Neural and Behavioural Effects of Bilingualism on Selective Attention

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Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the preface and specified in the text. It is not substantially the same as any work that has already been submitted before for any degree or other qualification except as declared in the preface and specified in the text. It does not exceed the prescribed word limit for the School of Biology Degree Committee.

Abstract

Bilingualism has been shown to modulate the neural mechanisms of selective attention, with differences between monolinguals and bilinguals observed even when they display equivalent behavioural performance in a selective attention task. This suggests that the crucial consequence of learning and using multiple languages might be that it triggers neuroplastic adaptation that allows bilinguals to achieve optimal performance under increased processing demands. This functional plasticity yielding equivalent outcomes (also known as degeneracy) is a common feature in biological systems, allowing flexible adaptation to changing environments.

Yet the exact mechanism by which bilingualism affects selective attention is still not entirely clear. While the currently dominant view suggests that the need for constant management of competing languages in bilinguals increases attentional capacity; another possibility is that this language control may be drawing on the available attentional resources such that they need to be economised to support optimal task performance. Another question concerns the development of this adaptation over time, where the demands of competition and inhibition between co-activated languages might be reconfiguring the patterns of attentional processes right from the onset, such that the effects can be seen by the time children can respond to selective attention tasks. Alternatively, these modifications might have a protracted maturation dependent on the length and intensity of exposure to the demands of bilingualism, in which case they would manifest differently in adults and in children, as well as in speakers with different levels of exposure to L2. Finally, another aspect is to establish the extent to which these modifications might affect attentional processing beyond the language domain, extending to auditory processing more generally. Here I present a series of behavioural and neuroimaging experiments that address these questions.

To investigate whether bilingualism enhances attentional processing or triggers redistribution of the existing capacity, I used EEG to track the neural encoding of attended continuous speech in monolingual and bilingual children aged 7-12, in the context of different types of acoustic and linguistic interference. Participants attended to a narrative in English while four different types of interference were presented to the unattended ear. The neural encoding of attended and unattended streams was assessed by reconstructing their speech envelopes from the EEG data in each condition, using the mTRF toolbox. Results showed more accurate reconstruction of the attended envelopes than ignored ones across all conditions for both bilinguals and monolinguals. Critically however, there was no evidence of enhanced attentional processing in bilinguals; instead data showed a pattern consistent with redistribution of the available capacity, economised to achieve optimal performance on the selective attention task. The follow up behavioural experiments tested the limits of this adaptation by using a dual task (dichotic listening + visual attention) to further increase processing load. The results over three experiments (on children, and adults with different levels of exposure to L2) showed consistently comparable performance on both tasks for monolingual and bilingual adults, suggesting that bilingual adaptation can accommodate high processing loads. However there were also subtle differences in performance on the secondary (visual) task between the monolingual and bilingual children, and across the two groups of bilingual adults, suggesting that maturation and exposure do exert influence on this functional adaptation. The findings of the final EEG study on auditory processing beyond language domain indicate comparable but attenuated modification of attentional processing in bilinguals, compared to the first EEG study using linguistic interference.

Findings from all experiments are explored in the context of theories of selective attention and bilingualism.

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Chapter 1: Introduction

1.1 The Aim

Bilinguals acquire and use their second language without apparent difficulties. This belies that fact that bilingualism is a major processing demand for the cognitive system; which has been shown to shape the brain, through neuroplastic adaptation in brain structure and modifications in neural processing. However, the development, effects and extent of such modifications are not fully clear.

In the research that follows, I investigate the effects of bilingualism on selective attention in children and adults of differing language exposure, with a series of complementary neural and behavioural experiments based on a naturalistic dichotic listening task. I aim to integrate three distinct but interrelated research questions: are neural and behavioural modifications discernible in childhood or only after protracted maturation or exposure to a second language? Do the increased processing demands of bilingualism enhance attentional capacity, or lead to an economisation of limited attentional resource, in order to optimise performance; and do any such effects evolve over time and experience? And finally, do these modifications affect any group's behaviour beyond the language domain? The answers to these questions will create a more nuanced and fuller understanding of the modifications conferred by bilingualism to selective attentional processes.

1.2 Selective attention

"My experience is what I agree to attend to."
(James, 1890)

Selective attention is the ability to direct focus to relevant stimuli while ignoring the irrelevant stimuli constantly bombarding the senses. It is a critical process without which the brain would be overloaded with sensory information and unable to prioritise any information. In nature, it has both ecological and evolutionary implications: animals respond adaptively to prioritised information that affects survival and reproduction, such as alertness to predators (Clark & Dukas, 2003). Research on selective attention in the human brain has generated much debate about its bases and mechanisms. I summarise key theoretical positions below.

1.2.1 Theories of selective attention processing

Despite the above definition's origin in the 19th century, research into selective attention took several decades to gain momentum. Research into auditory selective attention accelerated in the 1950s, when researchers focused on selective listening and the "cocktail party" paradigm. Researchers wanted to know how a listener confronted with many sounds (in the same vein as a partygoer in the midst of many conversations) manages to pick out the stream that is most relevant and ignore the unwanted noise. Furthermore, researchers wanted to investigate the difference in processing the target (attended) stream and irrelevant (unattended) stream. Many studies on this topic used the classic 'selective shadowing' task (Cherry, 1953; Broadbent, 1958; Moray, 1959). In these, two different speech streams were played to different ears over headphones, and listeners were asked to concentrate on one target stream and repeat ('shadow') it as quickly as possible. The aims of the studies were twofold: establish which features enabled the differentiation of the two streams and, determine what, if anything, the listeners retained of the message they were not shadowing. The results were clear: in order for efficient shadowing to take place, the streams needed to have clear physical differences, such as being played to different ears, or if not, originate from different locations or have different physical properties such as pitches/genders. Additionally, participants found it extremely difficult to retain any of the non-shadowed (unattended) stream, even when the speech contained anomalies such as a single word repeated in it many times, or even a switch to a different language (Broadbent, 1958; Moray, 1959). This was true even when volume was kept consistent across the two streams, meaning the content of the second stream would have been noticed if attention had not been diverted away from it. The only exception was the reporting of very obvious physical properties, such as a complete change in the gender or pitch of the voice, the presentation of a loud tone; or silence after the stream ended. These findings led to Broadbent's filter theory (Broadbent, 1958), which not only compared the attentional limits of humans to the central processing limits of a computer, but also proposed a theory of *early selection*, a two stage processing mechanism, in which all physical properties of stimulus are processed in parallel initially, after which, due to constrained capacity, only limited abstract properties of the unattended stream (meaning, identity of spoken words) are extracted. Notably, such abstract properties progress through the filter as a result of physical characteristic, such as pitch or location. This explains why participants noticed changes in the physical properties of the non-shadowed speech, such as a change in the gender of the speaker, but not the content.

This led to a rival *late selection* account (Deutsch & Deutsch, 1963; Norman, 1968), which proposed that unattended streams were fully processed, but that participants' inability to respond to questions was a function of memory, rather than perceptual processing. This was substantiated using indirect methods of testing for the processing of unattended stimuli – such as in the controversial study (Corteen & Dunn, 1974) which paired certain words with electric shocks to stimulate a physiological response. Participants demonstrated some response even when these words were in the unattended stream. In an extension of this, participants produced a discernible response when the unattended words were synonyms of those that had been associated with electric shocks, suggesting some semantic processing (Von Wright, J. M., Anderson, K., & Stenman, U., 1975).

Treisman proposed an alternative *attenuated selection* theory (Treisman, 1960; Treisman, 1969), which suggested that some unattended stimuli are processed rather than filtered out completely, but the inputs are weaker than in target stimuli processing. In Treisman's research, the unattended stimuli that were retained had specific features: either because they had especial significance to the listener (such as the words associated with electric shocks as described above, or the participant's own name, as discovered by Moray [1959]); or because they had been primed by contextual clues in the attended stream.

Such theories of early selection and late selection extended to the study of perceptual processing in vision, and these seemingly contradictory perspectives reconciled in a later theory proposed by Lavie and Tsal (Lavie & Tsal, 1994; Lavie, 1995), who found tasks with a high perceptual load resulted in early selection processing, and results from tasks with a low perceptual load favoured late selection processing. They concluded that the type of processing depended on the demands of the target task on attentional (in the case of vision, perceptual) capacity. If the target task is high in load, this consumes all capacity, leaving none spare for distractor processing (early selection); whereas if the target task is undemanding, spare capacity is released to process more of the distractor (late processing).

1.2.2 Attentional capacity

All the above theories of selective attention assume the important theoretical position that people have a finite attentional capacity, i.e., that human performance is supported by a limited pool of mental "effort" (attention) (Kahneman, 1973) which can only process a restricted amount of information at any given point (Broadbent, 1965; Clark & Dukas, 2003). This limited processing capacity can be allocated across stimuli (Kahneman, 1973; Navon & Gopher, 1979) to maintain optimal performance as long as total capacity is not exceeded (Moray, 1967). However, increasing competition for the limited capacity resource leads to an attentional bottleneck (Pashler, 1994) and deterioration in performance. According to early theories, the deterioration due to resource competition is not necessarily linear or "calamitous" but follows what is coined "the principle of graceful degradation" (Norman & Bobrow, 1975). Later studies applied engineering and computational processing theories to the allocation of these limited attentional resources, formulating models such as the multiple resource theory (Wickens, 2008). One application of such models has been to incorporate the acquisition and competence of a second language as a demand on attentional resource (Wickens, 2007). The implications of this underpin the behavioural experiments later in this thesis.

