contexts

	Accuracy		
	Mean	SD	Median
English	5.78	1.96	6
Chinese	7.86	1.94	8
Dual-language	6.31	2.04	6.5
Dense code-switching	5.36	2.06	6

In general, participants' response accuracy for comprehension questions was significantly different across contexts, F (3, 140) = 11.54, $p < .001$, partial η^2 =.198. Specifically, participants performed more accurately in answering comprehension questions in the Chinese single-language context as compared to the English single-language (t = 4.58, Cohen's d = 1.15, $p < .001$), dual-language (t = 3.42, Cohen's d = .84, p = .01) and dense code-switching (t = 5.49, Cohen's d = 1.34, $p < .001$) contexts; however, no significant differences in their response accuracy across rest of the three interactional contexts. In line with the study hypothesis, bilinguals' dominant language context was found to significantly modulate their language comprehension performance.

7.2.4 Study discussion and conclusion

This study has examined the impacts of different interactional contexts on the cognitive control underlying bilingual language processing. As bilingual language processing requires efficiently managing co-activated languages while inhibiting the non-target linguistic items, resulting in modulation of bilinguals' ability in cognitive control (Grant et al., 2015; Linck et al., 2012), the dual-language context, with greater demands on bilingual language management, was predicted to boost bilinguals' cognitive control efficiency. Furthermore, considering the effects of language dominance on bilingual language processing, this study predicted that bilinguals would outperform in language comprehension in the Chinese single-language context. As expected, the results supported the connection between language processing context and adaptive changes to cognitive control mechanisms, showing the facilitatory effects of processing languages in the dual-language and dominant language contexts on domain-general inhibitory control. As expected, participants' RTs for incongruent trials in the dual-language context were significantly reduced as compared to other contexts. However, bilinguals in L2 single-language and dense code-switching contexts did not show significant improvement in their RTs in flanker tasks.

According to the ACH (Green & Abutalebi, 2013), bilinguals adaptively select control strategies to deal with varying cognitive demands in different interactional contexts. For instance, a dual-language context requires constant exercising of bilinguals' cognitive control through frequent selective inhibition of non-targeted ones over co-activated languages and intensive engagement and disengagement in two languages, leading to bilinguals' enhanced efficiency in cognitive control. The carry-over effects of the dual-language context on bilinguals' flanker task performance provided evidence for the interaction between language processing context and non-linguistic cognitive control (Wu & Thierry, 2013). In particular, it further indicates how control strategies adapt to cognitive demands posed by different types of interactional contexts and bilingual utterances in language comprehension processes. Furthermore, it supported the greater effectiveness of nonverbal conflict monitoring and resolution attributed to language processing in mixed language speech contexts, in which processing information conflicts boosts the brain's enhanced cognitive control to engage in similar cognitive operations (Adler et al., 2020; Botvinick et al., 1999). That is, as language comprehenders need to be prepared to deal with any code-switching which may occur in utterances and resolve cross-linguistic conflicts efficiently, constant practice in processing languages in mixed language contexts boosts their efficiency in conflict monitoring and resolution in both verbal and nonverbal tasks.

In addition, the study showed the modulation of dominant language on bilinguals' inhibitory control efficiency. Consistent with the study hypothesis, the study also revealed that bilinguals in their dominant language context outperformed in language comprehension, reflecting the role of language proficiency in sculpting bilinguals' cognitive control during language comprehension (Blumenfeld & Marian, 2013). As language dominance is not only generally defined through proficiency but also goes beyond it, factors related to bilinguals' language experience are also important in affecting their language comprehension processes. This finding, in line with Bonfieni et al. (2019), reflected that language dominance, uniting the proficiency of language and other relative bilingual experience, facilitates both bilinguals' language and cognitive control processes.

However, the exclusiveness of bilinguals' cognitive control advantages in the dual-language context might derive from their habitual language use experience. Even participants in the study are Chinese-English bilinguals with regular experience of using Chinese and English in UK, they are prone to use two languages separately for different purposes or in different occasions without intensive code-switching practices in daily communications. Therefore, processing dialogue with code-switching utterances could be challenging for them, leading to increased cognitive efforts to control the competing linguistic items and further hindering their concentrations on language comprehension and dialogue meaning processing. It further suggests that processing bilingual utterances involve experience-based linguistic skills; specifically, bilinguals with intensive exposure to a code-switching environment might require less cognitive control effort to integrate code-switching into comprehension (Adler et al., 2020; Gross et al., 2019; Valdes Kroff et al., 2013).

Taken together, this study provided empirical evidence for the Adaptive Control Hypothesis (Green & Abutalebi, 2013) from the perspective of language comprehension, suggesting that single-language, dual-language and dense code-switching contexts modulate language control processes by adaptively changing the level of inhibitory demands. Critically, it further suggests the impact of language dominance on bilinguals' language and cognitive control processes. Besides, the study indicated the multifaceted character of bilingual language experience and its facilitations on language comprehension. More studies focusing on bilinguals' language use in natural communications should be carried out in future to better understand the consequences of bilingualism on domain-general cognitive control.

In the next section of Chapter 7, I will compare the effects of bilinguals' habitual language use experience on their cognitive control underlying comprehending different code-switching utterances in induced and naturalistic language use conditions.

7.3 Empirical Study 4: The effects of code-switching and L2 proficiency on cognitive control in habitual and manipulated language use conditions

7.3.1 Study introduction

It has been addressed that bilingualism is an interactive and dynamic experience shaped by bilingual individuals' experience of language use (Grosjean, 2013; Surrain & Luk, 2019); therefore, exploring the interactive effects of individual differences in code-switching patterns and interactional contexts on bilinguals' domain-general cognitive control underlying language processing is necessary. The Adaptive Control Hypothesis (Green & Abutalebi, 2013) and the Control Process Model (Green, 2018; Green & Li, 2014) further elaborately discuss the adaptations of cognitive control underlying different patterns of code-switching, and predict that the ways in which bilinguals habitually mix and switch their languages may have different impacts on cognitive control.

This study includes two experiments to examine the effects of code-switching processing and L2 proficiency on domain-general cognitive control in both habitual and induced bilingual language use conditions. Experiment 1 investigated how bilinguals' L2 proficiency and habitual code-switching patterns affected their inhibitory control performance, while Experiment 2 used self-paced bilingual utterances reading interleaved with nonverbal flanker trials to manipulate bilinguals in different bilingual language conditions, and examine their different engagement of inhibitory control when processing bilingual utterances with different code-switching patterns. In sum, through the two experiments, this study intends to explore:

1) How do different patterns of code-switching and L2 proficiency affect bilinguals’ inhibitory control in both habitual and manipulated bilingual language use conditions?
2) Is cognitive control also adaptively engaged in reading different patterns of code-switching? If so, how does comprehending utterances with intersentential switching modulate bilinguals’ inhibitory control performance?

Moreover, this study hypothesises that 1) bilinguals with higher L2 proficiency will perform better in nonverbal inhibitory control tasks; 2) processing different patterns of code-switching utterances will impose different extents of effects on bilingual participants’ inhibitory control performance. Specifically, specifically, processing intersentential switching sentences would modulate bilinguals’ efficiency in nonverbal inhibitory control tasks.

7.3.2 Methods

Participants for this online study were recruited from among Chinese-English bilingual adults living in English-speaking countries (including the USA, Australia, Canada, the UK and Singapore). Only individuals residing in these English-speaking countries at the time of the study and making regular use of Chinese and English every day were invited to join the study. An information sheet and consent form were provided to individuals who expressed an interest in this study so that they could decide whether to participate or not. No data were collected until participants had signed an informed consent form. Prior to data collection, the researcher briefly introduced the participants to the goals of the study, and all consenting participants took part in it.

Participants

Forty-seven healthy right-handed adult Chinese-English bilinguals took part in this study. Three participants were excluded due to technical problems during data collection. Two other participants withdrew halfway through. Another two were excluded because they had left English-speaking countries more than one year earlier, which could cause L2 exposure bias as compared to other participants. In total, data from 40 healthy participants (9 males; mean age = 25, SD = 2.58, range 21~29) were included in the data analysis.

Participants' language learning and using experience was measured through a Chinese-English bilingual language background questionnaire adapted from Anderson et al. (2018) and Li et al., (2006). All participants are native Chinese Mandarin speakers and they were raised in Chinese-Mandarin speaking families. They started to learn English as a second language in mainstream primary schools in China (mean age 7.6 years). Before they immigrated to English-speaking countries, these participants all resided in Chinese-dominant communities and consistently use L1 in daily communication. At the time of the experiment, they had been residing in an English-speaking country for around three years on average.

Also, participants' code-switching habits were measured through a language switching judgement task (Hofweber et al., 2016, 2020) and two online questionnaires: the Bilingual Switching Questionnaire (Rodriguez-Fornells et al.,2012) and the Code-switching and Interactional Contexts Questionnaire (Hartanto & Yang, 2016).

The LexTALE test (Lemhöfer & Broersma, 2012) was used to objectively measure participants' English (L2) proficiency. In general, participants had moderately high proficiency in L2 English (mean = 66.31, SD = 10.14). All included participants are Chinese Mandarin native speakers, and learned their English after the age of 7.63 (SD = 3.47) on average. A shortened version of Raven's Advanced Progressive Matrices, (Raven et al., 1998) with 12 test items included, was used to measure participants' baseline cognitive ability and fluid intelligence. In this task, participants were given 30 seconds to respond to each test item, and their percentages of correct responses were calculated. Table 7.5 below summarises participants' demographic and bilingual language experience information.

Table 7.5 The demographic and bilingual language background information of the Chinese-English bilingual participants

	Mean	*SD*	Range
Age	25.08	2.58	21~29
L2 AoA	7.63	3.47	1~19
L2 environment exposure duration (years)	2.97	2.17	0.2~9.8
LexTALE score (%)	66.31	10.14	48.75~87.5
Self-reported L2 reading proficiency (none:1- native-like:10)	6.00	0.78	3~7
Self-reported L2 speaking proficiency (none:1- native-like:10)	5.05	1.22	2~7
Self-reported L2 understanding proficiency (none:1- native-like:10)	5.58	1.01	3~7
Self-reported L2 writing proficiency (none:1- native-like:10)	5.00	1.01	3~7
Code-switching Frequency Judgement Task			
Chinese to English alternation frequency (Max:25)	13.55	3.41	7~22
English to Chinese alternation frequency (Max:25)	11.88	3.41	6~21
English insertion frequency (Max:25)	19.63	3.98	11~25
Chinese insertion frequency (Max:25)	7.10	2.19	5~12
Dense code-switching frequency (Max:25)	6.80	2.62	5~15
Code-switching and Interactional Context Questionnaire Information			
Dual-language Score	4.55	1.20	2.00~8.00
Single-language Score	65.00	24.58	9.00~98.80
Index of intersentential switching	1.98	0.72	1.00~3.70
Index of intrasentential switching	2.94	0.99	1.05~4.60
Bilingual Switching Questionnaire Information			
L1 switching tendencies (never:1 - always:5; Maximum:15)	7.40	1.87	4.00~12.00
L2 switching tendencies (never:1 - always:5; Maximum:15)	7.92	1.93	4.00~13.00
Contextual switch (never:1 - always:5; Maximum:15)	8.43	2.48	4.00~14.00
Unintended switch (never:1 - always:5; Maximum:15)	7.12	1.98	3.00~11.00

Materials and Measurement

Bilingual code-switching habits measurement

The Chinese version of the Bilingual Switching Questionnaire (BSWQ) adapted from Rodriguez-Fornells et al. (2012) was used to assess participants' habitual code-switching practices. The questionnaire consisted of 12 items to measure bilinguals' code-switching habits as regards four constructs: L1 switching tendency, L2 switching tendency, contextual switching and unintended switching. Each construct contains three Likert-scale items with a scale of 1–5. Participants were instructed to self-reported the degree of their code-switching habits described in each construct. A higher score for one construct indicates more frequent use of a specific code-switching behaviour.

Contextual switching indexes the frequency of language switching triggered by a particular topic, situation or environment, while unintended switching measures bilingual speakers' frequency of unintentional language switching in communication, or language switching in use due to lack of awareness. L1 switch tendency reflects switching back from L2 to L1 during code-switching, while L2 switch tendency indicates bilingual speakers' tendency to switch from L1 to L2 in bilingual communication (Rodriguez-Fornells et al., 2012).

The Chinese version of the Code-switching and Interactional Contexts Questionnaire used in this study was translated from Hartanto & Yang's

(2016) original English version questionnaire. Four important indexes that are closely associated with participants’ code-switching behaviours and habitual bilingual contexts were assessed. The score for dual-language context (DLC) reflects the extent to which Chinese and English are used within the same situation in general. A higher DLC score reflects a greater degree of dual-language bilingualism and the co-occurrence of both languages in daily communication (Kałamała et al., 2020). The index of single language context (SLC) bilingualism assesses the extent of participants’ use of two languages separately in different situations (i.e., using one language in one situation and the other in another situation). Higher SLC scores reflect participants’ more intensive practice of using two languages separately. The indices of intersentential code-switching and intrasentential code-switching, respectively, measure participants’ overall intersentential code-switching and intrasentential code-switching frequencies in four different daily-life associated situations: home, work, school and other situations. Higher values for intrasentential switching reflect participants’ greater frequency of mixing two languages in one single utterance, while frequent alternations between two languages are reflected in higher scores on the intersentential switching index.

However, asking participants to recall and self-rate their frequency of using each code-switching pattern in communication may lead to biased results since it is hard for them to clearly classify their code-switching patterns and classifications may vary across individuals. To minimise randomness and individual differences in code-switching pattern classification and frequency ratings, this study further used a code-switching frequency judgement task adapted from Hofweber et al. (2016, 2020) to objectively assess participants' habitual code-switching practices. This task modified the original task to read and rate different code-switching utterances. In this task, different types of code-switching utterances were presented in a pseudo-random order on a screen. Participants were instructed to read an utterance and then rate how likely they are to produce a pattern of code-switching in their daily conversations, 5 = most likely, 1 = least likely.

At the beginning of the task, two Chinese monolingual sentences and two English monolingual sentences were presented to make sure the participants were ready for the task. Twenty-five utterances in five different switching patterns, intrasentential switching (i.e., English insertions and Chinese insertions), intersentential switching (i.e., English to Chinese alternations and Chinese to English alternations) and dense code-switching, were included in this task. The utterances used in this task can be found in the Table 7.6 below. Participants' frequency for each code-switching pattern was measured by summing the scores for five utterances in each pattern.

Table 7.6 Examples of the bilingual utterances used in the code-switching frequency judgement task

	Examples
English insertions	又没有 dress code，今晚你穿啥都可以。
Chinese insertions	My tutorials 都在早上，but my lectures are in the afternoon.
English to Chinese alternations	If anything happened，我绝对活不下来。
Chinese to English alternations	一谈到生育他们就会说这是女人的职责，women are designed for it.
Dense code-switching	你别 forget 明天 call and remind 我啦，我们去 market 买 coconut pie 正好这些 pie 是 buy three for two.

Experiment 1: Spatial Stroop Task

The nonverbal Stroop task used in this study was adapted from Blumenfeld and Marian (2011, 2013), and is consistent with the one used in Study 2 discussed above. Similarly, participants in this task needed to judge an arrow's direction regardless of the location of the arrow as quickly and accurately as possible. For example, participants need to press the "left-arrow" button on the keyboard once they see a left-pointing arrow whether it appears on the left or right of the screen.

Different from the task design of the Study 2, the proportion of incongruent and congruent spatial Stroop trials in this study was 1:3, with 40 incongruent trials and 120 congruent trials. Each trial began with the presence of a fixation cross at the centre of the screen for 500ms, followed by a 700ms blank sheet and a 1,500ms presentation of the stimulus. Ten practice trials were included at the beginning of this task. Trials in each block were presented pseudo-randomly, and four blocks were counterbalanced across participants.

