EFFECTS OF MULTILINGUALISM ON BRAIN STRUCTURE, COGNITION AND LANGUAGE PROCESSING

By

YEE JIA'EN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Chair : Yap Ngee Thai, PhD
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Recent evidence suggests that the control demands in multilingualism may diverge from that of bilingualism, and changes in brain structure and function occur with knowing more languages. Much remains to be understood regarding the ways in which multilingualism interacts with brain structure, cognition, and language processing. Firstly, while it is now understood through bilingualism research that certain brain regions adapt with increasing language experience, the trajectory and limits of these restructuring remain unclear as the number of languages one knows increases further, particularly so in subcortical structures. This is despite multilingualism being a common phenomenon in many parts of the world. Findings from past bilingual studies have shown patterns of volumetric expansions that are followed with reductions as language experience increases; possibly signifying renormalisation. Building upon the Dynamic Restructuring Model, the first study examined subcortical adaptations across 56 monolinguals, bilinguals, trilinguals and quadrilinguals using structural MRI. Volumetric analyses of five subcortical structures that underlie language control and processing were performed. The results uniquely show that structural adaptations of the caudate nucleus, nucleus accumbens, putamen, globus pallidus and thalamus are non-linear, and different structures renormalise with different amounts of experience. In the second study, multilingualism is examined deeper to include both the influence of both number of languages and literacy experiences on implicit statistical learning (ISL) as it is unclear if merely being able to speak more than one language would bring about cognitive advantages. Past studies have not investigated ISL despite it being fundamental in executive functions, and did not consider the effects of orthographic transparency despite the different demands in cognitive resources. Furthermore, opaque orthographies involve more statistical information and requires the employment of more implicit learning mechanisms. The results show that being multilingual does not confer benefits in ISL, but literacy in more opaque orthographies could improve ISL performance. This suggests that managing more opaque orthographies may

help to develop greater capacities to detect statistical regularities of inputs and lead to greater competence and flexibility in extracting regularities in general. Finally, apart from interactions with brain structure and cognition, multilingualism relates with language processing in dynamic ways due to the multivalent combinations between different phonological and orthographic systems. For example, opaque orthographies require one to rely more heavily on phonological awareness (PA) and grow increasingly sensitive to both consistent and inconsistent correspondences between graphemes and phonemes. While bilingualism research has shown evidence of PA transfer across languages of different opacity, it is unclear if additionally taxing on phonological awareness through more opaque literacy experiences in multilinguals would bring about enhancements in this language processing function. Thus, in the last study, three groups of subjects who differed in their exposure to opaque orthographies were assessed on English rhyme judgements. The results of the behavioural phonological decision task show that more exposure to a bigger proportion of opaque orthographies is associated with better phonological processing. Overall, these three studies provide novel evidence, and advance our understanding of some ways in which multilingualism interacts with brain structure, cognition, and language processing.

Keywords: multilingualism, subcortical structures, phonological processing, rhyme judgement, cognition, implicit learning, language processing

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KESAN MULTIBAHASA TERHADAP STRUKTUR OTAK, KOGNISI DAN PEMPROSESAN BAHASA