1.2.3 Neural bases of selective attention in adults

Brain activity associated with selective attention is evident in mostly prefrontal areas (Salo et al., 2017). Neural responses to preparatory cues (which signal the stimulus to be attended before the target appears) engage a primarily fronto-parietal network (Bressler et al., 2008; Corbetta & Shulman, 2002). Tests of selective attention, such as the Flanker and Stroop (where the participant must suppress distracting information in order to focus on a target arrow or colour) have identified frontal lobes (Konishi, 2011) and the anterior cingulate cortex (ACC) for the management of conflict resolution (Walsh et al., 2011). Further investigations have suggested that the ACC is responsible for the *monitoring* of attentional conflict, and subsequently sends signals to frontal regions to *resolve* the conflict (Botvinick et al., 2004; Bush et al., 2000; MacDonald et al., 2000).

1.2.4 Developmental considerations

The maturation of selective attention is a key developmental process, hence even subtle modifications to this process have the potential to generate significant consequences. The importance of the development of selective attention reflects findings that it is not only linked to inhibitory control (Walsh et al., 2011) and working memory (Veer et al., 2017), but associated with the development of a variety of skills including speech (Astheimer & Sanders, 2012), metalinguistic skills (Astheimer et al., 2014) and arithmetic (Moll et al., 2015). In fact, selective attention has been proposed as one of the key foundational skills for overall academic success in children (Stevens & Bavelier, 2012; Hampton Wray et al., 2017).

Nonetheless, the neural systems associated with selective attention in adulthood, summarised in the section above, have a notably protracted period of structural development from infancy (Giedd et al., 1999; Gogtay et al., 2004; Sowell et al., 2001; Tsujimoto, 2008). The consequences of this protracted maturation on behavioural performance mean that children display attenuated ability to allocate attention relative to adults. This results in their allocating proportionately more attention to irrelevant stimuli at the expense of relevant stimuli in selective attention tasks (for reviews, see: Ridderinkhof & van der Stelt, 2000; Plude et al., 1994).

Given one of the aims of this study was to investigate the emerging effects of bilingualism on selective attention in development, it was important to establish an age range in which a proficient level of selective attention could reliably be assumed. Auditory selective attention is proposed to have developed by age 3-5 (Stevens & Bavelier, 2012) and auditory dichotic tasks have been carried out on children as young as 4 years old (Hampton Wray et al., 2017). Yet a minimum age of 6 has been recommended (Sanders et al., 2006), reflecting the inconsistent results and high variance in response speed and accuracy in the younger children (Takio et al., 2009). In addition, the established view is that selective attention only stabilises around the age of 7 (Gomes et al., 2007) and reaches maturity by the age 8 or 9 (P. R. Jones et al., 2015). Given these considerations, in the following experiments participants were recruited in the age bracket of 7-12, as this age range not only represents a developmental plateau for selective attention in childhood, but is also likely to generate relatively stable effects whilst ensuring that children can reliably perform a selective attention task.

1.3 Bilingualism

Bilingualism, or proficiency in a second language, has been valued historically for social, economic and political reasons: as a marker of social status, to enable international trade, espionage and diplomacy, and to disseminate cultural and political ideas across nations, to name just a few. In the last century, it has become a focus for psychologists and neuroscientists, who have taken an interest in the processing of multiple languages, its implications for cognition and neurobiological effects on the brain. Evidence shows that the use of multiple languages leads to parallel activation and competition between them, requiring the speaker to prioritise one and inhibit the non-target language(s) (Green, 1998). These additional processing demands have been shown to shape the brain, through neuroplastic adaptation in brain structure (Mechelli et al., 2004; Klein et al., 2014; Burgaleta et al., 2016; Hayakawa & Marian, 2019; Hämäläinen et al., 2017); connectivity between regions associated with "language" and "control" (L. Li et al., 2015); and modifications in neural processing (Garbin et al., 2010; Luk et al., 2010; Kousaie & Phillips, 2012). These effects have been shown consistently across the lifespan, from childhood (Jasińska & Petitto, 2013; Archila-Suerte et al., 2018; Pliatsikas et al., 2020), into adulthood (Bialystok et al., 2005; Mechelli et al., 2004; Filippi et al., 2011) and old age (Luk et al., 2011; Abutalebi et al., 2015; Frutos-Lucas et al., 2020).

Some of these adaptations in brain structure have been associated with neuroprotective benefits in old age. Cognitive impairment and early stages of dementia are associated with grey matter loss, disruption of white matter and deterioration of the temporal poles and orbitofrontal cortex (Abutalebi & Green, 2016). Studies have shown bilingualism is associated with anterior lobe integrity (Abutalebi et al., 2014), greater myelination of white matter in the frontal lobes and corpus callosum (demyelination is associated with neurodegenerative conditions) and greater grey matter density in the dorsal anterior cingulate cortex, pre-supplementary motor areas, and temporal, inferior parietal lobe (where reduced grey matter is observable in the early stages of dementia) (see Abutalebi & Green, 2016, for a review).

There is also behavioural evidence that lifelong bilingualism confers neuroprotective effects, through slower cognitive ageing (Bialystok et al., 2012; Abutalebi, Guidi, et al., 2015) and a later onset of dementia (Gold, 2015; Bak & Robertson, 2017; Alladi et al., 2013; Estanga et al., 2017). Additionally, bilingualism has been associated independently with substantially reduced poststroke cognitive impairment (Alladi et al., 2016; Wood, 2016). These findings have led to the conclusion that bilingualism increases "cognitive reserve", the ability to maintain cognitive functions despite neural damage or brain pathology.

This is in stark contrast to the traditional view that bilingualism led to cognitive overload and "mental confusion" in children (Saer, 1923). This was corroborated by early studies showing that bilingual children performed significantly worse than their monolingual peers in I.Q. tests, arithmetic, reading and verbal intelligence (Jones & Stewart, 1951; Lewis, 1959; Macnamara, 1966; Manuel, 1935; Darcy, 1953), and bilingualism was seen as further disadvantaging children with specific language impairments (W. R. Jones & Stewart, 1951). The results of many of these studies have since been contested, on the grounds that they did not control for environmental factors such as socioeconomic status, immigrant status, language ability; or had used assessments which were not appropriately comparative (Hakuta, 1986). In addition, since a landmark study by Peal and Lambert (Peal & Lambert, 1962), in which bilingual children performed significantly better than monolinguals on both verbal and nonverbal intelligence tests, there have been studies across a variety of age groups and cognitive functions that have proposed a significant advantage shown by bilinguals in performance. One claim is that a natural consequence of increased language processing is enhanced metalinguistic skills (Hakuta, 1986). A review of 102 studies of pre-school children (Barac et al., 2014), however, observed ambivalent results for metalinguistic awareness. They concluded that the most consistent findings of bilingual behavioural outperformance were in studies of non-verbal executive control and theory of mind. The generalisation of bilingual attentional control beyond the language domain is discussed in section 1.5 of this chapter.

However, proposals on the cognitive advantages of bilingualism across the age span have been challenged, with a number of studies and reviews not finding evidence for enhanced behavioural performance in bilinguals (von Bastian et al., 2016; Darcy,

1953) even when using advanced techniques or extensive sample sizes (Samuel et al., 2018; Nichols et al., 2020).

Notably, neural differences between monolinguals and bilinguals have been observed even when they display equivalent behavioural performance (Bialystok et al., 2005; Kousaie & Phillips, 2012; Olguin et al., 2019; Luk et al., 2010). This suggests that bilingualism modulates the neural mechanisms of the cognitive processing required for these tasks, through neuroplastic adaptation that cannot be captured by behavioural tests alone.

1.4 Degeneracy

The examples above, of equivalent behavioural performance contrasting with neural differences observed in groups with different language experience (see also Chee et al., 2004), leads to the concept of degeneracy, defined as structurally diverse components leading to the same output or performing the same function. In contrast to the everyday meaning with negative connotations of decay, degeneracy in the scientific sense is arguably a desirable characteristic, making systems robust and enabling natural evolution (Whitacre & Bender, 2010; Edelman & Gally, 2001). Consequently, it has positive implications in the fields of genetics (Whitacre & Bender, 2010), healthcare (Tian et al., 2011) and biology (Joshi et al., 2013). Given that degenerate systems are functionally plastic (Mason et al., 2015), it is a logical extension to view the brain as a degenerate organ, which must provide reliable outputs despite inherent variability due to individual experience. Additionally, degeneracy is a marker of high-level skill or expertise (Seifert et al., 2016), supporting the hypothesis that the neuroplastic change effected by bilingualism is an example of a degenerate system (Green et al., 2006; Mason et al., 2015; Navarro-Torres et al., 2021).

Furthermore, a key corollary of degeneracy in complex structures, is pluripotentiality, i.e., the generation of different outputs from the same degenerate systems, depending on the circumstances. The brain, recognised as one of the most complex systems in the universe, has the capability to generate the same output from a variety of structurally different elements; these same elements can also generate different outputs independently (Tononi et al., 1999). This supports the hypothesis that not only does bilingualism result in a degenerate system, but that this system has pluripotentiality in its outputs depending on different contexts. This supports the possibility that systems tuned by language control have potential to extend to other domains.

1.5 Domain generality

One of Bialystok's key arguments (Bialystok, 1992) is that bilingual speakers develop an enhanced capacity for selective attentional control, driven by the experience of processing and producing multiple languages, and that furthermore, this control generalises beyond language control into non-verbal tasks. In support of this, Green and Abutalebi's Adaptive Control Hypothesis (Green & Abutalebi, 2013) details a framework for the mechanisms underlying bilingual control of attention, a process which they explicitly claim leads to "enhanced skills in cognitive control…deployed in nonverbal tasks". In support of Bialystok's hypothesis of bilingual enhanced attentional control, Green and Abutalebi (Abutalebi & Green, 2016) propose that, rather than just enhancing control of linguistic interference, the additional control of language employed by bilinguals is more likely to recruit evolutionary earlier systems, such as subcortical structures and the cerebellum, that underpin general attentional control and thus lead to changes in other non-verbal domains.