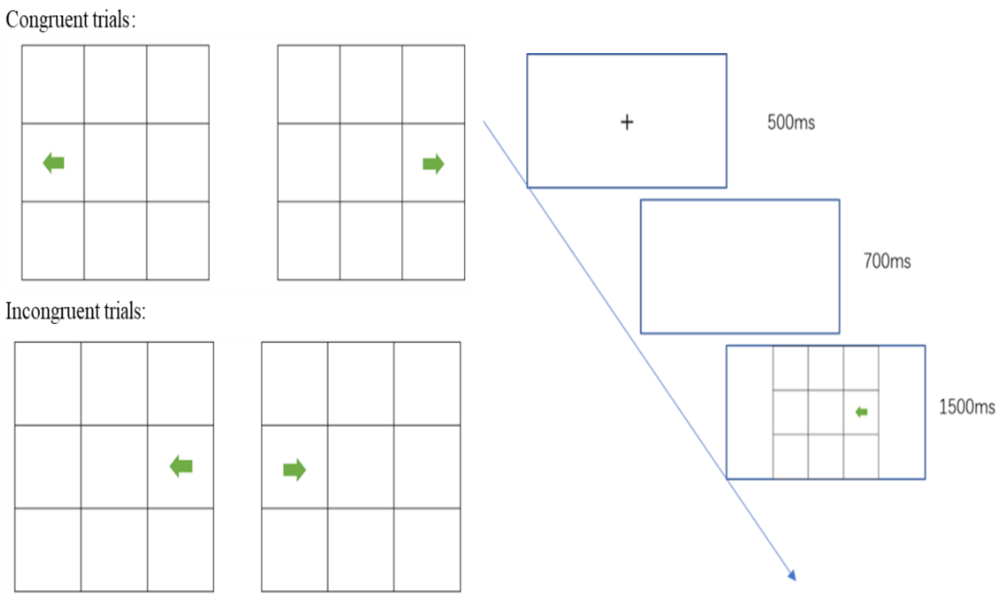

Figure 7.4 Display of the Spatial Stroop task in experiment 1

Experiment 1: Adapted Simon Task

This task modified the original Simon task (Simon, 1969) to measure participants' domain-general inhibitory control. This modified version changed the visual stimuli into strawberry and grape icons and presented the stimuli vertically (i.e., top and bottom) of the screen instead of the original left-right horizontal layout. This design aims to distinguish the stimuli layout in the spatial Stroop task and minimize the bias of right-handed effects of faster rightward responses to stimuli presented on the participants' right.

In this task, participants were asked to quickly and accurately respond to visual stimuli by making a downward response to a strawberry and an upward response to a bunch of grapes. The strawberry and grapes could be present at either the top or bottom of the screen. Where the strawberry and grapes appear is irrelevant as regards accurate responses in the task, that is, even if grapes appear at the bottom of the screen, participants should still press the corresponding key "up arrow" on the keyboard to respond.

Consistent with the spatial Stroop task, each trial in this task also began with a fixation cross for 500ms, and a 1,500ms presentation of the stimulus after a 700ms pause. There were 10 practice trials at the beginning to help participants understand the task instructions. The task included 120 congruent and 40 incongruent trials in all four blocks. Trials in each block were presented in a fixed pseudo-randomised order.

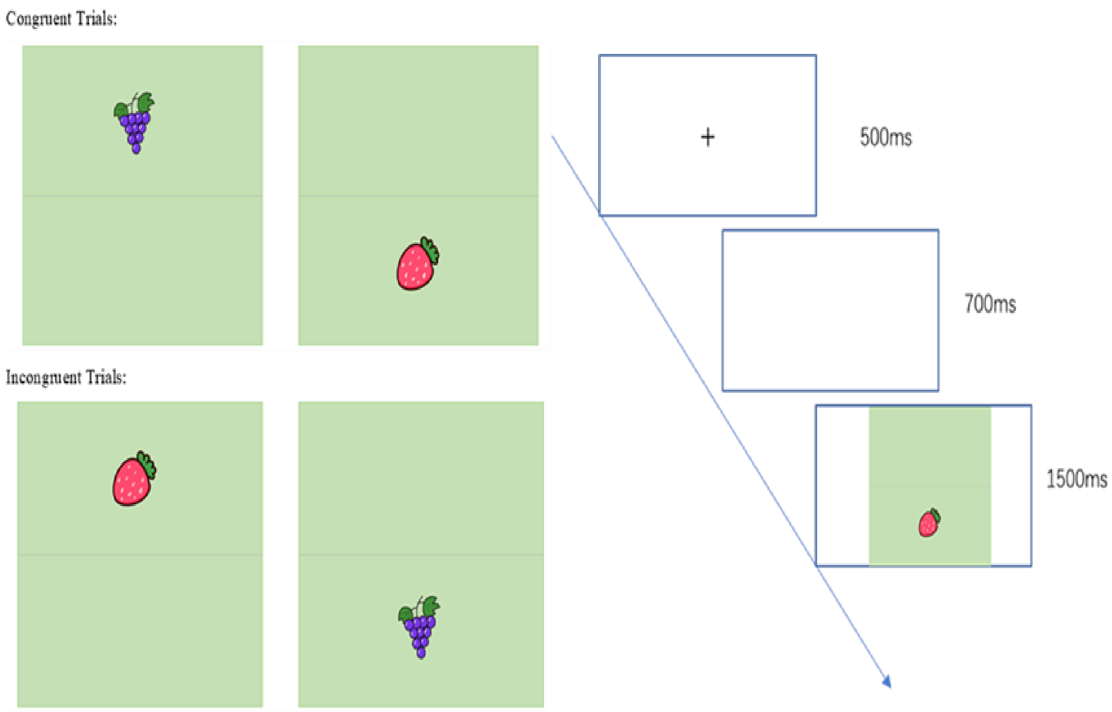

Figure 7.5 Demonstration of the adapted Simon Task used in experiment 1

Experiment 2: Self-paced reading combined intermittently with a flanker task

Different from Experiment 1, which investigates the association between bilinguals' habitual code-switching processing and domain-general inhibitory control performance, Experiment 2 zooms in on the effects of different patterns of code-switching on inhibitory control in a manipulated bilingual language processing condition. The self-paced reading combined intermittently with a flanker task in Experiment 2 was adapted from Adler et al., (2020) and Bosma and Pablos (2020), aiming to manipulate participants in different bilingual language processing conditions through reading utterances containing different code-switching patterns and explore the adaptive engagement of cognitive control in comprehending different code-switching utterances. Some examples of the stimulus sentences used in this task can be found in Table 7.7 below.

Table 7.7 Examples for the stimuli sentences with code-switching used in the self-paced reading intermitted with flanker task

	Sentence starting with L1	**Sentence starting with L2**
Language alternations	他后来也承认，what he did just made the situation worse.	If you can join us tomorrow, 那就更好了。
Language insertions	应届生申请 graduate scheme 有很多优势。	The museum 正在展出 a sculpture by an artist from Greece.
Dense code-switching	Five minutes 之后 next group 要开始 present 他们的 project.	你 follow 这批 product 看看 laser marker 少了没。

Participants in this task were instructed to perform a flanker task interleaved within code-switching sentence reading. They needed to read the sentence one word at a time in a noncumulative moving-window procedure. A fixation cross appeared at the beginning for 500ms, and participants pressed the space bar to read the sentence word-by-word at their own speed. The previous word disappeared with each new word. This procedure attempts to imitate the incremental unfolding of spoken language: input towards the end of sentences cannot benefit from any preview since it is masked until actually encountered[3]. After reading each stimulus sentence, a flanker trial (either congruent or incongruent) follows. In the flanker trial, participants press corresponding keys (i.e., left and right arrows) on the keyboard to indicate the

[3] Consistent with the study of Adler et al. (2020), this design aims to measure bilinguals' real-time comprehension on spoken bilingual utterances, not written sentences. It is to explore the differences in bilinguals' cognitive control underlying real-time interpretation of code-switching and monolingual sentences. The self-paced reading procedure, requiring participants to press the button to read the sentence word-by-word, concealed any preview of a code-switch in the sentence, which is critical in measuring bilinguals' real-time bilingual utterances comprehension (Adler et al., 2020).

pointing direction of the arrow at the centre of the screen. The response time for each flanker trial is automatically stored.

In order to prevent participants predicting that a sentence would always be followed by a flanker trial, target trials (112 trials) were embedded within a large experimental context including different filler trials: 56 single flanker trials, 28 single stimulus sentences, and 21 sentences followed by 'yes/no comprehension questions'. 'Yes/no comprehension questions' were introduced to make sure the participants were paying attention during this task. In total, participants needed to complete 217 trials in seven sentence reading blocks and 22 practice trials (16 single flanker trials and six self-paced sentences reading) followed by 24 baseline flanker trials without sentence reading before the formal tasks were presented. Figure 7.6 shows the general procedure for this task.

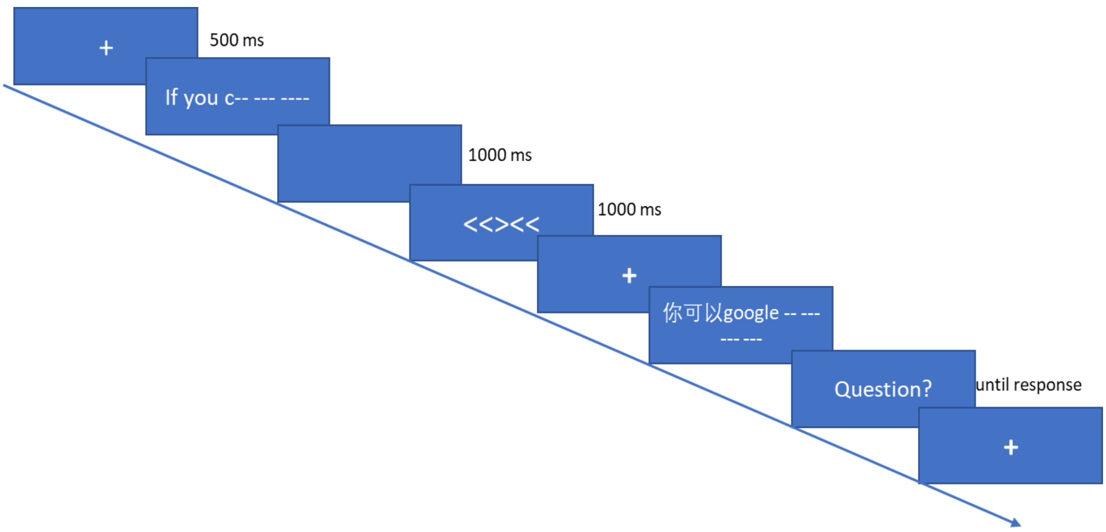

Figure 7.6 Procedure of the self-paced reading task intermitted with flanker trials

Procedure

Due to the unpredictable COVID-19 situation and the maintenance of a national lockdown policy in the UK, it was not possible to conduct face-to-face data collection in the lab. Therefore, participants who consented and registered for this study were instructed to complete all tasks remotely in their own quiet rooms. All tasks in this study were created using PsychoPy (Pierce et al., 2019) and hosted by the online platform Pavlovia (http://pavlovia.org/). Study instructions were explained carefully by the researcher to each participant through remote audio calls, and participants were given enough time to ask instruction-related questions. Then, online task links together with an e-copy of the study instructions were sent to consenting participants' email addresses.

At the beginning of data collection, the researcher invited participants to join a one-to-one online meeting session to complete a code-switching frequency judgement task by reading utterances with different patterns of code-switching and rating their frequencies of using such code-switching in communication. After that, participants were instructed to complete the aforementioned questionnaires, and the online LexTALE and Raven's Matrices test before starting the two experiments. Then, participants needed to complete the two experiments successively. Experiment 1 consisted of a spatial Stroop task and an adapted Simon task. The order of the two tasks was counterbalanced across participants. Participants in Experiment 2 needed to complete self-paced reading combined intermittently with flanker trials. Short breaks were allowed between each task and the two experiments.

Data preparation and data analysis

Data pre-processing

In the spatial Stroop task, RTs and response accuracy were recorded for a total of 6,400 trials (40 participants, 4 blocks, 40 trials per block). Eleven missing values (0.17% of trials) were excluded from the data analysis, and for the RTs, the following responses were also excluded from analysis (6.19%): incorrect responses (n = 233), correct responses with RT below 200ms (n = 1) and correct responses with RT above 2.5 standard deviations of participants' individual mean RT (n = 151), leaving 6,004 data points. Lastly, 6,004 trials (93.81% of the full data set) in the Stroop task were included in the analysis.

Similarly, participants' responses to a total of 6,400 trials (40 participants, 4 blocks, 40 trials per block) in the adapted Simon task were stored. Besides 52 missing values (0.81% of trials), the following responses: incorrect responses (n = 191), responses with RT below 200ms (n = 3) and correct responses with RT above 2.5 standard deviations of participants' individual mean RT (n = 189), were also excluded from the analysis (5.98%). Finally, RTs for 5,965 Simon trials (93.20% of the full data set) were included in the analysis.

In total, 5,440 responses to flanker trials interleaved within self-paced sentence reading were collected. Participants' RTs in the flanker task were analysed and only correct trial RT responses were included in the analysis (92.67% of the full data set). Hence, 186 incorrect responses, 71 missing data (1.31% of trials), two correct responses with RT below 200ms and 100 responses with RT above 2.5 standard deviations of participants' individual means were removed from the analysis.

Data analysis

Linear mixed effect models in R (Version 4.0.2; R Studio Team, 2020) were used to analyse participants' task performance in the two experiments. For the analysis of RTs, a mixed model was run, using the lmer function as implemented in the lme4 package for R (Version, 1.1 - 26; Bates et al., 2015). Participants' response accuracy in these tasks was analysed through the generalised linear mixed effects model with a logistic link function. The model was run with a glmer function as implemented in the lme4 package for R (1.1.21; Bates et al., 2015). The random effects of both subject and items were included in the analyses to account for variability across participants and different stimuli. Reported *p*-values were calculated based on Satterthwaite's method as implemented in the lmerTest package in R (Kuznetsova et al., 2017).

Experiment 1 explored the associations between code-switching processing and bilinguals' domain-general inhibitory control performance in the habitual language use condition. Interactions between z-scored bilingual language use-related variables (collected from questionnaires prior to the experiments) and participants' performance in the spatial Stroop task and adapted Simon task were analysed through linear mixed effect models.

In Experiment 2, participants' RTs and response accuracy in target flanker trials after reading different code-switching sentences were analysed through a linear mixed effect models to understand the effects of different code-switching patterns on bilinguals' inhibitory control in manipulated code-switching conditions. Z-scored values of bilingual code-switching experience related-variables were also fitted into the model to explore whether a bilingual code-switching habit also plays a role in affecting the engagement of cognitive control in bilingual language processing.

7.3.3 Results

Experiment 1 correlatively analysed bilinguals' code-switching habits and their performance on the spatial Stroop task and adapted Simon task, while Experiment 2 examined differences in flanker task performance after manipulating participants to read different code-switching sentences. Results of the two experiments are presented in the following sections.

Experiment 1: results for the spatial Stroop task and adapted Simon task

<u>*Stroop RTs*</u>

Results showed a main effect of congruency on participants' RT in the spatial Stroop task (β = 94.81, *SE* = 11.01, *t* = 8.61, *p* <.01), indicating that RTs for Stroop incongruent trials were significantly longer than RTs for congruent trials ($M_{congruent}$ = 453.01ms, $SE_{congruent}$ = 7.46; $M_{incongruent}$ = 547.82ms, $SE_{incongruent}$ =7.65). The Stroop effect ($RT_{incongruent}$ - $RT_{congruent}$) was also calculated and is presented in Table 7.8 together with participants' RTs in both congruent and incongruent Stroop trials.

Table 7.8 Participants' mean reaction time and response accuracy (n = 40) in the spatial Stroop task

	Reaction Time (ms)			**Response Accuracy (%)**		
	Mean	*SD*	*SE*	*Mean*	*SD*	*SE*
Congruent	453.01	47.21	7.46	98.16	0.59	0.09
Incongruent	547.82	48.38	7.65	90.46	7.86	1.24
Stroop effect	94.81	26.28	4.10	7.70	7.91	1.25

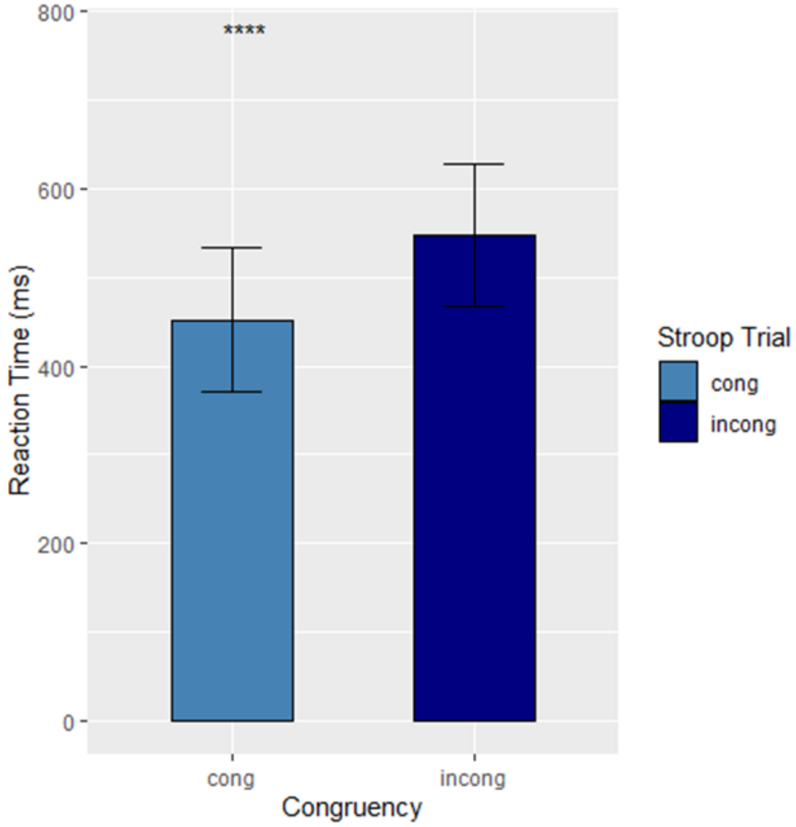

Figure 7.7 Mean reaction time (RT) for the spatial Stroop task. ns = no significant, *** indicates the p-value <.001, ** indicates the p-value<.01, * indicates the p-value<.05. Error bars represent standard errors. Cong means congruent trials, and incong means incongruent trials.