Oleh

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Bukti terkini menunjukkan bahawa tuntutan kawalan dalam multibahasa mungkin berbeza daripada bilingualisme, dan perubahan dalam struktur dan fungsi otak berlaku dengan mengetahui lebih banyak bahasa. Masih banyak yang perlu difahami mengenai cara multibahasa berinteraksi dengan struktur otak, kognisi dan pemprosesan bahasa. Pertama, walaupun kini difahami melalui penyelidikan dwibahasa bahawa kawasan otak tertentu menyesuaikan diri dengan pengalaman bahasa yang semakin meningkat, trajektori dan had penstrukturan semula ini masih tidak jelas apabila bilangan bahasa yang diketahui semakin meningkat, terutamanya dalam struktur subkortikal. Ini walaupun multibahasa menjadi fenomena biasa di banyak bahagian dunia. Dapatan daripada kajian dwibahasa lepas telah menunjukkan pola pengembangan volumetrik yang diikuti dengan pengurangan apabila pengalaman bahasa meningkat; mungkin menandakan penormalan semula. Membina Dynamic Restructuring Model, kajian pertama mengkaji penyesuaian subkortikal merentas 56 ekabahasa, dwibahasa, tiga bahasa dan empat bahasa menggunakan MRI struktur. Analisis volumetrik lima struktur subkortikal yang mendasari kawalan dan pemprosesan bahasa telah dilakukan. Hasilnya secara unik menunjukkan bahawa penyesuaian struktur nukleus caudate, nukleus accumbens, putamen, globus pallidus dan talamus adalah tidak linear, dan struktur yang berbeza dinormalisasi semula dengan jumlah pengalaman yang berbeza. Dalam kajian kedua, berbilang bahasa dikaji dengan lebih mendalam untuk memasukkan kedua-dua pengaruh bilangan bahasa dan pengalaman literasi terhadap pembelajaran statistik tersirat (ISL) kerana tidak jelas jika hanya boleh bercakap lebih daripada satu bahasa akan membawa kelebihan kognitif. Kajian lepas tidak menyiasat ISL walaupun ia asas dalam fungsi eksekutif, dan tidak mengambil kira kesan ketelusan ortografik walaupun terdapat permintaan yang berbeza dalam sumber kognitif. Tambahan pula, ortografi legap melibatkan lebih banyak maklumat statistik dan memerlukan penggunaan mekanisme pembelajaran yang lebih tersirat. Keputusan menunjukkan bahawa berbilang bahasa tidak

memberikan faedah dalam ISL, tetapi celik huruf dalam ortografi yang lebih legap boleh meningkatkan prestasi ISL. Ini menunjukkan bahawa mengurus ortografi yang lebih legap boleh membantu membangunkan kapasiti yang lebih besar untuk mengesan ketetapan statistik input dan membawa kepada kecekapan dan kefleksibelan yang lebih besar dalam mengekstrak ketetapan secara umum. Akhir sekali, selain daripada interaksi dengan struktur otak dan kognisi, berbilang bahasa berkaitan dengan pemprosesan bahasa secara dinamik disebabkan oleh gabungan multivalen antara sistem fonologi dan ortografik yang berbeza. Sebagai contoh, ortografi legap memerlukan seseorang untuk lebih bergantung pada kesedaran fonologi (PA) dan berkembang menjadi semakin sensitif terhadap kedua-dua koresponden yang konsisten dan tidak konsisten antara grafem dan fonem. Walaupun penyelidikan dwibahasa telah menunjukkan bukti pemindahan PA merentas bahasa dengan kelegapan yang berbeza, adalah tidak jelas sama ada mengenakan cukai tambahan pada kesedaran fonologi melalui pengalaman literasi yang lebih legap dalam berbilang bahasa akan membawa peningkatan dalam fungsi pemprosesan bahasa ini. Oleh itu, dalam kajian lepas, tiga kumpulan subjek yang berbeza dalam pendedahan mereka kepada ortografi legap telah dinilai berdasarkan pertimbangan sajak bahasa Inggeris. Keputusan tugasan keputusan fonologi tingkah laku menunjukkan bahawa lebih banyak pendedahan kepada bahagian ortografi legap yang lebih besar dikaitkan dengan pemprosesan fonologi yang lebih baik. Secara keseluruhan, ketiga-tiga kajian ini memberikan bukti baru, dan memajukan pemahaman kita tentang beberapa cara di mana multibahasa berinteraksi dengan struktur otak, kognisi dan pemprosesan bahasa.

Kata kunci: multibahasa, struktur subkortikal, pemprosesan fonologi, pertimbangan rima, kognisi, pembelajaran tersirat, pemprosesan bahasa

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LIST OF ABBREVIATIONS

ACH	Adaptive Control Hypothesis
AGL	Artificial Grammar Learning
AoA	Age of Acquisition
BAPSS	Bilingual Anterior to Posterior and Subcortical Shift
DRM	Dynamic Restructuring Model
GM	Grey matter
GPC	Grapheme-to-Phoneme Correspondences
ISL	Implicit Statistical Learning
PA	Phonological Awareness
RJT	Rhyme Judgement Task

CHAPTER 1

GENERAL INTRODUCTION

1.1 Bilingualism and Multilingualism

"A hallmark of the central nervous system is its tremendous capacity for change as a product of experience (Hilchey & Klein, 2011)."