A number of behavioural studies have been conducted to investigate these claims, using nonverbal tasks including the Dimensional Change Card Sort (DCCS) task, flanker task, Attentional Network (ANT) task, ambiguous figures and Simon task. A bilingual advantage was found across a variety of studies and age groups when using these tasks (Bialystok & Martin, 2004; Carlson & Meltzoff, 2008; Calvo & Bialystok, 2014; Bialystok & Shapero, 2005; Poarch & van Hell, 2012; Costa et al., 2008), even including pre-verbal infants, who had been raised in a bilingual environment, demonstrating enhanced selective attention through preferential eye tracking (Comishen et al., 2019; Kovács & Mehler, 2009).

However, this hypothesis of enhanced attentional control extending to non-verbal tasks is not universally recognised, and has been challenged by several vocal critics (Morton & Harper, 2007; Paap & Greenberg, 2013; Paap et al., 2014; Paap et al., 2015; Antón et al., 2014; Gathercole et al., 2014), who argue that any difference between groups can be attributed to confirmation and publication bias (Paap, 2016); or to variables other than bilingual experience (Lu & Proctor, 1995; Namazi & Thordardottir, 2010). Enhanced selective attention in bilingual infants has also been questioned (Kalashnikova et al., 2021). Given the "spotty" (Valian, 2015a) results acknowledged in reviews of the field of bilingual attentional control, the present research aims to explore further the patterns of differences between monolinguals and bilinguals beyond the language domain, by including a study that uses non-linguistic unattended stimuli in a version of the dichotic listening task.

1.6 Thesis outline

The main goal of the research described in this thesis to integrate three distinct but interrelated research projects:

1) Establish whether neural and behavioural modifications triggered by bilingualism are discernible in childhood.
2) Determine if the increased processing demands of bilingualism enhance attentional capacity, or lead to an economisation of limited attentional resource, in order to optimise performance; and if such effects differ by maturation and language experience.
3) Investigate the effect of these modifications on any group's behaviour beyond the language domain.

Chapter 2 reviews the current literature on selective attention, including theories of neural entrainment, and explains the themes introduced in this chapter in more detail, i.e., selective attention, developmental considerations, the influence of bilingualism and the intersection of these topics.

Chapter 3 introduces the methods used in the experiments presented in this thesis. It discusses the behavioural and imaging methods undertaken, including the dichotic listening task, which forms the basis of all my experiments, electroencephalography (EEG) used in the neural studies, and the dual task (auditory and visual) used in the behavioural experiments.

Chapter 4 describes the first EEG study[1], in which monolingual and bilingual children performed a dichotic listening task with linguistic attended and unattended stimuli. Their behavioural performance was assessed with comprehension questions on the target story and their neural responses captured with EEG and then compared to both the attended and unattended speech envelopes using the mTRF toolbox (Crosse et al., 2016). Both groups showed equivalent behavioural responses. In contrast, EEG data revealed differences between the groups, showing that the type of interference significantly modulated the neural encoding of attended speech in monolingual children but not in bilingual children, replicating the results previously observed in adults (Olguin et al., 2019). These results indicate that monolingual and bilingual children exhibit different patterns of neural entrainment to attended speech; and that the neural mechanisms of selective attention in bilinguals are reconfigured by the time children can reliably perform selective attention tasks.

Chapter 5 presents the follow up behavioural experiments which tested the limits of bilinguals' attentional processing capacity by using a dual task (dichotic listening + visual attention) to further increase processing load. The results over three experiments (on children, and adults with different levels of exposure to L2) consistently showed comparable overall performance of monolinguals and bilinguals

[1] A version of this chapter has been published in *Scientific Reports* (Phelps et al., 2022)

on both tasks, suggesting that bilinguals' adapted selective attention capacity can accommodate the high processing load of simultaneous demands in multiple domains. However there were also subtle differences in performance on the secondary (visual) task across the three groups of bilinguals, suggesting that maturation and exposure influence the functional adaptation of selective attention.

Chapter 6 describes the second EEG study, in which monolingual and bilingual children performed the dichotic listening task with non-linguistic unattended stimuli. Their behavioural and neural responses were captured in the same way as in the first EEG study. Again, both groups showed equivalent behavioural responses. EEG data revealed similar but attenuated patterns when compared to the first EEG study. Differences between the groups followed the same trend of lower indices of overall attention for bilingual children. These results support an account of constrained attentional capacity, even when performing nonlinguistic processing, which is economised to secure optimal behavioural performance.

Finally, Chapter 7 reviews the results of all the experiments and draws overall conclusions on the effects on selective attention of bilingualism and influence of maturation and language exposure. It also suggests theoretical implications and future directions.

Chapter 2: Literature Review

In the first chapter, I presented the three overarching research questions for this thesis, all concerning the effect of bilingualism on selective attention. In brief these were: firstly, establish whether and how bilingualism affects selective attention in childhood; secondly, determine whether bilingualism enhances attentional capacity or causes a redistribution of existing resource; and if such effects differ over time and exposure; thirdly, investigate the domain-generality of bilingual modifications to processing; and consider the implications of findings in each line of enquiry. Hence, this thesis explores the interactions between three overarching themes: selective attention; developmental influences; and bilingualism and its effect on processing. I explore the literature on each of these below, with an emphasis on the neural perspective of each theme. I also present some more detailed studies, which are particularly relevant to the experimental chapters that follow.

2.1 Neural basis for first and second language processing

A key assumption, introduced in Chapter 1, is that neuroplastic changes as a result of bilingualism are a consequence of parallel activation and competition between languages, requiring the bilingual speaker to prioritise one and inhibit the non-target language(s) (Green, 1998). This simultaneous activation and subsequent inhibition is considered to be the source of neuroplastic change as a consequence of bilingualism (Baum & Titone, 2014; Bialystok, 2017; Kroll, J. F., Dussias, P. E., Bogulski, C. A., & Kroff, J. R. V., 2012), and has been substantiated with numerous behavioural studies showing co-activation of lexical systems for bilinguals during linguistic tasks (Hatzidaki et al., 2011; Goldrick et al., 2016; Iniesta et al., 2021; Shook & Marian, 2019; Blumenfeld & Marian, 2013). Nevertheless, a persuasive counter argument, dubbed the “declarative/procedural model” (Ullman, 2001; Ullman, 2006), posited that L1 and L2 in the bilingual brain were processed in two distinct neural systems, supported by different memory systems (declarative or procedural memory) to meet the demands of L1 and L2 on lexicon and grammar. This hypothesis was partly based on cases of bilingual aphasics who recovered just one of their languages, indicating a neural distinction between the languages (Albert & Obler, 1978).

However, subsequent neural evidence showed that L1 and L2 in the bilingual brain were processed by the same neural networks (Perani & Abutalebi, 2005). Researchers found that acquisition of L1 and L2 syntax and grammar recruited the same neural devices, in both ERP (Friederici et al., 2002) and fMRI (Sakai et al., 2004; Tettamanti et al., 2002; Musso et al., 2003) studies. Similar findings emerged from a study using a semantic task (Illes et al., 1999) for Spanish-English bilinguals in their L1 and L2. fMRI revealed similar frontal lobe locations of activations for both languages, and there were no differences in the patterns of activation when words in L1 and L2 were directly compared.

Furthermore, studies across different languages found remarkably consistent left hemisphere brain activation for specific linguistic processing tasks in L2 (Chee et al., 1999; Klein et al., 1999). The similar pattern was found in spite of differences between the languages such as orthography, phonology and syntax, indicating a universal neural basis for L2 processing.

Some neural differences have been discovered, however, which have been attributed to factors such as: age of acquisition, proficiency and exposure to each language, with each factor assumed to vary computational demands. For example, imaging studies on bilinguals who varied by age of acquisition or proficiency (Wartenburger et al., 2003; Briellmann et al., 2004; Sakai et al., 2004) showed that all bilinguals used overlapping areas when performing tasks in L1 and L2 but that additional activation for L2 was only evident in late bilinguals and/or those with low proficiency. The above findings point to a common neural basis for L1 and L2 for semantic, syntactic and grammatical processing, with additional activation according to proficiency and age of acquisition.

The evidence of consistent brain patterns, modulated by factors such as language exposure, have been interpreted as strong evidence of brain plasticity, dependent on specific bilingual experience (Perani & Abutalebi, 2005; Green et al., 2006). This is consistent with the evidence presented in Section 2.4.

In sum, there is neural evidence substantiating the hypothesis that a bilingual's two languages are co-activated. It therefore follows that this co-activation requires the bilingual speaker to inhibit one language and prioritise the other at any given time, causing additional processing costs. Experience of managing these costs is assumed to cause the bilingualism-induced modifications described in Section 2.4, many of which directly affect the domain of selective attention (Bialystok, 2017).

2.2 Selective attention

Selective attention, or the act of choosing to focus on stimulus while filtering out irrelevant inputs, has been a subject of interest to psychologists since at least the 19th century with early experimental work performed in the laboratories of Donders (Donders, F. C., 1868), Titchener (Titchener, 1910), von Helmholtz (as described by Stumpf, 1895) and Wundt (Wundt, W. M., 1912). In 1910, Professor Hicks presented the paper "The Nature and Development of Attention" to the British Psychological Society (cited in Edgell, 1947). Since then, neurobiological studies have established that the rate of encountering environmental stimulus far exceeds the rate of the brain's ability to process information (Itti et al., 2005); and thus attentional mechanisms are needed to allow the brain to focus only on the most essential filtered information at any given moment (Driver & Frackowiak, 2001).