To investigate the effects of bilingual code-switching habits on participants' spatial Stroop task performance, z-scored bilingual L2 proficiency and frequency for each code-switching pattern were added into the linear mixed effects model. A random intercept for a Stroop item and one random intercept with a by-subject random slope of congruency were added initially, and the model reached best-fit convergence with participants' LexTALE scores included. Other variables related to bilingual different code-switching frequency did not significantly improve the model after inclusion. The final model describing the associations between Stroop RTs and bilingual L2 proficiency level is presented in Table 7.9.

Table 7.9 Fixed effects of the linear mixed effect model for RTs with congruency and z-scored bilingual code-switching habits variables as reference levels. Formula: RT ~ 1 + congruency + LexTale score + (1 + congruency | subject) + (1|item)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	500.82	8.66	57.86	**<.001**
Congruency	94.81	11.01	8.61	**<.01**
LexTale score	-14.23	6.97	-2.04	**<.05**

The model shown in Table 7.9 represented the interconnections between bilinguals' L2 proficiency level and their RTs in incongruent trials (β = -14.23, *SE* = 6.97, t = -2.04, p < .05). It indicated that bilinguals with higher L2 proficiency were prone to perform more efficiently in nonverbal incongruent Stroop trials.

Stroop accuracy

Participants' response accuracy was analysed through a generalised linear mixed effects model with a logistic link function. The maximal model fitted response accuracy with Stroop congruency and code-switching experience-related variables while including a random intercept for subject, a random intercept for item, and random slopes for congruency by subject and item. However, the maximal model did not converge. As bilingual code-switching experience and a random intercept for item did not improve the model, only a random intercept for subject to account for variability across participants was included. The final best-fit model is presented in Table 7.10.

Table 7.10 Fixed effects of the generalized linear mixed effect model for response accuracy with congruency. Formula: accuracy ~ 1 + congruency + (1 +congruency | subject)

Variable	Estimate	*SE*	*z*-value	*Pr* (>|z|)
Accuracy				
(Intercept)	3.97	0.11	36.68	**<.001**
Congruency	-1.53	0.19	-8.11	**<.001**

There was a significant effect for congruency (β = -1.53, *SE* = 0.19, *z* = -8.11, *p* <.001) on participants' response accuracy in this task, indicating that participants performed more accurately in congruent than incongruent trials (see Figure 7.8). Effects of bilingual code-switching habits on spatial Stroop task response accuracy were not found.

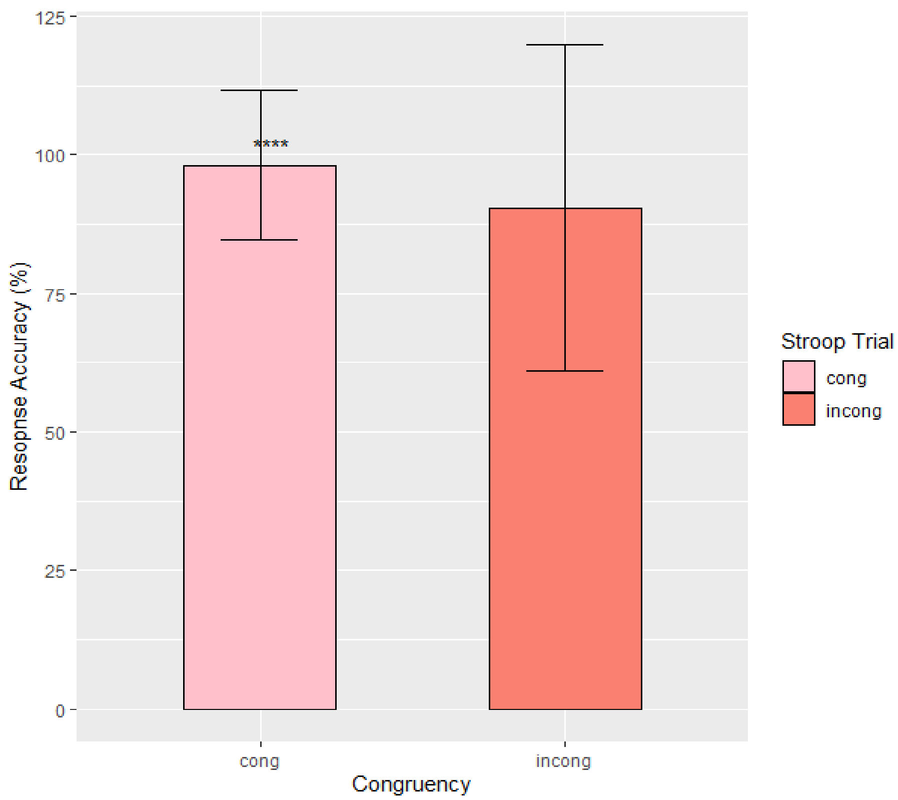

Figure 7.8 Mean response accuracy in the spatial Stroop task. ns = no significant, *** indicates the p-value <.001, ** indicates the p-value<.01, * indicates the p-value<.05. Error bars represent standard errors. Cong means congruent trials, and incong means incongruent trials.

Simon RTs

A random intercept for subject and a random intercept for item were added to the linear mixed model for analysing RTs in the adapted Simon task, and it reached convergence after a by-subject random slope for congruency was added. When z-scored bilingual language use-related variables were fitted into the model, it reached best-fit convergence.

Consistent with the spatial Stroop task, the main effect of congruency on participants' RTs (β = 85.93, *SE* = 12.89, *t* = 6.67, *p* <.001) was also found in this task (see Fig. 6), indicating that participants performed faster in congruent trials ($M_{congruent}$ = 537.86 ms, $SE_{congruent}$ =9.15) than incongruent trials ($M_{incongruent}$ = 618.61 ms, $SE_{incongruent}$ = 10.00). Table 7.11 below, shows participants' performance in this task.

Table 7.11 Participants' mean RTs and response accuracy (n = 40) in the adapted Simon task

	Reaction Time (ms)			**Response Accuracy (%)**		
	Mean	*SD*	*SE*	Mean	*SD*	*SE*
Congruent	537.86	57.85	9.15	98.60	1.07	0.17
Incongruent	618.61	63.23	10.00	91.58	14.73	2.33
Simon effect	80.75	57.20	9.04	7.02	14.15	2.24

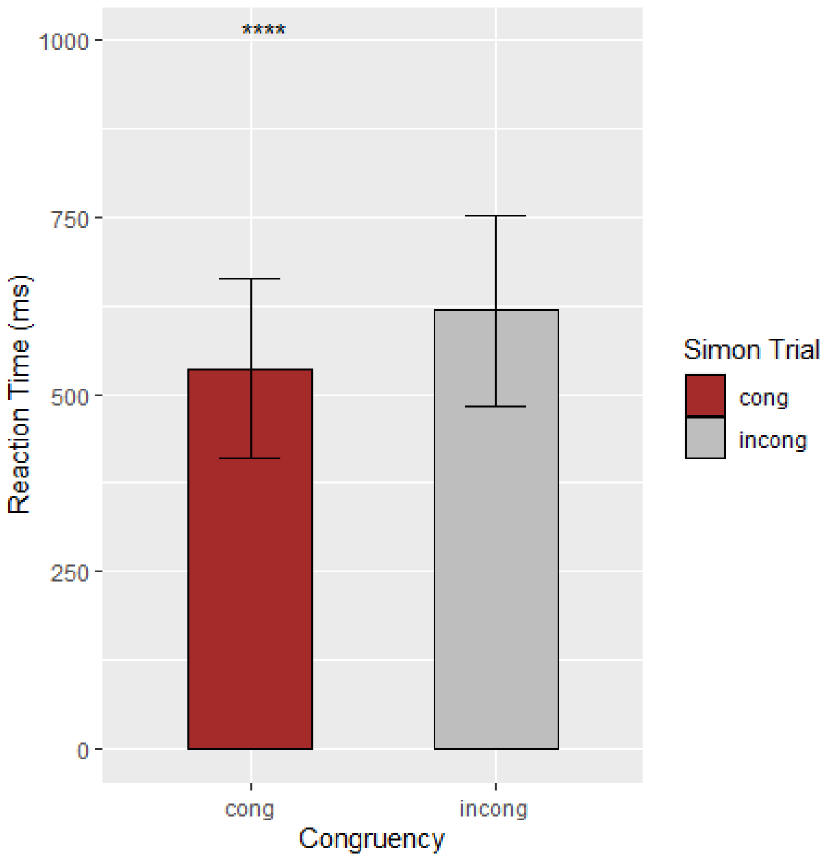

Figure 7.9 Mean reaction time (RT) in the adapted Simon task. ns = no significant, *** indicates the p-value <.001, ** indicates the p-value<.01, * indicates the p-value<.05. Error bars represent standard errors. Cong means congruent trials, and incong means incongruent trials.

The final model for the association between Simon RTs and bilingualism-related experience are presented as Table 7.12 below.

Table 7.12 Fixed effects of the linear mixed effect model for Reaction Time(ms) in the adapted Simon task with congruency and z-scored bilingualism experience-based variables as reference levels. Formula: RT ~ 1 + congruency + dual-language context index + single language scores + intersentential switching index + intrasentential switching index + L1 switch tendency + L2 switch tendency + contextual switch + unintended switch + alternation to English frequency + alternation to Chinese frequency + English insertion frequency + Chinese insertion frequency + dense code-switching frequency + (1 + congruency | subject) + (1 | item)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)	VIF Score
RTs (ms)					
(Intercept)	535.49	11.59	46.22	**<.001**	
Congruency	85.93	12.89	6.67	**<.001**	1.00
Dual-language context index	1.26	13.32	0.09		3.62
Single-language score	8.67	9.82	0.88		1.99
Inter-sentential switching index	33.82	11.17	3.02	**<.01**	2.62
Intra-sentential switching index	-17.90	12.30	-1.46		3.13
L1 switch tendency	-5.87	7.52	-0.78		1.91
L2 switch tendency	13.47	8.22	1.64		1.38
Contextual switch	-13.63	12.13	-1.12		3.04
Unintended switch	-11.16	10.98	-1.02		2.47
Alteration to English Frequency	-1.10	13.66	-0.08		3.88
Alteration to Chinese Frequency	14.40	14.93	0.97		4.57
English Insertion Frequency	26.25	15.39	1.71		4.87
Chinese Insertion Frequency	4.68	10.71	0.44		2.35
Dense Code-Switch Frequency	-6.86	9.80	-0.70		2.01

It further shows the main effects of inter-sentential index (β = 33.82, *SE* = 11.17, t = 2.93, p <.01) on bilinguals' RTs in this task, revealing a significant association between high frequency of processing utterances with intersentential switching and impeded inhibitory control efficiency. Other bilingual code-switching experience-related variables in the model did not show significant effects on participants' performance in this task. These result, however, do not strictly follow the predictions of the ACH and CPM, in which frequent processing of inter-sentential switching is expected to significantly boost bilinguals' efficiency in inhibitory control.

Simon accuracy

Participants' response accuracy was analysed using a generalized linear mixed effects model. A random intercept for subject and a random intercept for item were included in the model. No random slopes were included because the model did not converge. The model converged after adding bilingual language experience-based variables. However, with only a congruency effect included, adding bilingual code-switching experience-related variables did not improve the null model significantly. Therefore, the final model (see Table 7.13) retained the concise model format with only a congruency effect included.

Table 7.13 Fixed effects of the generalized linear mixed effect model for response accuracy with congruency. Formula: accuracy ~ 1 + congruency + (1 | subject) + (1 | item)

Variable	Estimate	*SE*	*z*-value	*Pr* (>|z|)
Accuracy (Intercept)	4.84	0.36	13.56	**<.001**
Congruency	-2.33	0.43	-5.39	**<.001**

The results show that participants performed with significantly higher response accuracy in congruent than incongruent trials (β = -2.33, *SE* = 0.43, *z* = -5.39, *p* < .001), and Figure 7.10, below, shows their response accuracy across different trials. There were, however, no significant effects of bilingual code-switching habits on participants' response accuracy in this task.

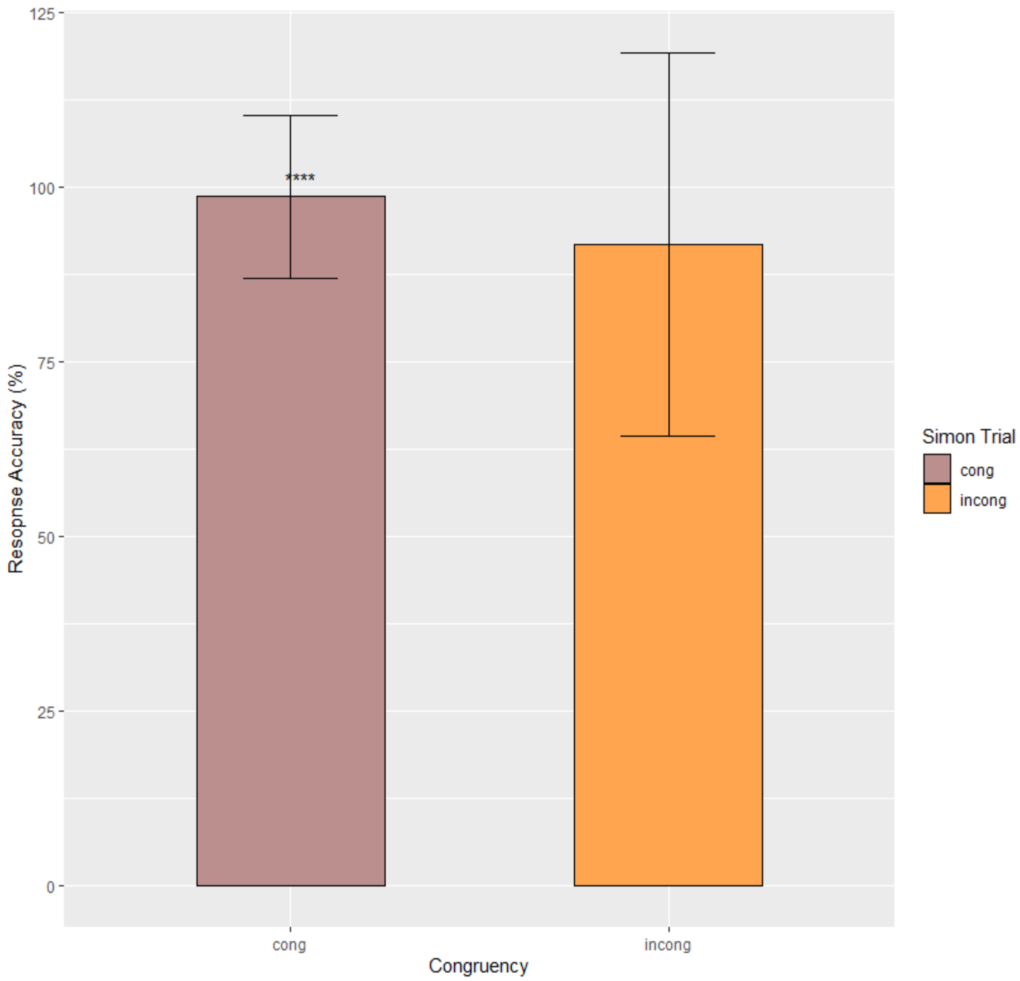

Figure 7.10 Mean response accuracy in the adapted Simon task. ns = no significant, *** indicates the p-value <.001, ** indicates the p-value<.01, * indicates the p-value<.05. Error bars represent standard errors. Cong means congruent trials, and incong means incongruent trials.

Experiment 2: Results of flanker task interleaved with self-paced reading

Participants’ performance in flanker trials after reading different code-switching sentences was analysed. Participants obtained an average score of 95.83% on interleaved comprehension questions, showing that they understood the task instructions and were paying attention during the task.

Flanker RT

Participants’ performance in flanker trials subsequent to different code-switching sentence reading was compared and presented in the Table 7.14 and Figure 7.11 below.