Indeed, the experiences and skills acquired in our lifetime have the influence to shape our cognition and neural organisation (Barnes & Finnerty, 2010; Lövdén et al., 2020; Pascual-Leone et al., 2005). Structural and functional changes in cognition and language processing occur through the acquisition of language; from illiteracy to literacy, and from knowing one language to knowing two (Dehaene, 2013; Dehaene, Cohen, et al., 2015; López-Barroso et al., 2020). The word 'bilingualism' has been used as an umbrella term to imply the use of multiple languages, and has a basic premise that orthographic differences and the further acquisition of additional languages would not make a difference. Additionally, it is not uncommon for studies to fail to differentiate between the use of two languages from the use of three or more languages where the term bilingualism is also used to refer to the ability to use two or more languages. However, newer evidence suggest that the implications of bilingualism may not be the same as that of multilingualism, with potentially varied consequences on brain structure, cognition and language processing. Furthermore, there remains a relatively small pool of research from multilinguals despite multilingualism becoming an increasingly common phenomenon around the world, where being able to speak three or more languages is the norm in many countries (Cenoz, 2013; Braun & Cline, 2014). This thesis aims to explore the interactions that multilingualism and multiliteracy have with brain structure, cognition and language processing. Understanding these interactions would shed light on whether past models or findings that have been developed with bilinguals could also be extended to explain for adaptations that occur through a multilingual experience. This chapter will introduce the project by discussing the background and context, the research problem and significance, aims, objectives, and questions of conducting this project.

To understand the adaptations in structure and both cognitive and language processing function that occur through language experience, it is important to first know that 1) the two languages of a bilingual are simultaneously activated at any point in time therefore influencing each other (Desmet & Duyck, 2007; Marian & Spivey, 2003), and 2) the languages of a multilingual (i.e. knows more than two languages) are likewise interfering with one another in a multi-directional way (Costa, Santesteban, et al., 2006; Schwieter, 2013). Evidence of such co-activation and interference have been docum ented in behavioural, EEG, eye-tracking and fMRI studies, which suggest that cognitive effects have

been found to arise from handling more than one language due to shared mechanisms. For example, the mechanisms used in general cognitive control are believed to also control the use of two competing languages. As a result of this, the consistent practice of one's languages is said to "train" a set of domain-general cognitive functions that are similarly involved in language control. Additionally, managing multiple languages necessitates additional cognitive resources. For instance, it has been argued that word retrieval is more challenging for a bilingual than a monolingual since bilinguals have fewer opportunities to articulate each word, and careful monitoring is required to prevent making mistakes (Parker Jones et al., 2012). Following this line of reasoning, a trilingual or multilingual would experience even greater conflict due to their access to additional lexical alternatives, the need to handle more orthographic variations and ability to inhibit additional languages (Schroeder & Marian, 2017). These suggest that there may exist a greater level of competition within a trilingual's mind than that of a bilingual, which must be resolved. Furthermore, a small pool of research is beginning to show that the control demands in a bilingual brain is not the same as that of a multilingual brain (Rothman et al., 2019) and bigger advantages in cognitive reserve has been found in trilinguals as compared to bilinguals (Schroeder & Marian, 2017). To cope with the bigger cognitive demands, multilinguals may therefore develop a correspondingly greater supply of cognitive resources, which could show up in studies of structural adaptations and cognition. However, there is a scarce amount of research conducted with multilinguals in the inter-related domains of structural and functional (cognition and language processing) adaptations. Additionally, the existing studies are either too few or consist of subjects of varied profiles, making it a challenge to obtain a clear or consistent picture of how multilingualism effects differ from bilingualism effects.