As discussed in the Introduction, early work in the 1950s focused mainly on selective attention in auditory language processing, using dichotic 'shadowing' tasks (Cherry, 1953; Broadbent, 1958; Moray, 1959) which formed the basis of the early, late and attenuated selection theories (Broadbent, 1958; Deutsch & Deutsch, 1963; Norman, 1968; Von Wright, J. M., Anderson, K., & Stenman, U., 1975; Treisman, 1960).

Chapter 1 presented the above key theoretical positions, with an emphasis on auditory selective attention. Selective attention in the auditory domain was not only the focus of much of the research in the mid twentieth century, but is also highlighted given that the primary task in each of the experimental chapters is a dichotic listening task. One of the behavioural studies in this thesis, however, also features a visual task so below I also briefly summarise the literature in visual selective attention.

Much of visual selective attention theory (to which interest shifted after initial focus on selective processing in the auditory domain) is consistent with Broadbent's filter theory (Broadbent, 1965), although the distinction between 'physical' vs 'semantic' properties which are extracted by the information processing filter are more easily applicable to auditory linguistic stimuli (such as words) than natural visual stimuli. Nevertheless, early work on visual selective attention, including 'iconic memory' research (Sperling, 1960) is analogous to Broadbent's filter theory and assumptions of the finite bandwidth of a limited-capacity processor. In short, the 'iconic memory' theory was derived from the observation that participants were not able to report all the numbers they saw when presented briefly with an array of letters (e.g., four rows of three), indicating limited capacity to process them all. When asked to focus on a subset, however, of the same array (such as the top row only), participants were able to report all the relevant letters without apparent difficulty. In subsequent studies analogous to a dichotic listening task, in which participants were asked to concentrate on shapes outlines in one of two colours, a spontaneous memory recognition test revealed accurate memory of attended shapes (outlined in the target colour), but no recollection of unattended shapes (outlined in the irrelevant colour) (Rock & Gutman, 1981). This phenomenon has also been dubbed "Inattentional Blindness' (Mack, A., & Rock, I., 1998), and cited as an example of early selection in visual selective attention. Subsequent studies, however, revealed a relationship between an ignored object on one trial and attended object on the next, suggesting that some features of the ignored trial were indeed retained (Tipper, 1985). These findings were interpreted as an example of late selection, in which features of unattended objects are processed but then actively inhibited (see also studies included in Monsell, S., & Driver, J., 2000). As summarised in Chapter 1, these contrasting interpretations were combined in a theory proposed by Lavie and Tsal (Lavie & Tsal, 1994; Lavie, 1995), who argued that early selection and late selection need not be mutually exclusive, but were instead a function of the task and its perceptual load. After finding that tasks with a high perceptual load resulted in early selection processing, and that tasks with a low perceptual load favoured late selection processing; they concluded that the type of processing depended on the demands of the target task on attentional (perceptual) capacity.

Another theory developed specifically for the visual modality is that of 'feature integration' (Treisman & Gelade, 1980), in which different aspects of visual stimuli are extracted separately but in parallel, and then integrated to produce multidimensional representations, with all features bound together. This theory was based on the results of visual search tasks, and multiple subsequent studies have tried to identify exactly how visual search is segmented and then reintegrated, with arguments for object-based (grouping by feature similarity) or space-based (grouping by location) models (Driver & Baylis, 1998). Further research into compromised attention as a result of brain damage has illuminated the debate, suggesting that neurological deficits in visual attention appear to be mainly spatial.

2.2.1 The neural basis for visual selective attention

Neural studies of visual selective attention have traditionally used either ERP (event related potentials) or functional imaging. ERP studies have shown a sensory response approximately 100ms after stimulus onset, typically with a larger ERP amplitude for attended stimuli than unattended stimuli, consistent with theories of increased neural activation to direct attention (Mangun et al., 1993). These results have been supplemented by functional imaging methods including PET and fMRI, which have demonstrated that neural activity (demonstrated by blood flow) in areas of the visual cortex are modulated by the demands of a visual selective attention task. One study showed that activation differed within the visual cortex between colour-related and movement-related judgements for the same stimuli (Corbetta et al., 2007).

Now let us turn back to auditory selective attention and examine its neural basis.

2.2.2 Auditory selective attention and neural entrainment

As summarised in Chapter 1, research into selective attention initially concentrated on behaviour in a dichotic listening task pioneered by Cherry (Cherry, 1953), a version of which is used in the experiments that follow in this thesis. More recently, research has made significant progress in understanding the mechanisms of selective listening which underpin the behavioural outcomes identified by Cherry and others (Cherry, 1953; Broadbent, 1958; Moray, 1959). Studies tracking neural response to natural speech streams have revealed that, during listening, low-frequency neural oscillations entrain to the temporal envelope of speech (Aiken & Picton, 2008), which contains acoustic information necessary for linguistic decoding and perceptual encoding (Zoefel & VanRullen, 2015). Entrainment to the speech envelope has been shown to play an important role for speech intelligibility (Obleser & Kayser, 2019; Zoefel et al., 2018; Power et al., 2016; Ríos-López et al., 2020; Peelle et al., 2013; Millman et al., 2014), while poorer speech envelope encoding has been associated with developmental dyslexia (Power et al., 2016). In addition, analysis of the range of neural oscillations has revealed activity in different brain regions (Kubanek et al., 2013), and different frequency bands (Mai et al., 2016; Attaheri et al., 2020; Di Liberto et al., 2015; Giraud & Poeppel, 2012a), suggesting that different sources of information present in the speech signal, such as higher-level semantic and syntactic cues, engage distinct neural components (Keitel et al., 2018; Ding & Simon, 2014). Such processes can also vary according to stage of development: for example, delta-theta oscillations have been identified as enabling language acquisition in infants (Attaheri et al., 2020a), as well as facilitating perceptual parsing in adults (Doelling et al., 2014).

During a dichotic listening task, preferential tracking of the attended stream, or the 'selective entrainment hypothesis' (Schroeder & Lakatos, 2009; Zion Golumbic et al., 2013; Giraud & Poeppel, 2012b), demonstrates a stronger correlation between neural activity and attended speech envelopes (Aiken & Picton, 2008; Di Liberto et al., 2018; Mesgarani & Chang, 2012; Olguin et al., 2018), reflecting prioritised processing of the attended stream. This is true even in acoustically challenging conditions (Fiedler et al., 2018).

In addition, the type of interference has been shown to modulate the strength of entrainment to the attended stream. This was confirmed by a study (Olguin et al., 2018) in which adults performed a dichotic listening task while attending to a target narrative in English under varied conditions of interference. These included a stream that directly competed with the target in English, a narrative in an unknown language, a non-linguistic stream, and silence. Electroencephalography (EEG) responses for each condition were cross correlated with the attended and unattended speech envelopes. In addition to the expected selective entrainment effect of more robust encoding for the attended envelopes than for the distractors; researchers also found that the type of the interfering stream significantly modulated the strength of correlations, with the most intelligible distractor (English) causing the strongest encoding in both attended and unattended streams. In contrast, the non intelligible distractors caused weaker encoding, revealing a modulation of selective entrainment response according to the type of distractor. Behavioural performance (comprehension) was equivalent across all conditions.

Another dichotic listening task used magnetoencephalography (MEG) to record responses of adults listening to natural speech in two conditions of interference: intelligible or non intelligible strings of syllables (Har-shai Yahav & Zion Golumbic, 2021). Again, there was no difference in behavioural performance (comprehension of the target narrative) across conditions. There was, however, evidence of enhanced tracking of the target stream in conditions of the intelligible distractor (consistent with the results of Olguin et al., 2018). MEG analysis showed neural activation for the intelligible distractor stream in regions associated with linguistic processing (left interior frontal and posterior parietal regions). The researchers (Har-shai Yahav & Zion Golumbic, 2021) concluded that selective attention does not fully eliminate the processing of ignored speech.

Furthermore, experience of bilingualism has been shown to affect these patterns of neural entrainment in different conditions, as shown in a study by Olguin et al. (2019). Here, two groups of bilingual adults (those with a typologically similar L1 and L2 and those with typologically dissimilar languages) performed the same task as the monolingual adults presented in a previous study discussed above (Olguin et al., 2018). When the behaviour (comprehension) and patterns of response of all three groups (including monolinguals) were compared, the groups displayed equivalent comprehension of the target narratives. There were, however, different patterns of responses between bilingual and monolingual adults to the interference conditions of varied linguistic intelligibility and non-linguistic comparators, with monolinguals showing significant variation between the conditions of interference according to intelligibity of the distractor stream (as discussed above), and bilinguals showing a neutral pattern of neural response between all the conditions of interference, with no indications of variation. These differences in patterns of response to conditions of interference between bilinguals and monolinguals were held constant across both groups of bilinguals (with different typological experience of L2). Some additional fine-grained differences between the bilingual groups were revealed, namely distinctions as a result of time-windows analysis, specifically in the context of the two types of linguistic interference. These subtle differences, however, did not impact the main finding of significantly different patterns of response to different conditions of auditory interference between (all) bilinguals and monolinguals, coupled with equivalent performance. To date this has only been explored with adults and the fully matured brain with a protracted exposure to bilingualism. Therefore any such study involving children must take neurodevelopmental considerations into account.