Table 7.14 Participants’ mean reaction time (n=40) in Flanker trials subsequent to different code-switching sentences reading

Sentence Reading Blocks	**Congruent**			**Incongruent**		
	Mean(ms)	**SD**	**SE**	**Mean(ms)**	**SD**	**SE**
Baseline (no reading)	531.92	71.09	11.24	531.93	61.11	9.66
English insertion	656.47	136.53	21.86	692.82	127.18	20.11
Chinese insertion	646.05	123.93	19.85	719.10	122.91	19.43
L2-L1 switching	628.82	119.94	19.21	693.26	123.51	19.53
L1-L2 switching	663.55	124.37	19.67	721.53	133.44	21.10
Dense code-switching	667.05	121.47	19.45	716.39	132.12	20.89
English only	660.58	128.45	20.57	723.40	128.02	20.24
Chinese only	642.43	116.62	18.67	685.61	120.03	18.98

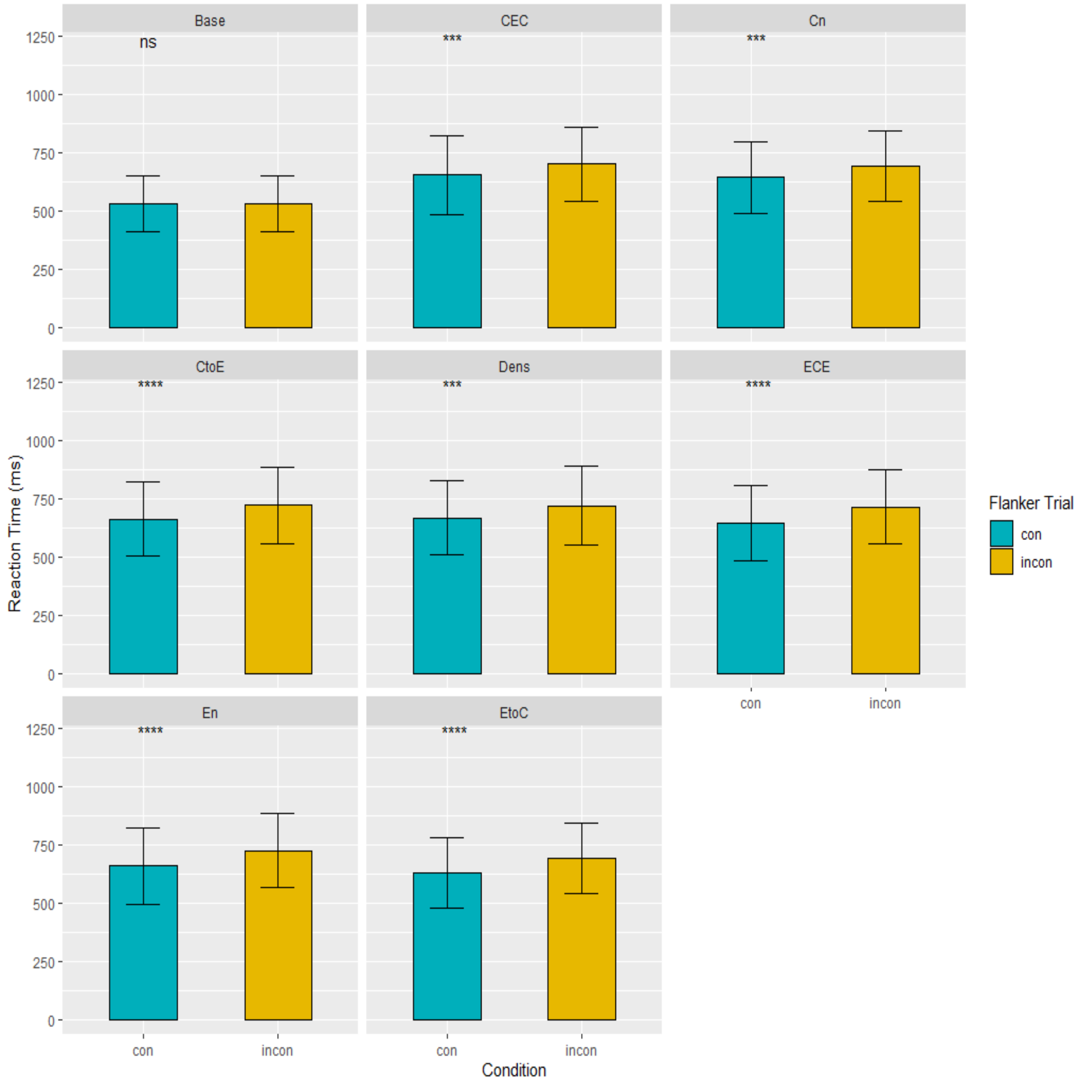

Figure 7.11 Comparison of reaction time in Flanker trials across different blocks. ns = no significant, *** indicates the p-value <.001, ** indicates the p-value<.01, * indicates the p-value<.05. con = congruent trials; incon = incongruent trials. Error bars represent standard errors. CEC = Chinese sentences with English insertions; ECE = English sentences with Chinese insertions; Dens = sentences with dense code-switching between two languages; CtoE = intersentential switching from Chinese to English (L1 alter to L2); EtoC = intersentential switching from English to Chinese (L2 alter to L1); En = English monolingual sentences; Cn = Chinese monolingual sentences.

The linear mixed effects model did not improve after z-scored bilingual language use-related variables were added. The final model retains a converged concise format including the fixed effects of block and flanker congruency interaction, a random intercept with a by-subject random slope for congruency and a random intercept for item. The effects of block and congruency interaction on participants' flanker RTs subsequent to reading sentence with different patterns of code-switching were shown as Table 7.15 below.

Table 7.15 Fixed effects of the linear mixed effect model for Reaction Time (ms) in Flanker task with congruency (congruent) and block interaction effects. Formula: RT ~ 1 + block * congruency + (1 + congruency | subject) + (1 | item)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	663.69	22.99	28.87	**<.001**
Congruency	-1.64	7.80	-0.21	
EN insertion Block	150.30	3.82	39.40	**<.001**
CN only Block	3.52	4.64	0.76	
CN insertion Block	-1.88	5.29	-0.35	
L2 to L1 switching Block	-12.23	5.00	-2.45	**<.05**
Dense switching Block	-9.66	4.52	-2.01	**<.05**
EN only Block	-31.72	6.08	-5.22	**<.001**
L1 to L2 switching Block	14.76	4.73	3.13	**<.01**
Congruency: EN insertion Block	53.57	7.70	6.95	**<.001**
Congruency: CN only Block	16.92	9.28	1.82	
Congruency: CN insertion Block	-2.83	10.58	-0.27	
Congruency: Dense switching Block	6.57	9.63	-0.68	
Congruency: EN only Block	-3.67	12.15	-0.30	
Congruency: L2 to L1 switching Block	13.74	9.99	1.38	
Congruency: L1 to L2 switching Block	12.76	9.45	1.35	

Compared to trials subsequent to sentence reading, participants on average performed fastest in the baseline flanker trials (β =150.30, *SE* = 3.82, *t* = 39.40, *p* <.001). Moreover, the main effect of sentence patterns on RTs in subsequent flanker task RTs was also found in the model. A post hoc analysis showed that after reading English (L2) to Chinese (L1) intersentential switching sentences, RTs for congruent trials were significantly reduced as compared to RTs followed by dense code-switching sentences (β =34.20, *SE* = 9.09, *t.ratio* = 3.76 , *p* <.05) and L1 to L2 intersentential switching sentences (β =32.82, *SE* = 9.02, *t.ratio* = 3.64 , *p* <.05). Moreover, participants responded faster in incongruent trials after reading sentences with L2 to L1 intersentential switching than reading English monolingual sentences (β =33.56, *SE* = 8.14, *t.ratio* = 4.12, *p* <.01). As for the effects of reading monolingual sentences, the results show that participants' RTs were significantly greater for incongruent trials after English than Chinese sentences (β = -34.21, *SE* = 8.22, *t.ratio* = -4.16, *p* <.01).

Flanker accuracy

A comparison of mean response accuracy between the baseline and other sentence-reading blocks was carried out (see Table 7.16). It showed that, in general, all participants performed accurately in both congruent and incongruent flanker trials.

Table 7.16 Participants' Response Accuracy (n=40) in Flanker trials subsequent to different code-switching sentences reading

Sentence Reading Blocks	Congruent			Incongruent		
	Mean(%)	SD	SE	Mean(%)	SD	SE
Baseline (no reading)	96.88	11.27	1.78	96.65	9.78	1.55
EN insertion	97.50	15.81	2.50	95.83	14.39	2.27
CN insertion	96.79	16.33	2.58	94.41	14.69	2.32
L2 to L1 switching	97.50	15.81	2.50	96.67	12.63	2.00
L1 to L2 switching	97.86	13.55	2.14	96.11	14.36	2.27
Dense switching	97.50	15.81	2.50	95.83	14.39	2.27
EN only	97.50	15.81	2.50	95.56	14.63	2.00
CN only	97.50	15.81	2.50	95.28	15.69	2.48

The generalised linear mixed effects model for analysing participants' response accuracy includes random intercepts for subject and item. As participant variability was found when performing congruent and incongruent trials, a random slope for congruency by subject was also included in the model. However, the model did not improve with z-scored bilingual language use-related variables added. Therefore, without these variables, the model retained best-fit model convergence.

The best-fitted generalized linear mixed effect model was presented as Table 7.17 below, describing the effects of congruency and different sentence reading on participants' response accuracy in the flanker task.

Table 7.17 Fixed effects of the generalized linear mixed effect model for response accuracy with congruency and block (baseline block) interaction effects. Formula: accuracy ~ 1 + congruency*block + (1 + congruency| subject) + (1 | item)

Variable	Estimate	*SE*	z-value	*Pr* (>|z|)
Accuracy (Intercept)	7.68	1.12	6.84	**<.001**
Congruency	-5.93	2.08	-2.84	**<.01**
Baseline Block	0.12	0.34	0.35	
EN insertion Block	-0.06	0.43	-0.14	
CN insertion Block	0.78	0.46	1.72	
Dense switching Block	-0.20	0.46	-0.42	
L1 to L2 switching Block	-0.48	0.46	-1.04	
EN only Block	0.25	0.57	0.43	
CN only Block	0.06	0.44	0.13	
Congruency: Baseline Block	-1.44	0.69	-2.09	**<.05**
Congruency: EN insertion Block	0.00	0.87	0.00	
Congruency: CN insertion Block	-0.30	0.91	-0.33	
Congruency: L1 to L2 switching Block	0.60	0.92	0.66	
Congruency: EN only Block	0.50	1.15	0.43	
Congruency: CN only Block	0.27	0.87	0.31	

The model shows that, in general, participants responded more accurately in congruent than incongruent trials (β = -5.93, *SE* = 2.08, *z* = -2.84, *p* <.01). However, there were no significant interaction effects between sentence reading and congruency, indicating that participants' response accuracy subsequent to different sentence reading was comparable without any significant differences.

7.3.4 Study discussion

This study examined the effects of bilingual code-switching and L2 proficiency on domain-general cognitive control through two experiments. Both experiments revealed the close interconnections between bilinguals' language processing practices and their domain-general cognitive control task, especially inhibitory control performance.

Experiment 1 revealed that L2 proficiency is an important factor in facilitating bilinguals' inhibitory control efficiency, while their habitual code-switching practices did not show significant effects on their inhibitory control. Specifically, it does not fully support the prediction of the ACH (Green & Abutalebi, 2013) that intensive practices of intersentential switching can contribute to bilinguals' higher efficiency in inhibitory control. However, Experiment 2, which manipulated participants in different code-switching processing conditions, indicates carry-over effects of code-switching patterns on inhibitory control efficiency. Specifically, after manipulating participants in intersentential switching conditions, participants performed interference suppression and inhibition more efficiently. Moreover, the study highlights the necessity to consider code-switching effects on cognitive control in natural and manipulated language use conditions.

Effects of code-switching and L2 proficiency on inhibitory control in a habitual language use condition

Experiment 1 revealed bilingual L2 proficiency to be a significant predictor of the magnitude of a nonverbal Stroop effect, indicating that higher L2 proficiency is positively associated with bilinguals' inhibitory control efficiency. This finding reflects the association between bilingual language control and domain-general cognitive control implicated in Green's ICM (1998). High language proficiency increases the degree of language activation, giving rise to cognitive demands and practices of conflict resolution and interference suppression, and further enhances bilinguals' experience in efficiently managing their languages to reduce cross-linguistic conflicts and disfluency in bilingual communication (Abutalebi et al., 2013; Costa & Santesteban, 2004; Dash & Kar, 2020; Tse & Altarriba, 2014a). This is also consistent with previous studies (e.g., Bonfieni et al., 2019; Costa et al., 2009; Dash & Kar, 2020; Mishra et al., 2012; Prior et al., 2016; Yow and Li, 2015) supporting a dynamic connection between bilingual language proficiency and cognitive control efficiency. As relevant studies (e.g., Gullifer et al., 2018; Linck et al., 2015; Luque & Morgan-Short, 2021) have reported, different language control processes depend on bilingual proficiency and cognitive control processes adaptively changing to allow more efficient bilingual language management with increased L2 proficiency.

However, Experiment 1 failed to find the hypothesised association between frequent code-switching practice and efficient inhibitory control. Instead of the expected modulation of frequent intersentential switching on inhibitory control, the adapted Simon task contrastively showed an association between frequent intersentential switching and longer incongruent Simon RTs.

One possible reason for this finding is that these bilinguals' habitual intersentential switching in naturalistic communicative settings was not as demanding as processing intersentential switching in manipulated code-switching settings (i.e., lab-based cued code-switching) (Blanco-Elorrieta & Pylkkänen, 2017; de Bruin et al., 2018; Gollan et al., 2014; Lai & O'Brien, 2020). The frequency of intersentential switching measured in this study was bilinguals' frequency of processing utterances with alternative use of Chinese and English in daily conversations. Different from lab-based cued intersentential switching, this naturalistic intersentential switching does not seem to impose heavy demands on language planning, cognitive monitoring or inhibition. Bilinguals alternatively use two languages and process intersentential switching based on their interlocutors (see the extended CPM in Green, 2018), their communicative purpose (Green & Li, 2014) or interactional settings they are involved in; and such naturalistic and self-initiated switching allows them sufficient time to plan their language properly before production (Hartanto & Yang, 2016). The smaller cognitive demands on their habitual intersentential switching practices did not provide them with extensive experience to exercise their efficiency in maintaining goals and conflict resolution. Therefore, their frequency of processing intersentential switching in habitual language use conditions failed to positively associate with their performance in the inhibitory control task.

In addition, bilinguals' habitual bilingual language use contexts should not be ignored when discussing the interaction between code-switching and cognitive control. The connection between cognitive control and code-switching can be mapped with "behavioural ecologies" in different sociolinguistic contexts (Green & Abutalebi, 2013; Green & Li, 2014, 2016; Green, 2011). Costa et al. (2009) point out that bilingual language selection is highly context-dependent. For example, if two languages are mainly switched based on social context cues or used in different sociocultural settings (i.e., single-language context bilingual users), then less attentional control of bilingual language selection and control might be required due to the facilitation of context cues. However, bilinguals habitually exposed to regular code-switching environments might require less cognitive effort in code-switching, and correspondingly gain slight cognitive control benefits associated with code-switching practices (Kang & Lust, 2019a).

In this study, the participants were bilinguals residing in English-speaking countries who regularly engage in Chinese-English use environment. They consistently self-reported that they had limited experience of intensive code-switching, and habitually used Chinese at home or with Chinese interlocutors, while switching to English at work or with English-speaking partners. The questionnaire results showed participants obtained quite high single-language context scores (Mean = 65, SD = 24.58, range = 9.00 ~ 98.80), indexing their intensive use of two languages separately in their daily lives. Although they obtained experience of using Chinese and English alternatively, their intersentential switching processing was heavily driven by sociocultural context cues. Their habitual bilingual language use contexts and regular engagement in language alternation in their lives did not seem to facilitate their cognitive monitoring and inhibition efficiency very much. This finding is consistent with what Hofweber et al. (2016) reported, in that intersentential switching did not show significant facilitation of bilinguals' inhibitory control efficiency. However, it should be clarified that the result here does not reject the association between bilingual habitual code-switching and cognitive control; instead, it only reflects the small facilitatory effect of engaging in one specific code-switching pattern in daily language use on bilinguals' cognitive control. Since the boundaries across each specific code-switching practice and interactional context in natural language use are fuzzy, bilinguals can flexibly engage in bilingual utterances with various code-switching patterns or in different interactional contexts in their daily communication (Green & Li, 2014; Lai & O'Brien, 2020). To capture the dynamic interaction between bilingual habitual language use and cognitive outcomes, it is important for future relevant studies to discuss the effects of code-switching patterns by referring to bilinguals' total intensity of engagement in code-switching.