It is now understood that behaviours and day-to-day immersive experiences are able to shape our brains over time (Wenger & Kühn, 2021). They require specific sets of demands that influence the types of skills needed to undertake them, and are accompanied by corresponding changes in neurocognitive resources. For example, research has shown experience-induced structural and functional changes in relevant regions of the brain across modalities from "hard skills" like musical training (Putkinen & Tervaniemi, 2019) and physical exercise (El-Sayes et al., 2019) to "soft skills" like meditation (Guidotti et al., 2021) and even language use (Tao et al., 2021). A decade of research has shown bilingualism-induced changes on the brain (Pliatsikas, 2020), where there appears to be an expansion in areas that deliver cognitive control and language production due to the increased demands of these functions in switching between languages. Researchers have compared monolinguals with individuals along the bilingualism spectrum - from bilinguals of low language experiences such as L2 learners undergoing language training to highly experienced bilinguals such as simultaneous interpreters. Through these cross-sectional studies with bilinguals, researchers have come to a consensus that structural adaptations do occur in white matter, cortical and subcortical structures with increasing language experience, albeit with some mixed findings. Additionally, the evidence from individuals with high language experience such as multilinguals, and interpreters or translators who know more than two

languages remain extremely scarce. There thus exists only a small but growing pool of literature that shows differentiating effects between bilingual and multilingual brains. Even though a relatively consistent picture of adaptations in the bilingual brain has been painted in recent years, the adaptations in terms of which brain regions are implicated and the sequence of adaptations with the use of more than two languages remain unclear. Furthermore, the small pool of available research on multilinguals consists of individuals with mixed language profiles, making it challenging to see the additive effects of additional languages. Therefore, the structural effects of multilingualism will be further explored and discussed in Chapter 4.

The immersive experience of being multilingual also has significant implications on adaptations in cognition. Being able to accurately read and write in any one script involves the execution of simultaneous language processes. Examples of these processes include the retrieval of lexical entries, applying grammatical rules, learning regular and irregular phoneme-grapheme correspondences (Lubin et al., 2016), and analysing phonology and morphology (Alamargot & Chanquoy, 2001; Treiman, 2017). The reader would need to unconsciously orchestrate the decoding of visual representation of language; deconstruct linguistic segments, comprehend, apply grammatical rules, and generate language (Pikulski & Chard, 2005). These are complex tasks that recruit a wide range of executive functions such as attention, working memory, long-term memory, cognitive switching, monitoring and planning (Calabria et al., 2018; Hayes, 2006; Hooper, 2002). Hence, being able to do so for different scripts entails the understanding, manipulation, and application of multiple rule systems, which engages different amounts of cognitive resources (Lallier & Carreiras, 2018). Consequently, studies have found enhanced performance on executive functions such as inhibitory control in bilinguals when compared to monolinguals, due to the shared mechanisms between cognitive control and the switching between different language systems. However, the literature is plagued with mixed findings, with recent studies stressing the importance of considering language immersion and the orthographic properties of a bilingual or multilingual's languages when investigating cognitive advantages stemming from multiple language use. It is not well understood if the mere ability to speak multiple languages without being literate in these languages is sufficient to bring about the advantageous cognitive effects that have been found in bilinguals. Additionally, researchers have investigated the bilingualism effects on executive functions before first developing a better understanding of a far more fundamental domain-general cognitive function upon which higher-order cognitive processes like executive functions build. This ability is known as implicit statistical learning (ISL), which has received little to no attention in the study of multilingualism effects despite its extensive linguistic relevance.

ISL refers to the ability to extract regularities in our environment over time enables the extraction of statistical information such as frequency, variability, distribution, and co-occurrence which are embedded in the environment, and in turn facilitates adaptive changes to human behaviours (Erickson & Thiessen, 2015). It supports learning on a broad level across various aspects of human