2.3 Neuroanatomical and cognitive development overview

As would be expected, neuroanatomical development is associated with cognitive development (Passler et al., 1985; Crone & Ridderinkhof, 2011; Johnson, 2001). In particular, prefrontal areas have been linked to overall cognitive development (Casey et al., 2005; Majovski, 1989), especially those executive functions associated with selective attention such as inhibitory control (Konishi, 2011; Luna et al., 2001) and suppression of irrelevant information (Casey et al., 1997; Dempster, 1992). The parallel expansion of grey matter in prefrontal regions with age is proposed to correlate with an increase of control of interference (Bunge et al., 2002).

However, the development of prefrontal areas is protracted and non linear. Theories of development in early childhood broadly agree that the area comprising the frontal lobes increases sharply from birth to age 2, followed by a less pronounced growth spurt from about 4 - 7 years of age. From 7 onwards, there is a slow and much less dramatic increase in the size of the frontal lobes until adolescence (Dempster, 1992; Passler et al., 1985; Welsh & Pennington, 1988; Romine & Reynolds, 2005). Although total cerebral volume shows no significant increase after the age of 5, white matter volume increases with age and grey matter volumes increase during childhood and then decrease before adulthood (Durston et al., 2001), before stabilising at approximately age 22 (Dosenbach et al., 2010). In addition, MRI studies (Reiss et al., 1996; Sowell et al., 2001), reveal most prominent expansion in the prefrontal areas of the brain between the ages of 5-17, although growth is not uniformly correlated with chronological age (Sowell, Delis, et al., 2001). Neural studies using ERPs (Segalowitz & Davies, 2004) and EEG oscillations (Thatcher, 1991) agree that the prefrontal cortex is still developing into late adolescence.

As described in Chapter 1, development of selective attention, a core cognitive function, is closely associated with the maturation of the prefrontal cortex. In line with the “bumpy” process of structural maturation described above, development of cognitive functioning is also non linear, and developmental progression has been found to vary across tasks (Davidson et al., 2006). One proposal is that there are different developmental trajectories for executive functions labelled “basic” as opposed to “complex” (Crone & Steinbeis, 2017) or “hot” and “cool” (Prencipe et al., 2011). Basic/hot executive functions are defined as stimulus-driven and, as well as selective attention, include cognitive flexibility, working memory, inhibition and error monitoring. Complex/cool functions are defined as intentional processes, such planning or emotional regulation. Basic/hot stimulus-driven processing is proposed to have a shorter development, whereas complex or cool tasks show a different range of patterns in prefrontal areas into adolescence. Additionally, children’s cognitive functioning is not just a delayed or reduced version of adults’ performance. fMRI has revealed that different regions are activated relative to adults when children aged 7-12 perform cognitive tasks (Rueda et al., 2004; Casey et al., 1997). Several reasons for such variance in processing relative to adults have been proposed (Ridderinkhof & van der Stelt, 2000). One explanation is that participants of different ages may interpret, understand or perform task instructions in distinct ways and may have different motivation or endurance for following tasks for extended duration. Another is that as they develop, children may use different strategies to perform the tasks that do not necessarily correspond to age-related changes in processing. Furthermore, cognitive architecture does not have a linear development (as described above); therefore corresponding neural processes may not gradually increase in efficiency, but go through phases of qualitative reorganisation. This means that any measurement through tasks might reflect a qualitative phase change rather than gradual development in attentional processing. Finally, neural results may be influenced by changes in brain maturation that are unrelated to attentional processes, so any patterns shown may simply be a reflection of age-related change that is due to non-attentional factors.

Furthermore, tests of selective attention often tap a single domain – visual or auditory – which, as described below, show overlap in terms of phases of development, but also reveal distinct neural correlates.

2.3.1 Development of selective attention - visual

Studies of selective attention in children have first focused on the visual domain through nonverbal tasks such as (modified) Stroop, Simon and Flanker. Although tests have been performed successfully on children as young as 24 months (Poulin-Dubois et al., 2011), an early review of monolinguals (Comalli et al., 1962) recommended a minimum age of 7 years old, on the basis of reading ability. Typically, studies find that both reaction time and accuracy improve with age between 6 and 11 (Rueda et al., 2004). A comprehensive study of age differences in Stroop performance (Comalli et al., 1962) tested over 200 individuals ranging in age between 7 and 80. Results showed that visual selective attention improved with age from the age of 7 to adulthood, remained stable over the young adults into middle age, and declined for the oldest group tested (65-80, see also Wise et al., 1975).

2.3.2 Development of selective attention – auditory

Reviews have proposed that selective listening, in the same way as visual selective attention, improves through childhood and adolescence to early adulthood, and then declines in late adulthood (Dempster, 1992; Mueller et al., 2008). Comparisons of children between age categories or relative to adults have shown significant differences: for example 10 year olds performed four times better than 7 year olds when attending target words (Geffen & Sexton, 1978). In versions of Cherry's cocktail party task (Cherry, 1953), accuracy of repeating a target word while ignoring a distracting word improved linearly with age across several age groups of children (preschoolers: Hiscock & Kinsbourne, 1977; 3-12 year olds: Hiscock, M. & Kinsbourne, M., 1980; 5-6, 7-8 and 9-10 year olds, Anooshian & McCulloch, 1979; 7 and 9 year olds; Geffen & Wale, 1979; 8, 11 and 14 year olds, Doyle, 1973). Similarly, a study comparing children's (aged 4-11) and adults' performance in a tone-in-noise task, showed comparable performance in quiet conditions, but a significantly poorer performance by children in noisy conditions. Again, performance in noisy conditions was correlated with age and reached adult levels by the age of 9-11 (P. R. Jones et al., 2015).

In terms of neural indicators, the maturational development described above is reflected in neural studies that report step changes in the development of the auditory selective attention system. A study investigating the development of auditory attention using auditory evoked potentials (AEPs) (C. W. Ponton et al., 2000) on 118 participants aged 5-20 found that not only does maturation extend into adolescence, but that amplitude changes are more abrupt and step-like, in contrast to changes of latency that are more gradual. A related study (Ponton et al., 2002) found that different AEP components reach maturation at different ages: some by the age of six (specifically the middle latency response [MLR] components Pa and Pb, P_2, and the T-complex); some that mature consistently 50% per year (N_2); and a third group that mature more slowly (at a rate of 11-17% per year) comprising different components again (the AEP peaks P_1, N_{1b}, and TP_{200}). The above findings therefore indicate not only age-related maturation, but also variability across components and a non-linear trajectory.

When tested in the context of a dichotic listening task, different age groups displayed distinct amplitudes and latencies of ERPs (Karns, C. M., Isbell, E., Giuliano, R. J., & Neville, H. J., 2015). In this study, the only comprehension differences were less accuracy in the youngest age group (3-5) but across all others (10, 13, 16 and 18-25) comprehension was comparable while (non-uniform) maturational differences were observed for linguistic and nonlinguistic probes. Crucially, such changes in neural processing have been discerned in the absence of behavioural differences in performance (comprehension), indicating neural modifications that cannot be detected by behavioural tests alone. Such age-related neural differences despite equivalent performance have been found in both non-naturalistic (Mueller et al., 2008) and naturalistic listening tasks (Karns, C. M., Isbell, E., Giuliano, R. J., & Neville, H. J., 2015).

In addition to age, environmental factors have also been shown to exert an influence on the development of auditory attention, as demonstrated in neural responses to auditory tasks. One such environmental variable is socioeconomic status (SES).

Similar to studies investigating selective auditory attention across age groups (Karns, C. M., Isbell, E., Giuliano, R. J., & Neville, H. J., 2015), those examining the impact of SES on selective attention in children have also found different neural (ERP) patterns despite equivalent performance (comprehension), while controlling for age.

In one study investigating the development of auditory selective attention (Hampton Wray et al., 2017), groups of higher and lower SES children performed a listening task while their ERPs were measured and compared at age 4. As a follow-up, the children in the lower SES cohort were retested a year later. Findings showed that the age of 4, children of higher SES showed a significant effect of attention (higher ERPs for attended than unattended probes), and the children of lower SES showed no such effect (similar ERPs for attended and unattended). However, comprehension scores between the two groups at age 4 were not statistically different. When the lower SES children were retested a year later, at age 5 the attention effect in the lower SES group was comparable to the higher SES group at age 4 to the attended stream. The researchers concluded that not only did this represent a maturational delay of one year between the ages of 4 and 5 for the lower SES group (according to neural, not behavioural indices), but also a "divergent developmental pattern in neural mechanisms" according to SES background (Hampton Wray et al., 2017). This study was supported by others that had found neural differences in the higher and lower SES groups of 3-8 year olds despite comparable comprehension (Stevens et al., 2009), and differences in theta power between higher and lower SES pre-adolescent children (age 11-14) in attended and unattended streams, despite equivalent reaction times and accuracy (D'Angiulli et al., 2008). Finally, an 8 week intervention to improve selective attention on preschool children of lower SES (Neville et al., 2013) successfully improved attention to the attended stream.

The first SES study detailed above (Hampton Wray et al., 2017) and similar studies showing neural differences in groups of children of different socioeconomic status are especially relevant to the themes of this thesis for two reasons. First, they explicitly attribute differences in neural processing to environmental variables and thus support theories of neuroplasticity. This is analogous to bilingualism, another such environmental variable, which affects neural structure and processing, as summarised in Chapter 1 (Mechelli et al., 2004; Garbin et al., 2010; Burgaleta et al., 2016; Hayakawa & Marian, 2019; García-Pentón et al., 2014). The second is the finding of neural differences between the groups despite equivalent behaviour. One of the conclusions from the researchers into socioeconomic status and selective attention is that children of different SES backgrounds recruit different neural processes to achieve the same result (D'Angiulli et al., 2008). This again is similar to studies of bilingualism (in adult samples) which have found comparable behavioural performance but distinct neural patterns across a variety of methodologies: MEG (Bialystok, Craik, et al., 2005), fMRI (Luk et al., 2010; Chee et al., 2004; Román et al., 2015), EEG (Olguin et al., 2019) and ERP (Kousaie & Phillips, 2012; Kousaie & Phillips, 2017). These parallel results suggest that not only is the brain plastic, but a degenerate organ which, in spite of structurally diverse components, can generate equivalent outputs (see Chapter 1, also Navarro-Torres et al., 2021; Edelman & Gally, 2001; Green et al., 2006; Mason et al., 2015).