Failure to observe the facilitatory effects of intersentential switching on cognitive control may also be attributed to the adapted Simon task design. The current task was in a low-monitoring condition, with 30% of incongruent and 70% of congruent trials. However, bilingual outcomes of cognitive monitoring and inhibition performance have been mainly found in high-monitoring condition cognitive tasks (Costa et al., 2009; Hofweber et al., 2016;

Singh & Mishra, 2012), with 1:1 congruent-incongruent trials. Costa et al. (2009) compared bilinguals' performance on flanker tasks with different monitoring conditions, and the results indicated that bilinguals' efficiency in conflicting processing was only found in a high-monitoring condition because their cognitive monitoring resources were highly engaged in this condition. The unbalanced proportions between congruent and incongruent trials in this study did not closely involve cognitive demands on attention altering and conflict monitoring, which might make it difficult to observe participants' individual differences in cognitive control efficiency.

To sum up, Experiment 1 addressed that, in a habitual language use condition, bilinguals' L2 proficiency showed significant facilitatory effects on their inhibitory control efficiency, while code-switching patterns did not.

Effects of code-switching patterns on inhibitory control in a manipulated language use condition

Experiment 2 explored how cognitive control is adaptively engaged in different code-switching manipulations, and revealed the modulation of intersentential switching processing in bilinguals' inhibitory control.

In this experiment, participants were found to respond most efficiently in the baseline flanker task session without reading any sentences. Then, their RTs to flanker trials preceded by sentence reading increased. It seems that reading sentences imposed extra cognitive load on participants' domain-general cognitive control, leading to more effort to complete the flanker task successfully. In line with Adler et al.’s (2019) study, the current task supported the engagement of cognitive control in code-switching comprehension, and found that incongruent flanker RTs subsequent to L2 to L1 intersentential switching were significantly faster than RTs subsequent to L2 monolingual sentences. Moreover, participants’ congruent flanker RTs subsequent to L2 to L1 switching were significantly faster than RTs preceded by dense code-switching sentences. These findings revealed the immediate carry-over facilitatory effect of intersentential switching on bilinguals’ domain-general inhibitory control performance, which provides evidence for the ACH’s and CPM’s predictions from the perspective of manipulated bilingual language comprehension. As the conflict adaption mechanism suggests, the sustained behavioural adjustments induced in initial conflict resolution support behavioural facilitation to deal with subsequent new conflicts (Gratton et al., 1992; Novick et al., 2005). It seems that conflict monitoring and interference suppression in intersentential switching processing sustained after sentence reading further facilitated conflict resolution efficiency in the immediately following flanker task.

Furthermore, the manipulated dual-language context, where both languages were used alternatively and appeared together in the same communicative setting, imposed the most intensive demands on cognitive control, including conflict monitoring and inhibitory control, to facilitate the control of competing cross-linguistic items. However, intrasentential switching is supposed to be coordinated by a cooperative control configuration, in which relatively less control of co-activated languages is involved (Green, 2018). The reduced cognitive demands on language-set conflict monitoring and inhibition in intrasentential switching further mitigated bilinguals' efficiency in conflict resolution beyond the language domain (Gollan & Ferreira, 2009; Green & Li, 2014, 2016; Hartanto & Yang, 2020).

Interestingly, the task also revealed that RTs for incongruent trials subsequent to L1 monolingual sentences were comparable to RTs subsequent to L2 to L1 intersentential switching sentences. The results indicate that conflict adaptation efficiency might depend on the language being intersententially switched to (Bosma & Pablos, 2020:10). For example, in L2 to L1 intersentential switching, it is the cognitive demands on L1 processing that sustain and affect performance on an immediately following flanker trial. That is to say, reading L1 in both mixed language contexts and monolingual contexts requires bilinguals' sustained control of their L2, and magnitude of sustained inhibition on L2 are comparable. Therefore, processing L1 in both language switching and monolingual contexts could impose similar degrees of modulation on participants' performance in subsequent flanker task trials, leading to comparable RTs for trials following L2 to L1 intersentential switching and L1 monolingual sentences. Similarly, the observation of comparable flanker task performance subsequent to L1 to L2 switching and L2 monolingual utterances further supports the existence of sustained control in bilingual language processing in the mixed language context.

As for flanker task performance after monolingual sentence processing, participants performed more efficiently in incongruent trials subsequent to L1 rather than L2 sentence reading. The results were different from Hofweber et al. ’s (2020) study, in which they found bilinguals’ improved inhibitory control performance in the L2 single-language context. The possible reason could be that the profile of bilingual participants in this study is different from theirs. Bilingual participants in this study are younger and have relatively earlier experience of immersing into L2 environment (Mean age= 25; Mean duration of L2 environment exposure = 3 years), as compared to participants in their study. Furthermore, adapting to the L2 dominant environment could be less effortful for these younger adults as compared to those more L1-dominant middle-aged bilinguals.

Besides, as both BSWQ and the code-switching judgement task shown, bilingual participants in this study are habituated to insert English into Chinese during language switching (Mean English insertion frequency = 19.63), and have relatively high L2 switch tendencies (Mean = 7.92) in communication. That is to say, these Chinese-English bilinguals are heavily dependent on L2 insertions when code-switching, although they are single-language context bilingual users (Mean single-language score = 65) and prone to switch languages based on contextual cues. Therefore, entirely controlling and suppressing linguistic interferences from L2 in L1 processing could be difficult for them, and requires higher cognitive demands on L2 inhibition. The heightened levels on L2 inhibition further imposes immediate facilitatory effects on their performance on the following nonverbal flanker task, leading to improved efficiency in inhibitory control.

In addition, the degree of carry-over facilitatory effects on cognitive control was found to be associated with code-switching direction. Specifically, L2 to L1 switching, as compared to L1 to L2 switching, showed more significant facilitatory effects on participants' RTs for subsequent congruent flanker trials. According to previous evidence on the cause-and-effect interplay between cognitive control and language, conflict-control is supposed to be involved in resolving language comprehension difficulties (Hsu & Novick, 2016; Novick et al., 2014). As there were few difficulties in dominant language processing, participants could be more efficient in comprehending information conveyed in L1 without intensive linguistic conflicts control demands involved. Therefore, the lightened conflict-control demands on processing the immediately prior language (i.e., L1) enhanced bilinguals' cognitive control efficiency, which further lead to their better performance on trials without visual interference (i.e., congruent flanker trial). Furthermore, this finding is also in line with Bultena et al.'s studies (2015a, 2015b), in which they suggest that bilinguals' higher proficiency in L1 contributes to their efficiency in activating L1 linguistic resources, and less cognitive efforts in reading L2 to L1 switching (i.e., bottom-up language control schema in language comprehension). So, the relatively less cognitive efforts and efficient language control in prior L2-L1 switching significantly modulated bilinguals' conflicts monitoring and control efficiency.

To sum up, in this experiment, participants who read sentences with different code-switching patterns were constantly prepared by conflict control to deal with possible forthcoming cross-linguistic competition or misunderstandings caused by unexpected code-switching (Adler et al., 2020; Hsu & Novick, 2016; Valdés Kroff et al., 2018). The conflict-control demands manipulated in prior code-switching utterance processing could immediately facilitate participants' performance in a subsequent nonverbal cognitive control task (e.g., the flanker task). On the one hand, this finding reflects the immediate carry-over effects of code-switching patterns on bilinguals' inhibitory control in the manipulated code-switching condition; on the other hand, it shows that the degree of such facilitation is influenced by the language switching direction and the language that a sentence ultimately switches to.

7.3.5 Study conclusion

The two experiments have, respectively, discussed the effects of bilinguals' code-switching habits in daily communications on cognitive control and the modulation effects on cognitive control derived from code-switching processing manipulation. This study is an important attempt to distinguish the cognitive effects of code-switching processing between habitual and manipulated bilingual language conditions. As bilinguals' code-switching patterns are not fixed and might continuously change throughout their long-term habitual bilingual language use experience, Experiment 1 failed to find the expected interaction between intersentential switching patterns and bilinguals' cognitive control efficiency. However, the finding of intersentential switching effects on bilinguals' cognitive control facilitation in the manipulated bilingual language condition in Experiment 2 finds the adaptive engagement of domain-general cognitive control in different code-switching comprehension and supports the predictions made by the ACH.

In general, the study emphasises the necessity to consider differences of cognitive demands on habitual and manipulated code-switching processing; and future research with a more dynamic perspective on bilingualism development and cognitive benefits is suggested.

There are limitations to this study. Besides the small sample size, the psychometric properties of both cognitive control tasks and bilingual questionnaires were not discussed. Additionally, this study administered three similar nonverbal tasks involving inhibitory control assessment to avoid single-task measure bias, and the reliability and validity of the adapted Simon task as well as other tasks should be controlled to avoid inaccurate measurements and task impurity problems (Kałamała et al., 2020; Miyake et al., 2000b; Miyake & Friedman, 2012). Future relevant studies should carefully consider cognitive task and questionnaire psychometric properties and how to avoid measurement bias in a behavioural study design.

7.4 Summary of this Chapter

The two studies in this chapter investigated the effects of habitual bilingual language use experience on bilingual language comprehenders' inhibitory control efficiency in both induced and naturalistic language use conditions. Bilingual participants' inhibitory control performance was assessed through different nonverbal cognitive tasks, including flanker task, spatial Stroop task and Simon task, across the two studies.

Generally, the studies revealed the mediations of domain-general cognitive control in comprehending bilingual utterances, and provided evidence for bilinguals' adaptive deployments of cognitive control in comprehending different patterns of code-switching, which supported the proposals of ACH and CPM.

Noticeably, the magnitudes of bilingual language experience effects on cognitive control were found to vary across comprehending bilingual languages in the habitual and induced interactive conditions. Specifically, in bilinguals' habitual language interactive conditions, bilingual participants' L2 proficiency, rather than their habitual code-switching patterns and frequency, showed significant facilitations on their inhibitory control efficiency; while the high frequency of inter-sentential switching in daily communications did not show modulations on their inhibitory control. However, even the modulations of intersentential switching on bilinguals' inhibitory control in naturalistic bilingual language comprehension process were not observed, such effects were found in the induced language comprehension process. That is, the studies indicated that bilinguals' inhibitory control efficiency in both language reading and listening comprehension was significantly enhanced after they being induced in the dual-language contexts or frequent intersentential switching conditions. The findings, observed in the induce language comprehension conditions, supported the predictions discussed in the ACH and CPM, which further reflected the importance of considering cognitive demands variations across bilingual language processing in habitual and induced language use conditions.

Consistent with Chapter 6, studies in this chapter also indicated that bilinguals' habitual language use experience could impose significant effects on modulating their cognitive control efficiency in language comprehension processes. Additionally, the two studies highlight the necessity to distinguish the cognitive effects of comprehending bilingual speeches in bilingual individuals' habitual language use conditions or in the lab-based language inducement paradigm.

In the next chapter 8, general discussions and explanations on the key research questions of the whole project will be presented. Some limitations of the current project and suggestions for future research will also be introduced.

Chapter 8 General Discussion and Conclusion

8.1 Introduction and Overall Findings Summary

Bilingualism, in fact, can be regarded as a dynamic second language learning process, comprising different sociolinguistic and demographic features (Luk & Bialystok, 2013; Surrain & Luk, 2019). Confounding variables, including language proficiency, age of language acquisition, habitual language using patterns and L2 exposure related factors, are found to have the potential to affect bilingual adults' performance in language and cognitive tasks (Celik, Kokje, Meyer, Frölich & Teichmann, 2020). Therefore, these variables cannot be ignored in understanding the complicated relationships between bilingualism and cognitive outcomes.

So far, four empirical studies in my research project have been introduced and discussed. The core question about the interconnection between bilingualism and domain-general cognitive control underlying language processing among late bilingual adults was analysed through bilingual language production (studies 1 and 2) and comprehension (studies 3 and 4) perspectives. Although the findings varied slightly across the studies, they commonly indicated that bilingualism, as the most intense, sustained and integrative human experience, with multifaceted components in language acquisition and use, has potentially modulating effects on cognitive functioning for both language processing and other behaviours beyond language domains. In general, the whole project was built on three influential theoretical frameworks, ICM, ACH and CPM, for bilinguals' cognitive control mechanism in language control processes. The main aim of this thesis is to examine the predictions made in these theoretical frameworks, and explore how bilingual adults' habitual language use experience affects the cognitive control processing underlying their language production and comprehension performance. The thesis also presents comparisons of bilinguals' cognitive control mechanisms underlying their language processing in both naturalistic and induced (i.e., lab-based) language use conditions. It addresses how bilinguals deploy cognitive control differently to process languages in two conditions, and highlights the importance of accounting for the role of bilinguals' naturalistic communicative settings in discussing the cognitive effects of bilingualism.

Noticeably, most of the studies in this project were conducted (between 2020 and 2022) online due to the long-term influence of the global Covid-19 pandemic. This project is, innovatively, a significant attempt to conduct behavioural experiments through online platforms and test bilingual participants' linguistic and cognitive performance remotely. Compared to traditional lab-based experiments, online behavioural experiments seem to have become a new trend for future research because it is a more efficient way to test participants with more diverse cultural and language backgrounds around the world. More importantly, the findings revealed in both online and in-person studies in the project have comparable reliability and robustness. That is, in addition to providing more evidence for understanding bilingualism’s effects on cognitive control, the project is significant as it sheds new light on online behavioural study design and data collection. Table 8.1, below, summarises the findings of each study in this project.

Table 8.1 Summaries of all studies in this project: participants, behavioural tasks and findings

Study	Participants	To investigate	Behavioural Tasks	Findings
1	31 Chinese-English bilinguals; Mean age: 27.68 years	Effects of bilingual code-switching habits on participants' cognitive shifting and inhibition performance	Bilingual picture-naming task; Colour-shape switching task: cognitive shifting; Go/No-go task: response inhibition	• Habitual single-language context bilinguals with less practices in code-switching are experts in goal maintenance. • Frequent code-switchers showed efficiency in switching between different nonverbal tasks. • Frequent code-switchers are proficient in controlling nonverbal interferences and resolving response conflicts.
2	41 Chinese-English bilinguals; Mean age = 26 years	Interconnections between bilingual language use habits and cognitive control efficiency in Chinese-English bilinguals living in an L2 environment.	Spontaneous bilingual language production tasks (Naturalistic conversation task, Story Narration Task) Verbal Stroop Task: verbal inhibitory control; Spatial Stroop Task: nonverbal inhibitory control; Colour-shape switching Task: cognitive shifting	• Frequent intersentential switching is associated with bilinguals' greater verbal and nonverbal inhibitory control efficiency. • Intensive L2 environment exposure can significantly modulate bilinguals' nonverbal inhibitory control efficiency. • Habitual code-switchers are efficient in verbal inhibitory control. • Habitual single-language users showed heightened strength in proactive inhibition in the colour-shape switching task.
3	36 Chinese-English bilinguals	Effects of interactional contexts on participants' inhibitory control performance	Flanker task: nonverbal inhibitory control; Different bilingual dialogue listening;	• Both dual-language and dominant language contexts showed modulating effects on bilinguals' inhibitory control performance.

	Mean age: 24.25 years		After-listening comprehension questions	• Dominant language modulated bilinguals' language comprehension performance while the dual-language context did not.
4	40 Chinese-English bilinguals Mean age: 25.08 years	The different effects of bilingual language use experience on participants' inhibitory control performance in habitual and induced language use conditions.	Adapted Simon task: nonverbal inhibitory control; Spatial Stroop task: nonverbal inhibitory control; Flanker task: nonverbal inhibitory control; Self-paced bilingual utterances reading	• In the bilinguals' habitual language use condition, L2 proficiency showed facilitatory effects on bilinguals' inhibitory control performance, while their habitual code-switching patterns did not show such effects. • In the induced language use condition, reading intersentential switching sentences is significant to enhance bilinguals' inhibitory control efficiency.

In the following sections of this chapter, I will recap and discuss the main findings of these studies in relation to the three theoretical frameworks introduced previously. Some limitations of the project and future directions will then be discussed.

8.2 Relationship between bilingual habitual language use experience and cognitive control in language production

Study 1 discussed bilinguals' cognitive control mechanism in cued-language switching production while study 2 focused on bilinguals' language production in naturalistic conditions. Participants' habitual language use experience was assessed in both studies. The two studies point out that bilingual speakers' inhibitory control efficiency in language production, regardless of cued- or non-cued conditions, is significantly affected by their habitual code-switching practices and language use contexts. Frequent code-switchers with fluent Chinese-English co-use experience showed higher efficiency in inhibitory control for suppressing both verbal and nonverbal interference in the two studies. On the other hand, those habitual single-language context bilinguals lacking experience of code-switching were found to be more expert in proactive inhibition and goal maintenance. These findings are in line with the predictions of the ACH and CPM, indicating that cognitive control is adaptively deployed to mediate bilingual language production in different contexts or patterns. Noticeably, L2 exposure was also found to be an important factor in modulating the efficiency of inhibitory control in naturalistic language production processes, while such effects were not observed in participants' cued-language switching production.