cognition, including that of language which is an environment embedded with various statistical structures of elements. Using ISL mechanisms, the brain of a language user is able to process sophisticated and ambiguous perceptual signals such a word and associate it with semantics in the span of an eye blink (Federmeier, 2007). Additionally, it allows us to develop ways to encode sequences that are hidden in our environments. These ways include the use of transitional probabilities, extracting ordinal regularities, identifying recurring chunks and using algebraic rules. Importantly, unique to humans is the ability to create complex structures of nested trees from very simple sequential input that exist across environments (e.g., binary strings) and formulate flexible nested rules (Dehaene, Meyniel, et al., 2015). Such skills are required and employed in the use of languages. There is a plethora of evidence to suggest that implicit learning capabilities are crucial in the acquisition of an understanding of the sequential and structural nature of language (Conway et al., 2010). For example, ISL is implicated in processes of word segmentation (Thiessen et al., 2013), and the learning of phonology and syntax (Maye et al., 2002; Thompson & Newport, 2007). In any given language, there are various combinatory factors interacting with one another within and between levels from phonology, morphology, lexicon, syntax, semantics, to pragmatics. Different statistical information and rules thus apply to different languages, and some languages have slightly more complicated systems that may require the manipulation of more complex interactions. For example, the inconsistent grapheme-to-phoneme correspondences in opaque orthographies have far more irregularities that require the learning of more implicit rules, in contrast to the one-to-one ratio in transparent orthographies. Therefore, opaque orthographies rely more on ISL mechanisms, literacy in opaque orthographies thus mandates additional practice in ISL. However, no study has investigated the effects of opaque literacy experiences in ISL.

ISL is especially relevant in being multilingual or multiliterate as that would mean being exposed to a larger repertoire of statistical information. Weiss and colleagues (2020) posit that babies who are brought up in multilingual settings must build statistical representations for each of their languages and are able to detect the presence of various languages in the input they receive. This parallels with research conducted on the mutual exclusivity constraint, which found that multilingual children are less likely to rely on mutual exclusivity than monolingual children (Byers-Heinlein & Werker, 2009). It therefore appears that merely knowing that there are more languages in question opens our minds to more possibilities and could in turn facilitate more adaptive behaviours. Of the existing research, a few studies have shown that bilinguals perform better on statistical learning paradigms as compared to monolinguals (Vender et al., 2019; Ting et al., 2020) in support of the structural sensitivity theory (Kuo & Anderson, 2012). The structural sensitivity theory suggests that the regular exposure to more than one language could enable one to be more flexible at manipulating linguistic input and formulate linguistics structure since the multilingual individual is expected to be more sensitive to the structural attributes of language. However, very limited amounts of research have been conducted to examine the influence of multiple languages as well as multiliteracies on ISL performance even though different orthographies rely on

ISL with varying degrees, with opaque orthographies requiring the extraction of more implicit statistical components. Just as it has been suggested that the constant mental juggling of languages exercises and consequently enhances various executive functions, could different literacy experiences which rely on implicit learning abilities have an impact upon ISL performance?

Apart from implications on cognitive demands and brain structure, the use of multiple languages also has unique implications on language processing demands and linguistic skills as different languages come with variations in their properties. For instance, languages differ in features such as syntax, morphology, semantics, grammar, and orthographic properties which have unique combinatory rules and relations amongst them. A large number of studies (Blom et al., 2014; Morales et al., 2013; Schroeder & Marian, 2012) have investigated the effects of bilingualism without distinguishing the bilingual's two languages in terms of their orthographic properties – i.e., script type (alphabetical/non-alphabetical) and transparency despite stark differences in learnability and language processing demands. In its simplest instance, orthographies would have one sound for one symbol and each symbol would represent one sound. However, this relationship is not present in all natural languages of the world. Some languages have more ambiguity in transparency than others, making them more challenging to acquire and maintain. Different languages thus require different cognitive and linguistic skills that have been corroborated with neuroimaging studies (Bolger et al., 2005). With the interconnectedness between experience and function, consistently managing the demands of various languages of different transparencies may give rise to adaptations in language processing behaviours involved in opaque orthographies.