Not only is SES similar to bilingualism in being an environmental variable that influences attention; it is also a significant covariate (Naeem et al., 2018), particularly in childhood. As mentioned in the Introduction, a number of studies in the early to mid twentieth century claimed that bilingual children were at a cognitive disadvantage after they performed significantly worse than their monolingual peers in I.Q. tests (W. R. Jones & Stewart, 1951; Lewis, 1959; Wang, 1926); arithmetic and reading (Macnamara, 1966; Manuel, 1935) and verbal intelligence (Darcy, 1953), but a fundamental criticism of these studies was that they did not control for SES. Since those early studies, SES has been recognised and well-documented as an influence on cognitive development (Hoff, 2003; Walker et al., 1994; Andrews Espy et al., 2001; Mezzacappa, 2004), and more recent studies on the impact of bilingualism on cognitive performance in childhood, which have controlled explicitly for SES, have claimed a bilingual advantage as a separate effect from SES in tests of children from different backgrounds (Calvo & Bialystok, 2014; Carlson & Meltzoff, 2008). A positive effect of bilingualism has also been found in a sample comparing monolinguals and bilinguals in a lower SES group (Engel de Abreu et al., 2012), suggesting that bilingualism may mitigate any effects of lower SES on children's cognitive processing on tasks requiring selective attention (Blom et al., 2014).

2.4 Neuroplasticity and bilingualism

As discussed above, neural differences can exist despite behavioural equivalence, due to neuroplastic adaptations to environmental factors such as SES (as above) and bilingualism. The case for neuroplastic change as a consequence of bilingualism is well-documented (see Li et al., 2014 for review), with claims that bilingualism confers a "neural signature" (Kovelman et al., 2007; Jasińska & Petitto, 2014) even at the initial stages of learning a second language (Yang et al., 2015), and showing different activation in multiple regions from monolingual processing, especially in tasks of selective attention (Luk et al., 2010). There are findings that bilingualism influences the processing of the most basic linguistic stimuli. For example, bilingual adults have been shown to have stronger subcortical representation of fundamental frequency (F0) and more consistent neural responses to attended syllables (/ba) compared to monolinguals (Krizman et al., 2012; Krizman et al., 2014), even when they have been exposed to different combinations of languages (Skoe et al., 2017), indicating that bilingual experience has an impact on underlying neural processing of linguistic input regardless of the languages of exposure.

However, it has also been found that neural adaptation as a result of bilingualism can itself vary according to factors including, but not limited to: a) age of acquisition, affecting volume of cortical areas (Wei et al., 2015), distribution of white matter (Nichols & Joanisse, 2016) cortical thickness (Klein et al., 2014) or the processing of syllables (Zinszer et al., 2015); b) proficiency, affecting grey matter in the temporal pole (Abutalebi et al., 2013) and prefrontal activity (Videsott et al., 2010); c) language similarity, affecting activation when reading in the second language (Kim et al., 2016); or d) age, increasing activation (McNealy et al., 2011; Jasińska & Petitto, 2014).

Changes in the developing brain as a result of bilingualism have also been of great interest to researchers. Infants as young as 4-6 months have been found to have different phonetic processing as a result of bilingualism, using fNIRS (Petitto et al., 2012). Monolingual and bilingual children aged 8-11 were found to have structural differences in white matter tracts when scanned using magnetic resonance diffusion tensor imaging (MR-DTI) (Mohades et al., 2012). Neural activation was increased in left-hemisphere classic language areas for 7-10 year old bilinguals relative to monolinguals in an fNIRS study (Jasińska & Petitto, 2013). A neuroanatomical study of two groups of bilingual children aged 6-13 who differed in frequency of use of their L2 (Archila-Suerte et al., 2018) found significantly different neuroanatomical profiles according to language experience: children with "balanced bilingualism" (equal use of both L1 and L2) had thinner cortices of the left superior temporal gyrus (STG), left inferior frontal gyrus (IFG), left middle frontal gyrus (MFG) and a larger bilateral putamen, whereas "unbalanced bilinguals" (those who mainly used L1, and less frequent use of L2) showed thicker cortices of the same regions and a smaller putamen.

Together, the results from the above studies indicate that a "neural signature" (Kovelman et al., 2007) is not a single pattern or presents exclusively in language-specific regions. Rather, the effects of bilingualism have multiple ways of demonstrating neural change (grey matter, cortical thickness etc.) in different brain regions, and, furthermore, such manifestations are also subject to variation due to language experience (Kuhl et al., 2016).

Behavioural studies of children indicate that these neural modifications, as a result of bilingualism, at the very least correlate with behavioural measures of linguistic processing. These are apparent from earliest development. Newborn bilingual babies are already able to differentiate between the two languages that were spoken while they were in the womb (Byers-Heinlein et al., 2010). Bilingual infants are reported to have enhanced ability to discriminate between languages when watching silent videos in different languages (Sebastián-Gallés et al., 2012). Bilingual children aged 6-9 showed enhanced performance when learning the phonological patterns in a new language (Kuo & Anderson, 2012). Groups of bilingual children aged 7 and 9 showed enhanced phonological awareness and meta-linguistic skills despite lower vocabulary scores than their monolingual peers (Eviatar & Ibrahim, 2000). [Vocabulary scores for bilingual children have been shown to be lower in one language but equivalent across languages to a monolingual's single language (Pearson et al., 1993; Hoff et al., 2012)].

These differences in processing linguistic input can affect performance on tests of auditory selective attention in children. In one study (Filippi et al., 2015), researchers tested whole sentence comprehension by bilinguals and monolinguals under conditions of auditory interference. They compared bilingual and monolingual children's comprehension of simple (canonical) and complex (non-canonical) sentences with and without whole-sentence interference. The L2 of the bilingual children varied across nine languages, but all spoke English fluently. The target sentence was always spoken in English and the interference was presented in either English or Greek, and different combinations of target and distractor sentences in English and Greek were counterbalanced. Bilinguals performed better than monolinguals at comprehension of complex sentences when the interference was in Greek, the unknown language. This supported similar finding in adults (Filippi et al., 2012), in which the bilingual (Italian-English) group of adults significantly outperformed their Italian monolingual peers, especially in the comprehension of non-canonical sentences, in the condition of auditory interference (in either language, but particularly in their native Italian). There are several parallels between the above studies (Filippi et al., 2015; Filippi et al., 2012), and the studies in the experimental chapters that follow. Not only do these studies use an auditory task with different levels of interference, the later iteration (Filippi et al., 2015) directly compares children and adults performing a similar task. Equivalent patterns in behavioural results between bilingual children and adults suggested that children had already developed similar modifications to performance, to those shown by adults, as a result of bilingualism, within the parameters of this particular task. This implies that bilingualism had caused similar neural adaptation to auditory selective processing across both age groups, a finding very pertinent to the first and second questions addressed in this thesis, albeit with a differently designed dichotic listening task.

A different line of enquiry exploring bilingual auditory linguistic processing has been investigations of processing speech in noise. Studies have found that bilinguals routinely show poorer recognition of words in noise relative to monolinguals (Bradlow & Alexander, 2007; Mayo et al., 1997; Rogers et al., 2006). Across these studies, bilinguals required either a greater signal-to-noise ratio than monolinguals (Shi, 2010; Mayo et al., 1997) or increased clarity or predictability of the speech signal (Bradlow & Alexander, 2007) than monolinguals in order to perform the task. Age of acquisition and proficiency have been identified as contributing factors (late bilinguals or those with lower proficiency struggle more to identify the speech sounds) but not enough to account fully for a bilingual speech-in-noise disadvantage, as near-native proficiency bilinguals also demonstrated poorer performance in a speech in noise task than monolinguals; despite equivalent performance in a speech in quiet condition (Rogers et al., 2006). The proposed explanation for these findings is that the greater demands of managing two or more languages create greater processing demands for bilingual speakers, particularly when accessing lexical information within a sentence, similar to the hypothesis about constrained attentional capacity in bilinguals introduced in Chapter 1.

One study (Krizman et al., 2017) further explored the proposed bilingual disadvantage at recognizing speech in noise, by presenting five different conditions to bilingual and monolingual participants, with varying amounts of speech and non-speech in noise. They explicitly tested whether this specific processing disadvantage was language-dependent by including conditions of tones (non-linguistic input) as well as speech (linguistic) in noise. They found that performance differences between bilinguals and monolingual adolescents (aged 14-15) varied by condition and its linguistic processing load: bilingual adolescents (early, high-proficiency) performed worse than monolinguals when perceiving sentences. There was comparable performance between the two groups when perceiving individual words. Bilinguals performed better than monolinguals, however, at perceiving tones in noise. The researchers concluded that this pattern of differences indicates that any bilingual disadvantage when perceiving stimulus in noise is due to bottlenecks in language-dependent processing, while non-linguistic input is free of such constraints. These findings have direct relevance to several of the questions addressed in this thesis. In reference to determining the effects of bilingualism on attentional capacity, in the above study a bilingual "bottleneck" for linguistic processing was identified, consistent with the concept introduced in Chapter 1 of an attentional bottleneck (Pashler, 1994) caused by increasing competition for the limited capacity resource, which leads to a deterioration in performance. In the context of my investigations of bilingual processing of linguistic and non-linguistic interference in a dichotic listening task, the study described above showed different patterns of bilingual performance when processing linguistic and non-linguistic stimuli in noise, indicating not only differences by group (relative to monolingual performance) but by condition (sentence, word, tone). This will be compared and contrasted with my own results in the Discussion in Chapter 7.