As L2 exposure interconnects with bilinguals' ability in proactive inhibitory control of L1 and language dominance (Beatty-Martínez et al., 2020; Woumans et al., 2016; Zhang, Diaz, Guo & Kroll, 2021), more intensive L2 exposure should facilitate bilinguals' L1 control for L2 processing, which further contributes to the enhancement of their domain-general inhibitory control. Increasing L2 exposure should also reduce bilinguals' L1 use frequency and lighten their L1 dominance in daily communication, which leads to much easier access to L2 and greater flexibility in switching between two languages (Xie & Dong, 2021; Struys et al., 2019). Therefore, instead of fast modulation or carry-over effects, the modulating effect of L2 exposure on bilinguals' inhibitory control in language production is individuals' naturalistic language being experience-based, long-lasting and continuously developing.

The interconnections between bilinguals' code-switching production in cued and non-cued conditions and their cognitive shifting abilities were also analysed in the two studies. Consistently, results showed that the interactional contexts where bilinguals habitually use their languages played important roles in influencing their nonverbal cognitive shifting abilities. Specifically, habitual single-language context bilinguals, lacking practice in code-switching in daily communication, performed less efficiently in task-set switching; while those bilinguals with intensive experience of using languages in code-switching contexts were found to have greater efficiency in cognitive shifting. Noticeably, no association was found between bilinguals' performance in a cued code-switching task (i.e., picture-naming task) and their cognitive shifting performance in study 1. Study 2 further indicated a negative relationship between bilinguals' RT mixing costs in the cognitive shifting task and their extent of single-language context engagement. Therefore, the results reflect the modulating effects of code-switching contexts engagement on bilinguals' domain-general cognitive shifting abilities, suggesting a close correlation with the cognitive mechanism underlying verbal and nonverbal task-set switching. Moreover, in line with participants' cognitive inhibition performance measured in the two studies, the studies further reveal that bilinguals' proactive inhibition strength is supposed to be enhanced in single-language contexts, through constant exercise of global control over linguistic interference from a co-activated competing language for monolingual utterances production.

In sum, the two studies point to the essential role of sociolinguistic factors in bilingualism, such as bilinguals' habitual engagement in code-switching practices and contexts, influencing their cognitive control in language production processes. Furthermore, they highlight that such influence derives from bilinguals' long-term, dynamic and continuously-developing language use habits. That is, bilinguals' efficiency in cognitive inhibition, shifting, task disengagement and engagement and conflict monitoring and resolving is continuously trained through their intensive practice in managing competing linguistic resources in co-activated languages during code-switching production.

In this vein, sociolinguistics-related factors in bilingual language experience, such as language use patterns and contexts, are important in affecting the ecological validity of relevant research on the interconnection between bilingual language processing and cognitive control. More studies, accounting for these factors, are needed in future research.

8.3 Relationship between bilingual habitual language use experience and cognitive control in language comprehension

Studies 3 and 4 focused on bilingual language comprehension processes, and explored the association between bilingual language use experience and bilinguals' deployment of cognitive control in comprehending bilingual utterances. The effects of language proficiency and code-switching patterns on cognitive control in habitual and induced language use conditions were compared. Fast modulation effects of dual-language contexts or intersentential switching on bilinguals' inhibitory control efficiency in language comprehension processes in induced language use conditions were found. These results are in line with the predictions of the ACH and CPM, providing evidence for the variation in cognitive control deployment in processing languages in different contexts or processing utterances with different code-switching patterns. Since bilinguals need to constantly monitor and control verbal interference from two languages to process language switching at the clause level, multiple aspects of the cognitive control processes related to cue detection, task engagement and disengagement and selective response inhibition are involved and assumed to be exercised in this context. Study 3 also highlighted Chinese single-language context effects on bilinguals' inhibitory control, reflecting the role of language dominance in affecting bilinguals' language and cognitive control processes. These unbalanced bilinguals' cognitive demands on L2 inhibition are heightened to facilitate their language processing in the L1 single-language context, therefore, their heightened cognitive inhibition demands extended further to modulating their performance in the immediately-followed nonverbal inhibitory control task.

Different from the results for language comprehension in the induced language use conditions, L2 proficiency, rather than specific language use contexts or patterns, was found to impose significant modulating effects on bilinguals' inhibitory control in their habitual bilingual language comprehension processes in study 4. This finding reflected the inhibitory control model, in which the degree of language activation is supposed to be associated with the proficiency level in this language. A higher language activation level gives rises to cognitive demands to suppress interference from this language in communication, which further enhances bilinguals' practice in bilingual language management and efficiency in inhibitory control. Bilinguals' habitual code-switching patterns or specific interactional contexts did not show significant effects on their inhibitory control underlying language comprehension in their daily communication.

In sum, the two studies highlight the adaptations of cognitive control in processing bilingual languages in different patterns or contexts from the perspective of language comprehension, providing evidence for the ACH and CPM. Although bilingual language experience was observed to have modulating effects on bilinguals' inhibitory control, the degree of those effects varied across the naturalistic language use condition and lab-based language use manipulations. Fast modulation of code-switching patterns and interactional contexts was not found to be significantly associated with bilinguals' cognitive control underlying language processing in naturalistic language use conditions. Bilinguals are able to use any patterns of code-switching and engage in different contexts flexibly in naturalistic communication, therefore, factors related to their development of bilingualism experience, such as L2 proficiency, are assumed to have relatively long-term effects on both their language and cognitive control. Moreover, results from the two studies address the differences in cognitive demands to comprehend bilingual utterances in habitual and manipulated language use conditions, and so future research is suggested to take a dynamic perspective on individuals' bilingualism development and its interaction with cognitive control outcomes.

8.4 Project Limitations and Strengths

Due to the impact of the pandemic, all the studies in this project, except for study 3, which was conducted in 2019, were administered online. The pandemic also seriously affected participant recruitment for this project, leading to a relatively small sample size for each study. Compared to traditional lab-based behavioural experiments, it was more difficult to control and balance the experiment environment and equipment across individuals. Although each participant was clearly instructed to take part in the experiment in their own quiet room and was given enough time to practise the experimental procedure, noise related to participants' different equipment and different qualities of Internet connection was still hard to control and may have affected their response measurement or reaction time calculations. Furthermore, it was easier for participants to quit in the middle of online studies, resulting in higher withdrawal rates.

However, this project is one of the first attempts in bilingualism research to conduct behavioural experiments online and test bilingual individuals remotely. Several online experiment platforms were used and tested in the project, and have been introduced in this thesis. Such remote data collection method has the potential to become a new trend in future research in the post-pandemic era, since it offers a greener, more efficient and economic approach to test participants from more diverse cultural and language communities. It is promising to see increasing numbers of bilingual research-related studies being conducted online, which allows cross-comparisons of data collected online, and improves the validity and reliability of online experiment platforms.

Noticeably, the participants in this project were all Chinese-English bilingual adults, living in an L2 (English) environment. Therefore, the findings of this project might be limited to this specific linguistic and cultural group (Chinese-English bilinguals). Moreover, the participants were young adults, the majority of them being in their early 20s at the time of joining this project. Age could be another factor, interacting with their language use experience, to contribute to their outstanding performance in cognitive control tasks. In this vein, to have a clearer understanding of how bilingual language experience affects cognitive control, the project needs to be replicated in longitudinal studies or cross-sectional studies including participants from different age groups and linguistic-cultural communities (e.g., Japanese-English bilingual older people; Welsh-English bilingual children).

In addition, assessing bilinguals’ language use experience in this project predominantly relied on self-reported questionnaires, thus lacking objective measures to quantify their L1 and L2 use amounts in daily interactions. To fill these gaps, study 2 adopted a series of comprehensive approaches, including language entropy computation (Gullifer et al., 2018) and spontaneous language production tasks, to capture the characteristics of participants’ bilingual language use in naturalistic conditions. Although the positive evidence for adaptive cognitive control in naturalistic bilinguals' speech production revealed in study 2 might have been a constraint of these Chinese-English bilinguals, the bilingual language use experience measurement used in this study motivates future work to seek more reliable and valid approaches to compute bilingual language experience objectively.

Lastly, cross-lab and cross-disciplinary cooperation is necessary to enhance our understanding of the cognitive mechanisms underlying language processing and the connection between the developments of cognitive function and language experience. The results obtained in this project only indicate an association between language use and bilinguals' cognitive control performance; however, this association does not represent causation (Filippi, 2011), and whether bilinguals' cognitive control outcomes are due to their sustained bilingualism experience still needs more behavioural and neuroimaging data, or data from cross-lab investigations and longitudinal research projects.

8.5 Conclusion and Future Research Directions

Building on a series of theoretical frameworks, including the ICM (Green, 1998), ACH (Green & Abutalebi, 2013) and CPM (Green & Li, 2014), this research project discusses the interconnection between bilingual experience and human cognitive development through four behavioural studies. It further sheds new light on the cognitive control mechanism underlying bilingual language processing and bilinguals' cognitive outcomes attributed to their lifelong bilingualism.

The results presented in this thesis reflect the dynamic interaction between bilinguals' continuously-developing bilingualism experience and cognitive control ability, providing new evidence that the intensive and sustained experience of bilingual language processing has the potential to impose significant modulation effects on both language control but also cognitive functions related to nonverbal cognitive tasks. Although the results of the project only partially support the predictions of the ACH and CPM, the project emphasises the continuum features of bilingualism and the interactive role of sociolinguistics-related factors in bilingualism in terms of shaping and influencing individuals' cognitive development.

More questions and ideas were raised in the course of this project. However, it was not possible for me to extend my studies or conduct new experiments to explore these questions due to the time constraints of my PhD journey. For example, it would be exciting to explore the impact of additional sociolinguistics-related factors in bilingual experience, such as L2 exposure and language switching attitudes, on bilingual individuals' language and cognitive control processes. It is also worth exploring how cognitive control is deployed to process multimodal linguistic resources in different social contexts; and to examine whether the Adaptive Control Hypothesis can be further extended to explain the cognitive control mechanism involved in multimodal linguistic resources processing. Moreover, given the inconsistent findings for bilinguals' cognitive control in cued and non-cued code-switching processing, much more attention needs to be paid, in future work, on how to capture and assess bilinguals' language use experience and assess their cognitive control deployment in naturalistic communicative settings ae needed. Noticeably, this project only tested Chinese-English bilingual adults with a mean age of around 30 years old, therefore, studies focusing on all age groups of bilingual or multilingual speakers with more diverse language and cultural backgrounds are also needed to have a more comprehensive understanding of the dynamic development trajectory of individuals' bilingualism and cognitive functions.

This project has obtained positive results for the association between intensive practice in co-using two languages in one's daily life and bilingual adults' cognitive inhibition outcomes. If the cognitive outcomes observed in this project can be replicated in future work or broadly found to be true, the project could then have important implications for the general public. In particular, it provides individuals in society, including language educators, health professionals and bilingual families, with more scientific research evidence to debunk some common misconceptions and "myths" associated with bilingualism and bilingual education, such as the belief that a bilingual education will lead to children's incomplete language acquisition, or speaking more than one language will result in cognitive deficiencies. On the other hand, it can also motivate more cross-disciplinary research to explore the overlap of cognitive functions between language and nonverbal task processing, and allow a better understanding of the connection between brain plasticity and language learning/ using experience from a neuroscience perspective. Consequently, this promising and multifaceted bilingual research has strong potential to guide health professionals in the future to improve their assessments of and clinical therapies for people diagnosed with cognitive dementia, or patients with impaired cognitive functions.

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Appendices

Appendix I: Questionnaires used in this project to measure Chinese English bilingual participants’ language use experience

Bilingual Switching Questionnaire with Chinese translation *(Adapted from Rodriguez-Fornells., 2012)*

Please, try to answer to what degree the following questions represents the manner you use to talk or speak in Chinese and English. Many of these questions ask you to report your tendency to switch or mix languages during a conversation. Switching and mixing languages is a characteristic of some bilingual contexts or environments, as for example in Hong Kong. The present questionnaire aims to identify Chinese and English switching patterns that exists in London. If you have doubts about how to rate yourself in the following questions, please try to compare your manner of speaking and talking with that of most people, or those who you know very well.

请根据你日常使用中文与英语的方式来回答以下问题。你会被问及关于自己日常在对话中对两种语言切换和混用的倾向。语码转换和语码混用是常在某些双语场合或环境中出现的特点，本问卷旨在确认在目前日常生活中，您汉语和英语相互切换与混用的情况。如果不确定答案，请参考您身边或您熟悉的人在该社群中的交流方式，做出回答。

1. I do not remember or I cannot recall some English words when I am speaking in this language. 在我说英语时，我会不记得或想不起来有些英语单词。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

2. I do not remember or I cannot recall some Chinese words when I am speaking in this language. 在我说中文时，我会记不起来一些中文词汇。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

3. I tend to switch languages during a conversation (for example, I switch from Chinese to English or vice versa). 我在对话交流中会在两种语言间的相互切换，比如，在说中文时把一些表达切换成英文。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

4. When I cannot recall a word in English, I tend to immediately produce it in Chinese.
当我想不起某个英语词汇时，我会立即改用中文表达这个词。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

5. When I cannot recall a word in Chinese, I tend to immediately produce it in English. 当我想不起某个汉语词汇时，我会立即改用英文表达这个词。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

6. I do not realize when I switch the language during a conversation (e.g., from English to Chinese) or when I mix the two languages; I often realize it only if I am informed of the switch by another person. 我时常在会话中不自觉的使用两种语言，如果别人不提醒，自己并不会意识到自己在混用或交替使用两种语言。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

7. When I switch languages, I do it consciously. 我是有意识的(或刻意的）进行双语转换的。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

8. It is difficult for me to control the language switches I introduce during a conversation (e.g., from English to Chinese). 我很难控制我在对话中的语言切换（比如，很难控制自己在说中文时出现的一些英文表达）。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

9. Without intending to, I sometimes produce the Chinese words faster when I am speaking in English. 一般自然状态下，在我说英语时，我更容易且更快想到的是中文。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

10. Without intending to, I sometimes produce the English words faster when I am speaking in Chinese. 一般自然状态下，在我说中文时，我更容易且更快想到的是英语。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

11. There are situations in which I always switch between the two languages. 会有一些场合，使我一直交互使用两种语言

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

12. There are certain topics or issues for which I normally switch between the two languages. 会有一些话题或事件，我一般来说，在讨论的时候倾向于两种语言相互转换使用。

Never☐ Very frequently☐ Occasionally☐ Frequently☐ Always☐

Language and Social Background Questionnaire *(Adapted from Anderson et al., 2018)*

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

12.	Please indicate the highest level of education and occupation for each parent:				
Mother			Father		
1.		No high school diploma	1.		No high school diploma
2.		High school diploma	2.		High school diploma
3.		Some post-secondary education	3.		Some post-secondary education

4.		Post-secondary degree or diploma	4.		Post-secondary degree or diploma
5.		Graduate or professional degree	5.		Graduate or professional degree
Occupation:			Occupation:		
First Language:			First Language:		
Second Language:			Second Language:		
Other Language:			Other Language:		

13.	When did you move to English-speaking countries/regions?			
14.	Have you ever lived in a place where Chinese is not the dominant communicating language?		**Yes** ☐	**No** ☐

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

Language Background

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

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

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

16.1 **English**

	No Proficiency 0	5	High Proficiency 10
Speaking	●——	———	——●
Understanding	●——	———	——●
Reading	●——	———	——●
Writing	●——	———	——●

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

	None	Little	Some	Most	All
Speaking	☐	☐	☐	☐	☐
Listening	☐	☐	☐	☐	☐
Reading	☐	☐	☐	☐	☐
Writing	☐	☐	☐	☐	☐

17.1 **Chinese:**

	No Proficiency 0	5	High Proficiency 10
Speaking	●——	———	——●
Understanding	●——	———	——●
Reading	●——	———	——●
Writing	●——	———	——●

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

	None	Little	Some	Most	All
Speaking	☐	☐	☐	☐	☐
Listening	☐	☐	☐	☐	☐
Reading	☐	☐	☐	☐	☐
Writing	☐	☐	☐	☐	☐

Community Language Use Behaviour

18.	Please indicate which language(s) you most frequently heard or used in the following life stages, both inside and outside home.