As every writing system depends on a varied set of symbolic relations and demands different linguistic skills, the writing system that one engages in can influence literacy acquisition (Coulmas, 1989). Literacy experiences can therefore affect cross-language transfer in bilinguals and multilinguals. For example, the more similar the orthographic properties of a learner's two languages are, the more efficient the language skills' transfer (M. Wang, Park, et al., 2006). Bilinguals are better able to transfer literacy skills across languages when both languages are written in the same system (Bialystok, Luk, et al., 2005; Bialystok, McBride-Chang, et al., 2005). For example, Italian and Spanish are both languages that use the Latin alphabet and thus share the same phonological processes (Durgunoğlu, 2002), but the transfer between orthographically distant languages like Japanese and English are less established. The more dissimilar the orthographic properties of one's two languages, the more they vary in learnability levels (Hirshorn & Fiez, 2014), and require more effort due to the recruitment of different sets of orthographic and phonological skills (Goswami et al., 1998). As a bilingual or multilingual, mastering languages of dissimilar orthographic properties thus appears to be more challenging. However, metalinguistic awareness skills such as phonological awareness have been shown to be transferrable even between languages of different orthographic properties in studies with bilinguals

(Branum-Martin et al., 2012; Kuo et al., 2016). However, the results are mixed on whether phonological awareness is transferred from a more transparent orthography to a more opaque one or the other way round in bilinguals. It is far less understood on the cross-transfer between the languages of multilinguals that differ in orthographic transparency. More specifically, it is unclear if having more literacy experience with opaque orthographies would enhance phonological awareness. This is a question that will be addressed in Chapter 6 of this thesis.

In conclusion of this introductory chapter, I would like to reiterate the tight-knit relationship among experiences, structure and function that involves adaptations in multiple directions. Changes in experience in terms of the number of languages and opaque literacy have the influence to inspire adaptations in both brain structure and function in terms of both cognition (ISL) and language processing (phonological processing). While it was an ideal to assess the interactions between neurocognitive processes involved in ISL and phonological processing amongst multilinguals with different language profiles, this project was unable to do so due to data collection disruptions arising from the pandemic. However, drawing on the findings from the empirical chapters 4, 5 and 6, as well as the wider literature, light will be shed on these connections with greater elaboration in the final chapter of this thesis. Examples of their connections include 1) The underlying neural architecture of ISL appears to be shared with that of language processing and control that are known to adapt with changing language experiences (Christiansen et al., 2012; Howard & Howard, 2013). For instance, the medial temporal lobe and fronto-striatal circuits involving the prefrontal cortex, inferior frontal gyrus, putamen and caudate nucleus are found to be similarly involved in processing ISL (Bennett et al., 2011; Lieberman et al., 2004; Meyer et al., 2005; J. Yang & Li, 2012). For phonological processing, numerous studies have highlighted different patterns of brain activity for orthographies of different transparencies (Oliver et al., 2016; Paulesu et al., 2000). Structural changes may thus be possible, especially with the availability of substantial evidence showing corresponding changes in brain structure with changes in brain activity and experiences. Additionally, if having additional opaque literacy experiences does enhance ISL, adaptations in brain activity and structure may be observable.

To sum up, this thesis will extend the narrative pertaining to the use of more than one language, which is an almost universal experience. More research is showing that the implications of multilingualism and multiliteracies are different from the implications of bilingualism and biliteracies. It would thus be tricky to consider the two in the same way when investigating neurocognitive processes. Moreover, many models and hypothesis referenced in our understanding of language experience have been developed using only monolingual and bilingual data, which will not suffice in the study of multilinguals. It is not clear if the hypotheses could be applied similarly to multilingual populations. Furthermore, language background questionnaires and formulae have been and are being developed to quantify the bilingual experience without considering the multilingual experience and the orthographic properties of an

individual's various languages. These are then used as metrics to correlate with cognitive and language processing performances and draw major conclusions about the effects of knowing more than one language. Such tools would be inadequate for use amongst multilingual populations due to the added complexity in number of languages and the accompanying literacy components. Therefore, evidence from this project would firstly add to the inadequate pool of research conducted with multilinguals, showing that the multilingual brain is different in structure and function in terms of both cognition and language processing, as well as highlight the important role that literacy experiences play with their varying needs in cognitive and linguistic resources. More specifically, there is a lack of precision in the understanding of its impact on 1) brain anatomy, 2) a domain-general cognitive capability apart from executive functions, as well as 3) language processing itself. Differentiating between the use of two languages from the use of three or more may better allow the capture of any nuance that may have previously fallen through the cracks in past studies and extend our understanding of how multilingualism and its accompanying experience with various orthographic properties would make an impact on these three different aspects. These contributions could also encourage novel research directions that consider the nuances that these factors play by shedding light on issues such as why mixed findings have been identified in bilingualism studies, as well as inspire the extension of past models to incorporate multilingual data. Figure 1 is a visual representation of the contents of this thesis, highlighting the three foci and its variables and measures.