Additional investigations of monolingual and bilingual performance in both linguistic and non-linguistic tasks have revealed contrasting results to the findings described above (Krizman et al., 2017). A study which compared the performance of younger adult bilinguals and monolinguals during both a linguistic processing task and a non-verbal task (Blumenfeld & Marian, 2011), found no difference in performance in either task between the groups. The linguistic task consisted of listening to words and then identifying them by selecting their visual representations from a group of four pictures. This group of pictures also contained a linguistic competitor, e.g., if the target (spoken) word was "hamper", a picture of a hamper was accompanied by a picture of a hammer, as well as pictures of two other random words. Accuracy in the linguistic task was measured by pressing the correct button on a key pad to identify the target word. Simultaneous eye tracking measured the activation of competitor words and control words during word recognition, by recording the amount of time the participant looked at each (word) picture from the four options. In addition, the word recognition task was followed by one of three types of priming probe, which presented a grey asterisk in the same place as one of three variations: the target, competitor or one of the control (irrelevant) stimuli from the previous trial. Eye tracking measured how long attention rested on the grey asterisk quadrant of each priming trial. Attention on a control probe, which was designed to elicit minimal attention from the previous round, was considered the baseline. Response latencies (eye gaze time) for the grey asterisk when the competitor picture had been on the previous trial were considered to reflect inhibition and were expected to be longer than control probe trials. Finally, response latencies for target probes (where the grey asterisk was in the same quadrant as the target picture in the previous trial) were expected to elicit the shortest gaze relative to both the control and competitor probes, representing location facilitation as the previous trial had garnered maximum attention. The non-verbal task was a Stroop task, with speed and accuracy measured by responses on a key pad to congruent and incongruent arrows on a screen. Despite overall equivalent performance (accuracy) in both tasks between the groups, results showed different patterns for both inhibition and correlations between tasks (bilingual inhibition mechanisms between the linguistic and non-verbal tasks were correlated; monolinguals recruited different resources for each task). A follow up study tested older and younger adult bilinguals and monolinguals during the same linguistic processing and non-verbal tasks (Blumenfeld et al., 2016). Once again, there was no difference between monolingual and bilingual performance in either age group. There was, however, an age-related difference, which varied in magnitude between the groups. Bilinguals suffered less performance decline as they aged. Once again, results for both age groups revealed different patterns suggesting that, in both tasks, bilinguals recruited similar inhibition mechanisms; whereas monolinguals showed different mechanisms for performing the linguistic and non-linguistic tasks. The finding from both studies are directly relevant to my later comparisons of bilinguals in different age groups performing the same behavioural task (Blumenfeld et al., 2016); and the discussion about monolingual and bilingual performance in a nonverbal task (Blumenfeld & Marian, 2011; Blumenfeld et al., 2016).

The above study found equivalent behavioural performance between monolingual and bilingual participants, in two age groups, for both the linguistic and non-verbal tasks. These findings contrast with other studies that have found differences between monolinguals and bilinguals in age groups of younger and older adults. One such study tested both age and language groups in a non-verbal switching task (Gold et al., 2013), in which bilingual participants in both age groups outperformed their monolingual peers. Furthermore, concurrent fMRI data revealed that bilingual participants in both age groups showed decreased activation in the left lateral frontal cortex and cingulate cortex. The researchers concluded that lifelong bilingualism mitigates age-related declines in neural processing for cognitive control tasks (see also Costa & Sebastián-Gallés, 2014, for a review of how bilingualism affects processing across the lifespan).

2.5 Summary

In sum, the literature reviewed above synthesises findings on the topics of bilingualism, selective attention (visual and auditory), cognitive development, neuroplasticity and interactions of the above, supported by both behavioural and neural evidence. First I examined the neural basis for the claim that a bilingual's two languages are co-activated, leading to competition between them, which must be resolved. Experience of managing this continual competition has been shown to lead to neuroplasticity, specifically in the areas and processing associated with selective attention.

On the topic of selective attention, I summarised the key theoretical positions for visual selective attention and the neural basis of both visual and auditory selective attention. Auditory selective attention relies on tracking of the speech stream, which, according to the 'selective entrainment hypothesis' (Costa-Faidella et al., 2017), tracks the attended stream preferentially in conditions of interference or dichotic listening. Furthermore, response patterns in selective entrainment vary according to both the type of interference and due to factors such as bilingualism (Olguin et al., 2019), although to date this has not been tested on children.

On the topic of children and the developing brain, I summarised the development of both cognition and specifically selective attention in both the visual and auditory domains, with both behavioural and neural evidence. I presented evidence that the development of (auditory) selective attention is affected by factors such as age, and environmental factors including bilingualism, socioeconomic status, and combinations of the above.

This led to the topic of bilingualism and neuroplasticity, both generally and in the developing brain. This has been associated with modifications in linguistic performance in childhood, encompassing a linguistic advantage in one comprehension task (Filippi et al., 2015); a linguistic disadvantage, but non-verbal advantage in another (Krizman et al., 2017), and no behavioural difference in a third, but evidence of differences in processing through neurophysiological evidence (in this case, eye gaze) (Blumenfeld et al., 2016).

In this way, I have set the scene for the three questions that will be addressed in this thesis that draw on elements of bilingualism, selective attention, development, neuroplasticity, maturation, language experience and the impact of bilingualism on linguistic vs. non-verbal processing. After presenting my experimental chapters, I will review the findings in the context of some of the studies described above to evaluate where they fit in the landscape of the current literature.

Chapter 3: Methods

3.1 Introduction

The neural and behavioural studies used different but complementary methods to investigate the differences in monolingual and bilingual attentional processing. All the experiments used a dichotic listening task with variations in the attended and unattended conditions, and auditory stimuli, which differed according to the experiment. The dichotic listening task is detailed in Section 1.

In the investigations of neural encoding of attended and unattended speech, the dichotic listening task was combined with the neural data using EEG (electroencephalography), which were analysed using the mTRF toolbox. Section 2 describes the justification for using these methods; how the data were collected and cleaned using a pre-processing pipeline in EEG Toolbox; the calculation of the speech envelope; and the features and computation of the mTRF toolbox.

In the behavioural studies of multimodal attentional processing, a dual task paradigm was devised. Here the dichotic listening task was combined with an adapted version of visual T.O.V.A. (Task of Variables of Attention) to be performed simultaneously. Section 3 describes the dual task paradigm and T.O.V.A. in more detail.

3.2. Dichotic listening task

3.2.1 Overview

The task common to all the studies was a version of the dichotic listening task pioneered by Cherry (1953). His version was named the “cocktail party” task, due to its novel use of natural speech streams instead of clicks or tones, and similarity to the scenario of a partygoer who must ignore distracting noise in order to focus on a single conversation. In the task, participants are presented with two streams of auditory stimulus simultaneously, in different ears via headphones, and asked to concentrate on one, the target, and ignore the other, unattended stream. In the design used for the experiments in this thesis, target streams were created to be naturalistic speech and unattended streams were varied across conditions.

3.2.2 Dichotic listening and selective attention

The dichotic listening task as described above is a well-established tool for measuring selective attention. Behavioural and neural studies have used versions of it to investigate the locus of processing (Kimura, 1967; Har-shai Yahav & Zion Golumbic, 2021) and compare the strength of cortical response to the target stream relative to the unattended information (Kerlin et al., 2010). It is compatible with a range of neuroscientific methods such as MEG (magnetoencephalography, e.g., Ding & Simon, 2012), ECoG (electrocorticography, e.g., Zion Golumbic et al., 2013) fMRI (functional magnetic resonance imaging, e.g., Wikman et al., 2021) and EEG (electroencephalography, used in this study and others, including Olguin et al., 2019; Horton et al., 2014; Mesgarani & Chang, 2012; Fiedler et al., 2018; Broderick et al., 2018). The stimulus can be tailored to the age range and ability of the participants, and interference manipulated to test responses to a variety of linguistic and non-linguistic streams (Olguin et al., 2018; Har-shai Yahav & Zion Golumbic, 2021). It can use naturalistic stimulus, which produces more accurate and generalisable results (Hamilton & Huth, 2020) than single words, clicks or tones; and is a more engaging experience for the target participant age range in these studies. Therefore this version of the dichotic listening task was extremely suitable for both the behavioural and neural studies to assess auditory selective attention across age groups and language backgrounds, and test responses to various linguistic and nonlinguistic unattended stimuli.

3.2.3 Task design

The dichotic listening task was designed to investigate the effects on selective attention of listening to continuous speech, whilst ignoring different levels of linguistic and non-linguistic interference; and establish whether these patterns differed between monolingual and bilingual children and adults. Each experiment followed a similar procedure for the dichotic listening element; with different stimuli pairs according to the experiment, which are detailed more fully in each experimental chapter. In summary, both groups were presented with two competing continuous streams, which were played simultaneously in different channels of headphones. Participants were instructed to focus on the target narrative (attended stream) in either the left or right ear, and ignore the interference (unattended stream) in the other ear. Attended/unattended streams were counterbalanced between the left and right ears to avoid a dichotic right-ear advantage, especially in children (Berlin et al., 1973). The target stream was always in English, as this was the language common to all participants, and to provide equivalence between the target streams in all conditions. The narratives consisted of sentences concatenated to form continuous speech, which lasted approximately 3.3 minutes per presentation. These uninterrupted narratives in continuous speech enabled an assessment of comprehension in a setting that was both naturalistic and ecologically valid.