	All English	Mostly English	Half English half Chinese	Mostly Chinese	Only Chinese
Infancy	☐	☐	☐	☐	☐
Preschool age	☐	☐	☐	☐	☐
Primary School age	☐	☐	☐	☐	☐
High school age	☐	☐	☐	☐	☐
19.	Please indicate which language(s) you generally use when speaking to the following people.				
	All English	Mostly English	Half English half Chinese	Mostly Chinese	Only Chinese
Parents	☐	☐	☐	☐	☐
Siblings	☐	☐	☐	☐	☐
Grandparents	☐	☐	☐	☐	☐
Other Relatives	☐	☐	☐	☐	☐
Parents	☐	☐	☐	☐	☐
Siblings	☐	☐	☐	☐	☐
Grandparents	☐	☐	☐	☐	☐
Other Relatives	☐	☐	☐	☐	☐
Partner	☐	☐	☐	☐	☐
Roommate(s)	☐	☐	☐	☐	☐
Neighbours	☐	☐	☐	☐	☐
20.	Please indicate which language(s) you generally use in the following situations.				
	All English	Mostly English	Half English half Chinese	Mostly Chinese	Only Chinese
Home	☐	☐	☐	☐	☐
School	☐	☐	☐	☐	☐
Work	☐	☐	☐	☐	☐
Social activities (e.g., hanging out with friends, movies)	☐	☐	☐	☐	☐
Extracurricular activities (e.g.,	☐	☐	☐	☐	☐

hobbies, sports, volunteering, gaming)					
Shopping/ Restaurants/ Other commercial services	☐	☐	☐	☐	☐
Health care services/ Government/ Public offices/ Banks	☐	☐	☐	☐	☐
21.	Please indicate which language(s) you generally use for the following activities.				
	All English	Mostly English	Half English half Chinese	Mostly Chinese	Only Chinese
Reading	☐	☐	☐	☐	☐
Emailing	☐	☐	☐	☐	☐
Texting	☐	☐	☐	☐	☐
Social media (e.g., Facebook, Twitter etc.)	☐	☐	☐	☐	☐
Writing shopping lists, notes, etc.	☐	☐	☐	☐	☐
Watching TV/ listening to radio	☐	☐	☐	☐	☐
Watching movies	☐	☐	☐	☐	☐
Browsing on the Internet	☐	☐	☐	☐	☐

22.	Some people switch between the languages they know within a single conversation (i.e., while speaking in one language they may use sentences or words from the other language). This is known as "language-switching". Please indicate how often you engage in language-switching.					
		Never	Rarely	Sometimes	Frequently	Always
22.1	With parents and family	☐	☐	☐	☐	☐
22.2	With friends	☐	☐	☐	☐	☐
22.3	On social media (e.g., Facebook, Twitter)	☐	☐	☐	☐	☐

Code-Switching and International Contexts Questionnaire

(Adapted from Hartanto & Yang, 2016)

Q1 How much time do you spend in each of the following situations, in general? Note that your answers should add up to 100%

	Home	School/Campus	Work	Other than the three settings mentioned ahead
Percentage				

Section: Index of single-language context bilingualism

Q2 List the percent use of Chinese-Mandarin (your native language) and English (L2) at HOME. Put 0% if you do not use that particular language (note that your answers should add up to 100%).

	Chinese-Mandarin	English
Percentage		

Q3 List the percent use of Chinese-Mandarin (your native language) and English (L2) at SCHOOL/CAMPUS. Put 0% if you do not use that particular language (note that your answers should add up to 100%).

	Chinese-Mandarin	English
Percentage		

Q4 List the percent use of Chinese-Mandarin (your native language) and English (L2) at WORK. Put 0% if you do not use that particular language (note that your answers should add up to 100%).

	Chinese-Mandarin	English
Percentage		

Q5 List the percent use of Chinese-Mandarin (your native language) and English (L2) in situations OTHER THAN home, school, and work. Put 0% if you do not use that particular language (note that your answers should add up to 100%).

	Chinese-Mandarin	English
Percentage		

Section: Score of dual-language context bilingualism

Q6 Do you speak Chinese and English interchangeably within the same situation in general (e.g., using both English and Chinese at school)?

	Never	Rarely	Sometimes	Most of the Time	Always
Frequency	☐	☐	☐	☐	☐

Q7 Do you speak ONLY one language in one environment in general (e.g., using both English at school but Chinese at home)?

	Never	Rarely	Sometimes	Most of the Time	Always
Frequency	☐	☐	☐	☐	☐

Section: Index of intersentential code-switching

Q8 How often do you switch languages between sentences when speaking at the following given settings (e.g., you speak one sentence in English and another sentence in Chinese)?

	Never	Rarely	Sometimes	Most of the Time	Always
Home	☐	☐	☐	☐	☐
School/campus	☐	☐	☐	☐	☐
Work	☐	☐	☐	☐	☐
Situations OTHER THAN home, school, and work	☐	☐	☐	☐	☐

Section: Index of intrasentential code-switching

Q9 How often do you mix words of different languages when speaking in the following given settings (e.g., when you have trouble finding a word in Chinese, you tend to immediately replace it with an English word instead, or vice versa)?

	Never	Rarely	Sometimes	Most of the Time	Always
Home	☐	☐	☐	☐	☐
School/campus	☐	☐	☐	☐	☐
Work	☐	☐	☐	☐	☐
Situations OTHER THAN home, school, and work	☐	☐	☐	☐	☐

Language Experience and Proficiency Questionnaire (LEAP-Q)

(Adapted from Marian et al., 2007)

Section 1

Please list your Chinese and English in order of dominance

Please list Chinese and English in order of Acquisition (your native language first)

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

	Chinese	English
Percentage		

When choosing to read a text available in both of your languages (i.e., Chinese and English), in what percentage of cases would you choose to read it in each of your languages? Assume that the original was written in another language, which is unknown to you. (Percentages should add up to 100%)

	Chinese	English
Percentage		

When choosing a language to speak with a person who is equally fluent in both of your languages, what percentage of time would you speak each language? please report percent of total time. (Percentages should add up to 100%)

	Chinese	English
Percentage		

How many years of formal education do you have?

Please indicate your highest education level (e.g., Masters, High school, Ph.D.):

Please name the cultures with which you identify. On a scale from zero to ten, please rate the extent to which you identify with each culture.

	Chinese	British	American	Other:
Rate	0 (no) 5 (mediate) 10(complete identification)	0 (no) 5 (mediate) 10(complete identification)	0 (no) 5 (mediate) 10(complete identification)	0 (no) 5 (mediate) 10(complete identification)

Section 2: Questions related to your English knowledge

Age when you _______ English

Began acquiring	Became fluent in	Began reading in	Became fluent reading in

In your perception, how much of a foreign accent do you have in ENGLISH?

0	1	2	3	4	5	6	7	8	9	10
none					moderate					pervasive

Please rate how frequently others identify you as a non-native speaker based on your accent in ENGLISH:

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

Please rate to what extent you are currently exposed to ENGLISH in the following contexts:

	0 never	1	2	3	4	5 Half of the time	6	7	8	9	10 Always
Interacting with friends											
Interacting with family											
Watching TV											
Listening to music/radio											
Reading											
Language-lab/self-instruction											

On the following scale from zero to ten, please select how much the following factors contribute to your ENGLISH learning:

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

Interacting with friends											
Interacting with family											
Watching TV											
Listening to music/radio											
Reading											
Language-lab/self-instruction											

On the following scale from zero to ten, please select your level of proficiency in speaking, understanding and reading ENGLISH.

	0 never	1	2	3	4	5 Half of the time	6	7	8	9	10 Always
Speaking											
Understanding											
Reading											

Please identify the number of years and months you spent in ENGLISH environment:

	Year	Months
A country/region where English is spoken		
A community/family where English is spoken		
A school/working place where English is spoken		

Language History Questionnaire *(Adapted from Li, Sepanski & Zhao, 2006)*

L2 Language History Questionnaire (Version 2.0)

Please answer the following questions to the best of your knowledge.

PART A

1. Age (in years):

2. Sex: Male / Female

3. Education (degree obtained or school level attended):

4(a). Country of origin:

4(b). Country of Residence (currently):

5. If 4(a) and 4(b) are the same, how long have you lived in a foreign country where your second language is spoken? If 4(a) and 4(b) are different, how long have you been in the country of your current residence? (in years)

6. What is your native language? (If you grew up with more than one language, please specify)

7. Do you speak English as your second language?

YES
NO (If you answered NO, you need not to continue this form)

8. If you answered YES to question 7, please specify the age at which you started to learn ENGLISH in the following situations (write age next to any situation that applies).

At home: __________
In school: __________
After arriving in ENGLISH speaking country __________

9. How did you learn ENGLISH up to this point? (check all that apply)

(Mainly Mostly Occasionally) through formal classroom instruction.

(Mainly Mostly Occasionally) through interacting with people.

A mixture of both, but (More classroom More interaction Equally both).

Other (**specify:** ______________________________________).

10. List all foreign languages (including ENGLISH) you know in order of most proficient to least proficient. Rate your ability on the following aspects in each language. Please rate according to the following scale (write down the number in the table):

Very poor Poor Fair Functional Good Very good Native-like
1 __________
2__________3__________4___________5__________6__________7__________

Language	**Reading proficiency**	**Writing proficiency**	**Speaking fluency**	**Listening ability**

11. Provide the age at which you were first exposed to each foreign language (including ENGLISH) in terms of speaking, reading, and writing, and the number of years you have spent on learning each language.

Language	**Age first exposed to the language**			**Number of years learning**
	Speaking	**Reading**	**Writing**	

12. Do you have a foreign accent in ENGLISH you speak? If so, please rate the strength of your accent according to the following scale (write down the number in the table):

1No Accent 2Very Weak 3 Weak 4Intermediate 5Strong 6Very Strong

PART B

13. Estimate, in terms of percentages, how often you use your native language (i.e., Chinese) and English per day (in all daily activities combined, circle one that applied):

Chinese:	<25%	25%	50%	75%	100%
English:	<25%	25%	50%	75%	100%

14. Estimate, in terms of hours per day, how often you are engaged in the following activities with **CHINSES and ENGLISH**

Activities	**CHINESE**	**ENGLISH**
Listen to Radio/ Watching TV:	_______(hrs)	_______(hrs)
Reading for fun:	_______(hrs)	_______(hrs)
Reading for work:	_______(hrs)	_______(hrs)
Reading on the Internet:	_______(hrs)	_______(hrs)
Writing emails to friends:	_______(hrs)	_______(hrs)
Writing articles/papers:	_______(hrs)	_______(hrs)

15. Estimate, in terms of hours per day, how often you speak (or used to speak) **CHINSES and ENGLISH** with the following people.

	CHINESE	**ENGLISH**
Parents	_______(hrs)	_______(hrs)
Grandparents	_______(hrs)	_______(hrs)
Brothers/Sisters/Relatives	_______(hrs)	_______(hrs)
Other family members	_______(hrs)	_______(hrs)

16. Estimate, in terms of hours per day, how often you now speak your native and second languages with the following people.

	CHINESE	**ENGLISH**
Spouse/partner:	_______(hrs)	_______(hrs)
Friends:	_______(hrs)	_______(hrs)
Classmates:	_______(hrs)	_______(hrs)
Co-workers/teachers:	_______(hrs)	_______(hrs)

17. Write down the name of the language in which you received instruction in school, for each schooling level:

Primary/Elementary School: ___________
Secondary/Middle School: ___________
High School: ___________
College/University: ___________

18. In which languages do you usually:

Language

count, add, multiply, and do simple arithmetic

Dream

Express anger or affection

19. When you are speaking, do you ever mix words or sentences from CHINESE and ENGLISH? (If NO, skip to question 21).

20. List the languages that you mix and rate the frequency of mixing in normal conversation with the following people according to the following scale:

	1 Rarely	2 Occasionally	3 Sometimes	4 Frequently	5 Very frequently
Spouse/family members Spouse/family members					
Friends					
Co-workers/teachers					
Classmates					

21. In which language (among CHINESE and ENGLISH) do you feel you usually do better? Write the name of the language under each condition.

	At home	**At work**
Reading	____________	____________
Writing	____________	____________
Speaking	____________	____________
Understanding	____________	____________

22. Among CHINESE and ENGLISH, which language is the one that you would prefer to use in these situations?

At home ____________
At work ____________
At a party____________
In general ____________

23. If you have lived or travelled in other countries for more than three months, please indicate the name(s) of the country or countries, your length of stay, and the language(s) you learned or tried to learn.

24. If you have taken a standardized test of proficiency for languages other than your native language (e.g., TOEFL or Test of English as a Foreign Language), please indicate the scores you received for each.

Language	**Scores**	**Name of the Test**
____________	____________	____________

25. If there is anything else that you feel is interesting or important about your language background or language use, please comment below.

PART C

(Do you have additional questions that you feel are not included above? If yes, please write down your questions and answers on separate sheets.)

Appendix II: Computation of bilingual participants' code-switching indexes and single/dual-language contexts scores based on the code-switching and interactional context questionnaire (Hartanto & Yang, 2016)

Index of single-language context bilingualism:

This index calculates the extent to which one specific language is used in one context, as opposed to the usage of another one language in a distinct context. This index is computed through the following formula:

$$\sum_{i=1}^{4} \frac{p_i \times c_i}{100}$$

where

$$c_i = |(|(percentages\ of\ L1 - percentage\ of\ L2)| - percentage\ of\ L3| - percentage\ of\ L4)|$$

$$p_i = the\ total\ amount\ of\ time\ spent\ in\ each\ context$$

As participants in this project are Chinese-English bilinguals, and they consistency reported that they have rare experience of using any other languages in addition to Chinese and English, percentages of using L3 and L4 mentioned in above-formula are coded as 0.

c_i is the absolute discrepancy between the percentage of time L1 was used and the total percentage of time L2 was used.

Score of dual-language context bilingualism

This factor reflects the extent to which two languages are co-used or used within the same situation in general. The value is computed by summing participants' responses on the two questions in the "section: score of dual-language context bilingualism". However, participants' responses to the Q7, which is asking the degree of in single-language context, should be reversed coded. Score of dual-language context bilingualism ranges from 2 to 10, and a greater value reflecting a greater degree of dual-language context bilingualism.

Index of intersentential code-switching

This factor estimates bilinguals' overall intersentential code-switching in daily interactions across the four different contexts (i.e., home. School/campus/work and other situations). Participants reported the percentage of time they spent in each situation in Q1, and the also reported their frequency of producing intersentential code-switching in Q8. Therefore, the index of intersentential code-switching computation formula is:

$$\sum_{i=1}^{4} \frac{p_i \times s_i}{100}$$

where

$$p_i = the\ total\ amount\ of\ time\ spent\ in\ each\ context$$

$$s_i\ = the\ value\ of\ intersentential\ code\_switching\ within\ each\ context$$

Index of intrasentential code-switching

This factor estimates bilinguals' overall intrasentential code-switching in daily interactions across the four different contexts (i.e., home. School/campus/work and other situations). Participants reported the percentage of time they spent in each situation in Q1, and the also reported their frequency of producing intrasentential code-switching in Q9. Therefore, the index of intrasentential code-switching computation formula is:

$$\sum_{i=1}^{4} \frac{p_i \times m_i}{100}$$

where

$$p_i = the\ total\ amount\ of\ time\ spent\ in\ each\ context$$

$$m_i\ = the\ value\ of\ intrasentential\ code\_switching\ within\ each\ context$$

Appendix III: Digit span lists used in the forward and backward digit span task

Forward		Backward
1 7		2 4
6 3		5 7
5 8 2		6 2 9
6 9 4		4 1 5
6 4 3 9		3 2 7 9
7 2 8 6		4 9 6 8
4 2 7 3 1		1 5 2 8 6
7 5 8 3 6		6 1 8 4 3
6 1 9 4 7 3		5 3 9 4 1 8
3 9 2 4 8 7		7 2 4 8 5 6
5 9 1 7 4 2 8		8 1 2 9 3 6 5
4 1 7 9 3 8 6		4 7 3 9 1 2 8
5 8 1 9 2 6 4 7		9 4 3 7 6 2 5 8
3 8 2 9 5 1 7 4		7 2 8 1 9 6 5 3
2 7 5 8 6 2 5 8 4		
7 1 3 9 4 2 5 6 8		

Score forward: __/16 + Score Backward: __/14 = Total score: __/30

Appendix IV: Picture sets for story narrations in single-language and bilingual language conditions

Single-language condition

Picture set 1: Hua Mulan story

[a set of 12 pictures]

Picture Set 2: the little match girl

[a set of 12 pictures]

Bilingual language condition

Picture set 3: three little pigs

[a set of 13 pictures]

Appendix V: Prompts for the story narration task

Researcher: Please have a look at the pictures. Try to recount the story portraited by these pictures. Now, let's suppose you are telling this story to one of your English-speaking friends, please use English to tell the story.

Participant: …

Researcher: Okay, 5 mins, time is up. Please have a short break.