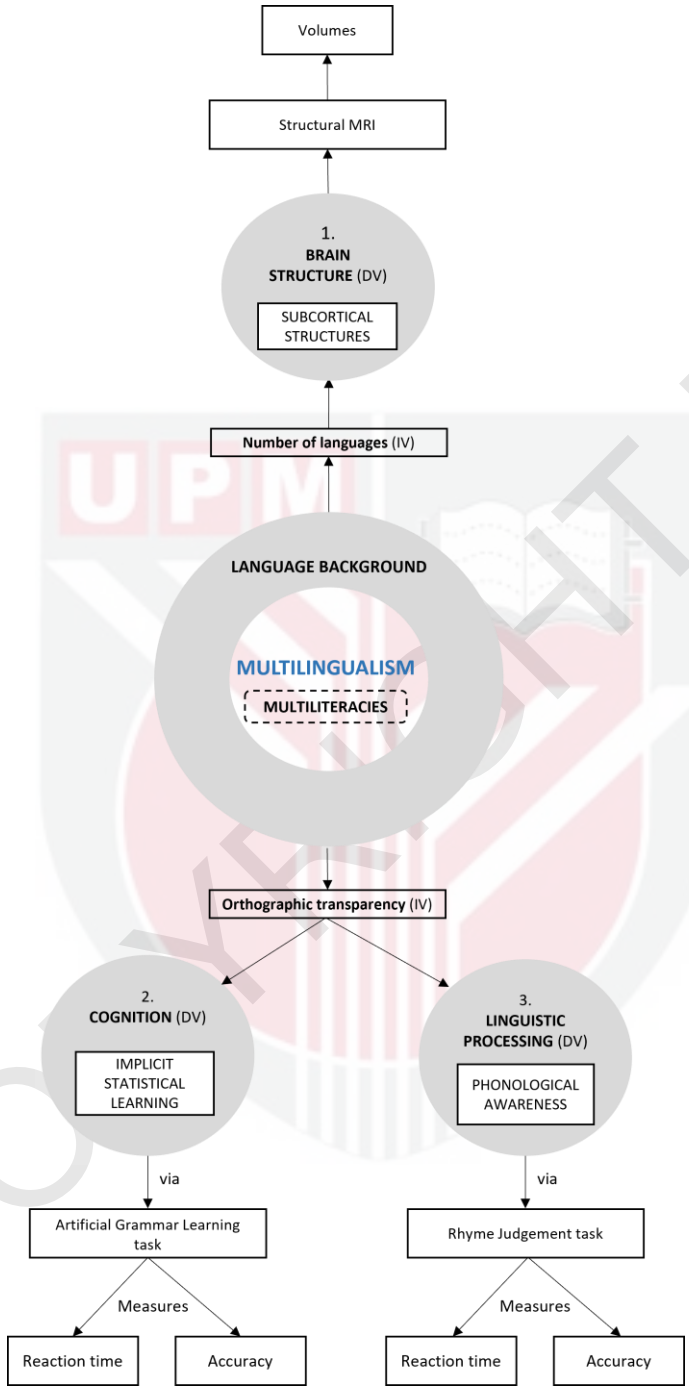

Figure 1: Conceptual framework of this thesis, illustrating the interactions between multilingualism and three aspects – brain structure, cognition and language processing.