------short breaks------

Researcher: 好的。假设现在你需要看图把这个故事讲给一位你只会说中文的中国朋友，请尽可能用中文叙述图片上展示出的故事。(Now, you need to retell this story to a Chinese-speaking friend, please retell the story based on the pictures I shown you in Chinese.)

Participant: …

Researcher: 好的，时间到。(OK. 5 mins, time is up.)

------short breaks------

(The other set of pictures for single-language story narration are also instructed in the same way as shown above)

Researcher: 现在, please go through this set of pictures. 假设你要根据这些 pictures 讲一个 story 给你的 Chinese-English bilingual friend. 因为你的会话对象 can understand both Chinese and English, 所以你可以在叙述中自由的使用中英文 (Now, please go through this set of pictures. Let's suppose that you are going to tell a story based on these pictures to your Chinese-English bilingual friend. You can use two languages and switch between them in a voluntary manner during your narrations, because your friend can understand both Chinese and English very well.)

Participant: …

Researcher: Great. 时间到。(Great, time is up.)

Appendix VI

The full best-fitted fixed effects of the linear mixed effect model for RT (ms) in the verbal Stroop task with congruency*block and factors related to habitual bilingual language use and participants' spontaneous language production performance as reference levels.
Formula: RT ~ 1 + block * congruency + Z_scored_LexTALE test score + L2AoA + Yrs_in_English environment * congruency + L1 switch tendency + L2 switch tendency + Contextual switch + unintended switch + single-language index * congruency + dual-language score * congruency + intersentential switching index * congruency + intrasentential switching index * congruency + Home_entropy * block * congruency + School_entropy * block * congruency + Work_entropy * block * congruency + social_entropy*block*congruency+ pause ratio in English narration of Mulan story + pause ratio in Chinese narration of Mulan story + pause ratio in English narration of match girl story + pause ratio in Chinese narration of match girl story + pause ratio in bilingual narration+ pause ratio in bilingual conversation + mean pause duration in conversation + intersentential switching frequency in conversation + intrasentential switching in conversation + Chinese frequency in conversation + English frequency in conversation + mean pause duration in English narration of match girl story + mean pause duration in Chinese narration of match girl story + mean pause duration in English narration of Mulan story + mean pause duration in Chinese narration of Mulan story + mean pause duration in bilingual narration + (1 + congruency + block | subject)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	-1161.3893	8332.75	-0.14	0.89
block	-119.24	36.85	-3.24	**.003**
congruency	138.99	163.67	0.85	0.40
block:congruency	7.22	60.31	0.12	0.90
z_scored LexTALE score	-8.22	40.21	-0.20	0.84
L2AoA	-12.86	9.83	-1.31	0.22
Yrs_in_EN	29.96	16.65	1.80	0.11
L1 switch tendency	37.42	19.89	1.88	.09
L2 switch tendency	20.51	20.25	1.01	0.34
Contextual switch	-7.73	11.79	-0.66	0.53
Unintended switch	27.43	16.89	1.62	0.14
single-language index	9.49	3.39	2.80	**.02**
dual-language score	-27.11	21.71	-1.25	0.24
intersentential switching index	-274.95	68.79	-4.00	**.003**
intrasentential switching index	122.65	54.46	2.25	.05
Home_entropy	230.63	126.78	1.82	.10

School_entropy	465.34	228.29	2.04	.07
Work_entropy	64.69	110.82	0.58	.57
Social_entropy	221.89	117.64	1.89	.09
En_MulanP.ratio	-2866.56	1085.99	-2.64	**.03**
Cn_MulanP.ratio	-2451.84	1072.15	-2.29	.05
En_matchP.ratio	-867.76	899.76	-0.96	.36
Cn_matchP.ratio	1068.19	855.82	1.25	.24
Bilingual narration P.ratio	3506.57	949.66	3.69	**.005**
Conversation P.ratio	-3689.72	1255.10	-2.94	**.02**
mean.conversation_P_dur	30.79	30.83	1.00	.34
interSw_freq_conversation	1224.08	8535.33	0.14	.89
IntraSw_freq_conversation	1379.23	8111.09	0.17	.87
Cn_freq_conversation	1994.78	8276.73	0.24	.81
En_freq_conversation	1377.61	8188.55	0.17	.87
MeanEn_match_P.dur	-497.61	212.94	-2.34	**.04**
MeanCn_match_P.dur	-193.79	111.31	-1.74	.12
MeanCn_mulan_P.dur	-126.38	67.24	-1.88	.09
MeanEn_mulanEn_P.dur	387.33	168.36	2.30	.05
Mean bilingual narration_P.dur	66.48	124.62	0.53	.61
Congruency:Yrs_in_EN	-16.28	5.84	-2.79	**.009**
congruency: single-language index	0.15	1.27	0.12	.91
congruency: dual-language score	14.76	7.63	1.93	.06
congruency: intersentential switching index	18.79	23.05	0.82	.42
congruency: intrasentential switching index	-10.26	19.44	-0.53	.60
block: home_entropy	80.08	36.75	2.18	**.04**
congruency: home_entropy	-76.43	52.83	-1.45	.16
block: School_entropy	54.12	42.42	1.28	.21
congruency: School_entropy	2.92	56.40	0.05	.96
block: work_entropy	-30.54	35.56	-0.87	.39
congruency:work_entropy	28.66	42.11	0.68	.50
block: social_entropy	25.54	41.18	0.62	.54
congruency: social entropy	-8.26	49.28	-0.17	.87
block:congruency: home_entropy	48.95	60.08	0.82	.42
block:congruency: School_entropy	149.89	69.56	2.16	**.03**
block:congruency: work_entropy	-113.80	58.34	-1.95	.05
block:congruency: social entropy	-23.28	67.39	-0.35	.73

Appendix VII

The full best-fitted fixed effects of the linear mixed effect model for RT (ms) in the spatial Stroop task with congruency*block and factors related to habitual bilingual language use and participants' spontaneous language production performance as reference levels.

Formula: RT ~ 1 + block * congruency + Z_scored_LexTALE test score + Yrs_in_English environment * congruency + single-language index + dual-language score + intersentential switching index + intrasentential switching index + Home_entropy * block + School_entropy * block + Work_entropy * block + social_entropy*block + pause ratio in English narration of Mulan story + pause ratio in Chinese narration of Mulan story + pause ratio in Chinese narration of match girl story + pause ratio in bilingual narration+ pause ratio in bilingual conversation + intersentential switching frequency in bilingual narration + intrasentential switching in bilingual narration + (1 + congruency *block | subject)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	468.31	131.95	3.55	**.002**
block	-15.51	13.73	-1.12	.27
congruency	88.13	8.67	10.16	**<.0001**
block:congruency	70.14	10.26	6.84	**<.0001**
z_scored LexTALE score	-36.38	12.54	-2.90	**.008**
Yrs_in_EN	2.47	4.92	0.50	.62
single-language index	1.97	1.06	1.86	.08
dual-language score	-2.16	6.43	-0.34	.74
intersentential switching index	-83.30	21.71	-3.84	**.001**
intrasentential switching index	32.84	17.08	1.28	.21
Home_entropy	107.21	42.45	2.53	**.02**
School_entropy	28.18	50.95	0.55	.59
Work_entropy	26.43	35.59	0.74	.46
Social_entropy	78.68	43.49	1.81	.08
En_MulanP.ratio	-566.80	320.51	-1.77	**.09**
Cn_MulanP.ratio	-552.42	299.87	-1.84	.08
Cn_matchP.ratio	869.79	308.48	2.82	**.01**
Bilingual narration P.ratio	187.77	242.35	0.78	.45
Conversation P.ratio	-950.86	335.16	-2.84	**.009**
interSw_freq_bilingual narration	427.17	160.58	2.66	**.01**
IntraSw_freq_ bilingual narration	-222.55	90.93	-2.45	**.02**
Congruency:Yrs_in_EN	-5.49	1.98	-2.77	**.009**
block: home_entropy	54.38	13.99	3.89	**.0004**
block: School_entropy	-37.22	15.55	-2.39	**.02**

block: work_entropy	16.77	13.35	1.26	.22
block: social_entropy	-10.20	15.22	-0.67	.51

Appendix VIII

The full best-fitted fixed effects of the linear mixed effect model for mixing and switch costs in RT (ms) in the colour-shape switching task with interactives of trial type and factors related to habitual bilingual language use and language entropy as reference levels. Formula: RT ~ 1 + costs type + Z_scored_LexTALE test score*costs type + L2 AoA* costs type + single-language index* costs type + dual-language score* costs type + intersentential switching index* costs type + intrasentential switching index * costs type + Home_entropy * costs type + School_entropy * costs type + Work_entropy * costs type + social_entropy* costs type + (1 | subject)

Variable	Estimate	*SE*	*t*-value	*Pr* (>|t|)
RTs (ms)				
(Intercept)	953.58	350.58	2.72	**.01**
Mixing costs ($RT_{repeated} – RT_{single}$)	-553.98	147.20	-3.76	**.0002**
Switch costs ($RT_{switch} – RT_{repeated}$)	-15.70	134.04	-0.12	.91
z_scored LexTALE score	7.66	28.79	0.27	.79
L2 AoA	-2.28	8.61	-0.26	.79
single-language index	1.90	2.76	0.69	.50
dual-language score	13.06	16.03	0.82	.42
intersentential switching index	22.13	47.96	0.46	.65
intrasentential switching index	-12.29	39.68	-0.31	.76
Home_entropy	41.90	113.13	0.37	.71
School_entropy	211.67	128.67	1.65	.11
Work_entropy	-116.88	89.80	-1.30	.20
Social_entropy	-109.89	110.39	-1.00	.33
Mixing costs: z_scored LexTALE score	-14.99	11.88	-1.26	.21
Switch costs: z_scored LexTALE score	24.37	10.78	2.26	**.02**
Mixing costs:L2 AoA	16.03	3.69	4.35	**<.0001**
Switch costs:L2 AoA	-4.69	3.39	-1.38	.17
Mixing costs: single-language index	1.27	1.15	1.01	.27
Switch costs: single-language index	-0.60	1.05	-0.57	.57
Mixing costs: dual-language score	45.04	6.69	6.74	**<.0001**
Switch costs: dual-language score	10.09	6.00	1.68	.09
Mixing costs: intersentential switching index	88.11	21.11	4.17	**<.0001**
Switch costs: intersentential switching index	6.82	19.91	0.34	.73
Mixing costs: intrasentential switching index	-57.37	16.74	-3.43	**.0006**

Switch costs: intrasentential switching index	-8.89	15.23	-0.58	.56
Mixing costs: home_entropy	69.13	48.01	1.44	.15
Switch costs: home_entropy	83.31	44.10	1.89	.06
Mixing costs: School_entropy	-143.41	54.12	-2.65	**.008**
Switch costs: School_entropy	-49.03	19.48	-0.99	.32
Mixing costs: work_entropy	115.70	38.27	3.02	**.003**
Switch costs: work_entropy	-1.04	35.32	-0.03	.98
Mixing costs: social_entropy	-83.76	46.65	-1.80	.07
Switch costs: social_entropy	59.38	43.25	1.37	.17

Appendix IX

SUBTLEX resources provide frequencies of words based on television and film subtitles to better approximate to everyday language exposure, and this corpus has a better language register than corpora related to written sources for psycholinguistic research. The SUBTLEXus contains 74,286 word forms with frequency values calculated from a 52 million-word corpus of subtitles from 8,388 American films and television series broadcast between 1990 and 2007 (Brysbaert & New, 2009 p. 87). The SUBTLEXch corpus is based on 6,243 different language contexts (7,148 subtitle files) from movies and television series (Cai & Brysbaert, 2010). Table A1 below shows word frequency and Zipf values for Chinese and English words used in the four dialogues which were calculated based on the aforementioned two online linguistic corpora.

Table A9 Summary of the word frequency and Zipf values for both Chinese and English words used in the dialogues.

		Frequency/Million(fpmw)		Zipf Value	
	Total word count	Mean	SD	Mean	SD
English-only dialogue	151	2777.15	6308.18	5.47	1.09
Chinese-only dialogue	302	2731.57	7414.77	5.45	1.11
Chinese-English dual-language dialogue (English count)	216	3005.18	6596.56	5.49	1.29
Chinese-English dual-language dialogue (Chinese count)	173	3357.42	6263.56	5.49	1.35
Mixed languages dialogue (English count)	195	2274.16	6044.82	5.08	1.35
Mixed languages dialogue (Chinese count)	307	3387.22	5023.92	5.67	1.05

* Zipf-value (Van Heuven, Mandera, Keuleers & Brysbaert, 2014) scale is a logarithmic scale (values 1–3 = low-frequency words; 4–7 = high-frequency words).

Appendix X

Participants were instructed to listen to a three-minute dialogue to determine their language status before doing the flanker task. There are four dialogue listening sessions, with each type of dialogue involved in each session. Examples of each type of dialogue are presented below.

Table A10.1 Examples of language listening inducement materials. Translations for these exemplar sentences are showed in brackets

	Dialogue listening Examples
English-only	Tom: Hi, I am Tom. Where are you from, Sally? Sally: I am from Seattle, Washington in the USA.
Chinese-only	吴楠：刘斌，你累啦？ (Wu Nan: Liu Bin, are you tired?) 刘斌：是啊，吴楠。我半年都没运动了，我不行了。好累。 (Liu Bin: Yes, Wu Nan. I haven’t exercised for half a year. I can’t do it anymore, so tired.)
Chinese-English dual-language	A: 丽丽后天过生日，那天我们一起去怎么样？ (A: The day after tomorrow is Lily’s birthday. How about we go to her party together?) B：好主意。后天。Tuesday, wait, I am afraid I am not available on that day. Next Tuesday is a busy day for me. (B: Good idea. The day after tomorrow… Tuesday, wait, I am afraid I am not available on that day. Next Tuesday is a busy day for me.)
Dense code-switching	A： Hello，林. 不知道你最近 O 不 OK 啊？读 PhD 的事儿你有跟你 preferred 的 supervisor 见面聊吗? (A: Hello, Lynn. How are you recently? How about your PhD application? Have you met the supervisor you preferred to apply?) B：唉。hard to say 啊。你居然突然 care 起来我，真是 surprised me. (B: Ugh. Hard to say. It really surprised me that you care about me suddenly.)

Table A10.2 Examples of comprehension questions after each dialogue-listening. Translations for these exemplars are showed in brackets

	Comprehension Question Examples
English-only	Q: Where does Sally come from? Answer: Seattle
Chinese-only	Q: 刘斌觉得什么太累了? Answer: 跑步 (Q: Which activity makes Liu Bin feel tired? Answer: Jogging)
Chinese-English dual-language	Q: 丽丽周几过生日? Answer: 周二 (Q: when is Lily’s birthday? Answer: Tuesday) Q: What did Ann say about her next Tuesday? Answer: Busy
Dense code-switching	Q: 小周不去 go shopping，她 next week 要? Answer:要做一个 presentation (Q: Xiao Zhou decide not to go shopping, because what she will do next week? Answer: do a presentation)

Appendix XI

In this study, direction-pointing stimuli involved in each flanker task constantly change across different interactional contexts to avoid participant fatigue. These direction-pointing stimuli are displayed in Figure A11, below.

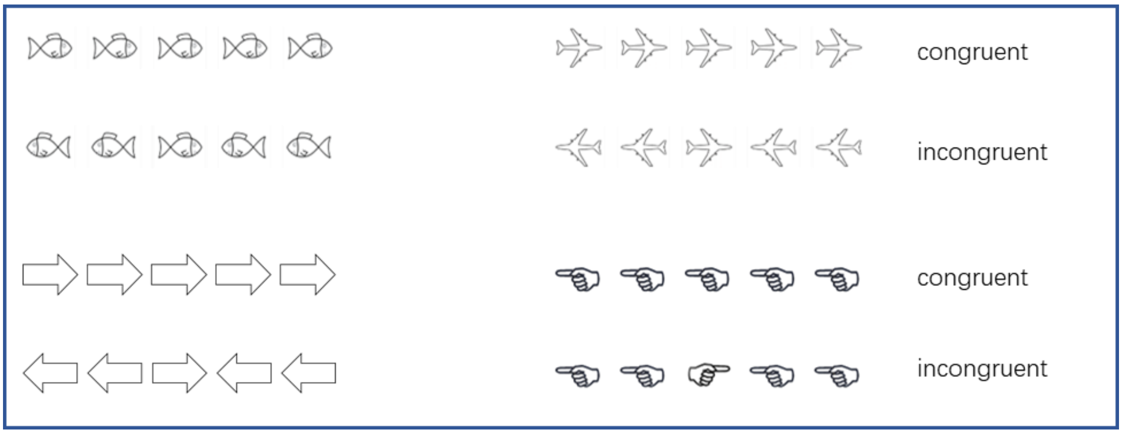

Figure A11. Example of visual stimuli in the flanker tasks used in this study