1.2 Research aim

Apart from a small set of neuroimaging data that includes monolingual speakers from the UK and quadrilingual speakers from the Czech Republic, the population recruited for this study are Malaysian bilinguals and multilinguals. Malaysian subjects were chosen due to their highly multilingual and multicultural nature where most of them speak at least two languages as they learn English and Malay in schools, and some are also literate in their respective Mother tongue languages (David et al., 2017). This population is part of a large proportion of the world where multilingualism is the norm, and bi-/multilingual education is not uncommon (Braun & Cline, 2014). The types of languages used in this region span across a considerable range in terms of orthographic properties, hence facilitating comparisons on a wider spectrum. With this multilingual population, this thesis aims to explore the adaptive changes to (subcortical) brain structure, cognition (implicit statistical learning) and language processing (phonological awareness) as functions of multilingualism and multiliteracies. Therefore, by comparing subjects across a spectrum in terms of the number of languages they know and the orthographic properties that they have mastery over, this thesis contributes to a small but steadily growing field of research that seeks to understand the brain's potential for change. Understanding the structural brain adaptations that occur with multilingualism would extend existing theoretical models that have been based largely on bilingualism research, and facilitate further anatomical predictions associated with increasing number of languages. Understanding the effects of multiliteracies on language processing itself and shedding light on the domain-general cognitive benefits associated with multilingualism could also inform language policies and promote a multilingual education.

1.2.1 Research objectives

1. To describe the subcortical structural changes that may occur as the number of languages one knows increases.
2. To determine the impact of the number of languages and experience with different orthographic properties on implicit statistical learning performance.
3. To examine whether literacy in more opaque orthographies would be associated with better phonological processing performance.

1.2.2 Research questions (RQ)

RQ 1.1: Which subcortical structures adapt with increasing number of languages?
RQ 1.2: What is the pattern of subcortical restructuring as the number of languages increases?

RQ 2.1: To what extent would the implicit learning of regularities occur in bilinguals and multilinguals?
RQ 2.2: To what extent is there a multilingualism effect of implicit statistical learning?
RQ 2.3: Would bilinguals and multilinguals be able to extract hierarchical relationships / regularities higher up the hierarchy?
RQ 2.4: Would literacy in an opaque orthography bring an advantage in the learning of statistical regularities?
RQ 3.1: Would performance be poorer on opaque conditions?
RQ 3.2: Are there differences in rhyme judgement performance between multilinguals who are literate in more opaque orthographies and multilinguals who are not?

1.3 Relationships among chapters

In Chapter 2, this thesis will review the literature of the concepts and studies revolving around multilingualism and language processing, brain structure and cognition. The first part of the literature review will cover information about the main orthographies in the world, providing statistics and linguistic information particularly on orthographies that are central to this project. This part of the literature review will also focus on orthographic transparency, a linguistic feature central to Chapters 5 and 6, particularly for the comparisons across languages that will be made in the following chapters. It will then highlight studies relating to a specific metalinguistic awareness skill – Phonological awareness (PA), which is essential in the processing of language and strongly influenced by linguistic and writing systems (Perfetti & Zhang, 1995), and will be assessed in Chapter 6. The next segment of the literature review will highlight the interactions between language and brain structure. It contains information about regions of the brain relevant to language processing and language control and highlights past findings on structural and functional changes in the brain that are modulated by language experiences. The last segment of the literature review covers past studies on the interaction between language and cognition, with an additional focus on implicit statistical learning and the artificial grammar which is central to the study.

Chapters 4, 5 and 6 revolve around the interactions between multilingualism/ multiliteracies and brain structure, cognition and language processing respectively. Chapter 4 presents empirical data on the effects of multilingualism on structural changes at the subcortical level by comparing the volumes of key subcortical structures across monolinguals, bilinguals, trilinguals and quadrilinguals that were obtained through MRI. Chapter 5 investigates the interaction between multilingualism and implicit statistical learning by means of an artificial grammar paradigm. More specifically, it considers multiliteracies and explores the influence of language properties on performance in a domain-general cognitive task. In Chapter 6, the interactions between multiliteracies and language processing are investigated through a behavioural rhyme judgement task which assesses phonological awareness. Empirical data on

how one's literacy experience can influence phonological awareness will be provided and discussed. Finally, the thesis will close with a summary of the findings from all three chapters, limitations of the project, future directions as well as a general conclusion.

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