Conditions. Each experiment consisted of four auditory conditions: in the first, all participants attended to a target story in English without any interference (Single Talker). In the subsequent three conditions, the target story in English was paired with different levels of interference. The type of interference and length of the conditions differed according to the experiment, and is detailed in the experimental chapters. The EEG experiments consisted of two 3.3 minute blocks per condition; the behavioural experiments presented a single 3.3 minute block per condition. In addition, the EEG experiments used different unattended stimuli (linguistic distractors in EEG Experiment 1, non-linguistic noise in EEG Experiment 2); the behavioural experiments shared the same unattended stimuli as EEG Experiment 1. These are detailed in the relevant chapters.

Stimuli. The target stories for the attended ear in the EEG experiments were four stories in English specifically aimed at children. Two of these stories were used as the attended stimulus in the behavioural experiments, which were shorter in duration than the EEG experiments, and used half of each target story per condition. The use of children's stories, with simple syntax and vocabulary, ensured that all participants would be able to understand them and that there would be no variance in target content comprehensibility across conditions.

The target streams for the unattended ear varied by experiment, except for the first condition, which was always silence in the unattended ear (Single Talker condition). In the first EEG experiment and the behavioural experiments, the unattended streams in the remaining three conditions were stories in English (English-English condition), an unknown language (English-Latin condition) and an acoustic stream derived from one of the target stories (English-Musical Rain condition). In the second EEG experiment, which tested response to non-linguistic interference, the three unattended streams after Single Talker were a simple and repetitive melody (English-Music condition), a recording of children in a classroom with no distinguishable words (English-Babble condition) and a stream of vehicle noise (English-Traffic condition).

The stories in English were sourced from online resource storynory.com. Care was taken to choose stories that were not universally familiar (e.g., Pinocchio, Cinderella), where participants may have been able to answer comprehension questions about the target story without paying full attention. After selecting more obscure or original stories, some details were further changed, and the stories were transcribed into narratives 120 sentences long, with each sentence lasting approximately 3 seconds in length. The four attended English stories were then recorded sentence by sentence by a native English female speaker. The unattended linguistic stimuli were recorded by different female speakers. Gender of the speaker was kept the same for all stories (same female voice for all target stories, different female voices for interference), to reduce segregation strategies based on talker's gender (Brungart & Simpson, 2007). Transcripts of the attended English stories, unattended English story and unattended Latin story can be found in Appendix A.

Each target story was then split into 2 blocks and participants attended to the first half in either the left or right ear (randomly assigned in EEG experiments, left ear first in behavioural experiments), with interference in the other, and then swapped ears for Block 2. Each block (half of a story) consisted of 60 sentences, with all 60 sentences concatenated with a 300ms gap between them to create a single block lasting 3.3 minutes. Block 1 was always the first half of the target story and Block 2 the second half.

All stories' volumes were normalised to ensure equivalent average amplitude. The stimulus of Musical Rain used in EEG1 and the behavioural studies was identical in length, root mean squared level and long-term spectrotemporal distribution of energy to its corresponding target story, but did not trigger a speech percept (Uppenkamp et al., 2006). It was generated in MATLAB by extracting temporal envelopes of the target sentences and filling them with 10ms fragments of synthesised vowels jittered in frequency and periodicity.

Instructions were recorded by the same female speaker of the target stories. These were played before each block in the target ear, telling the participant*: "This is your right/left ear. Please listen carefully to the story in this ear, on your right/left side, and ignore the story or sound in the other ear".*

Comprehension. To ensure that participants were attending to the target story, they were instructed at the start of each experiment that they would have to answer ten either/or questions about the target story at the end of each block. Participants were assured that these were straightforward questions – e.g., "This is a story about a KING/QUEEN" and they were asked to choose the correct response each time.

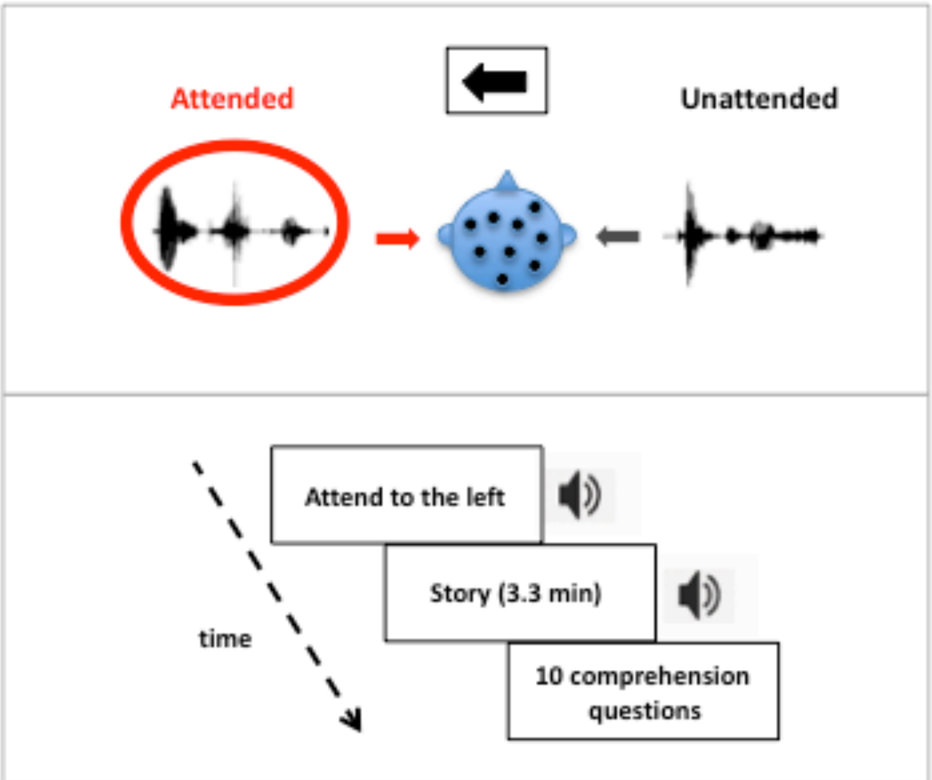
There were ten questions after each block, resulting in behavioural scores out of a total of 80 questions for the participants in the EEG experiments, and 40 comprehension questions in the behavioural studies.

The questions covered the content at the beginning, middle and end of each story and the distribution of correct responses was evenly distributed between the first and second option to each question.   The comprehension questions can be found in Appendix B.

Figure 1 is an illustration of the dichotic listening task procedure.

Figure 1

Dichotic listening task experimental procedure



Note : Participants were instructed to attend to one side. The stimuli were presented for 3.3 min, and participants were then asked to complete 10 comprehension questions about the attended story.

3.3 EEG

3.3.1 Overview

EEG (electroencephalography) is a method of recording surface electrical activity, via multi-electrode recordings from the cortex, which represents the neural activity beneath (Pizzagalli, 2007). The output is data showing the voltages of the brain's electrical activity in different states (e.g., resting state, response to stimulus). EEG data can be analysed in different ways: as ERPs (event-related potentials, averaged EEG responses that are time-locked to the processing of stimuli); or ongoing EEG signals, for example neuronal oscillations (signals correlating with, but not precisely time locked with, cognitive events). An additional advantage of EEG is the multidimensional nature of the data, which describe time, space, frequency and power of the signal and thus allow a breadth of analysis (Cohen, 2014). EEG data provide coarse spatial but high temporal resolution, which makes EEG suitable for tracking overall response to stimuli where temporal precision is prioritised over spatial localisation. Indeed, the high temporal resolution of EEG, reflecting direct activation of neurons in response to stimulus, is especially suited to a study investigating neural encoding of speech.

EEG is particularly suitable for use with children (Bell & Cuevas, 2012). It is non-invasive and relatively simple to administer; the caps/nets can accommodate different head sizes; the recording session can be varied according to the participants' attention span; the equipment is not particularly cumbersome and its application does not distress children or cause claustrophobia; and the data are of sufficient quality for meaningful analysis after pre-processing, even allowing for age-related interference. Consequently, it has been used successfully in a range of studies with children including infants (Kalashnikova et al., 2018), younger children (Stevens et al., 2009; Coch et al., 2005; Sanders et al., 2006; Bartgis et al., 2003) and pre-adolescents (Power et al., 2013; Gomes et al., 2007). It is thus an established technique for neural data collection of the target age group of children aged 7-12 for these studies.

3.3.2 EEG in speech and attention tasks

One of the established ways of assessing the brain's processing of speech is by recording the neuronal oscillations mentioned above, and assessing how well they track (or encode) properties of the speech, such as the speech envelope, or semantic information. The neural encoding of speech envelopes is a well-established method for investigating attentional processing, following the 'selective entrainment hypothesis' (Zion Golumbic et al., 2013; Giraud & Poeppel, 2012b), which proposes that attention causes low-frequency neural oscillations to entrain to the temporal envelope of speech. As described in Chapter 2, there is a large body of evidence confirming robust correlation between attended speech envelopes and neural activity (Aiken & Picton, 2008; Di Liberto et al., 2018; Mesgarani & Chang, 2012; Olguin et al., 2018) and showing that the neural encoding of speech envelopes plays an important role for speech intelligibility in both adults (Obleser & Kayser, 2019) and children (Power et al., 2016; Ríos-López et al., 2020).

When this is applied to the cocktail party task, it has been shown that as listeners attend to one speech stream in the presence of competing interference, auditory neurons differentially track changes in the speech envelope of the attended stream (O'Sullivan et al., 2015). Furthermore, the pattern of this tracking differs according to both the type of interference (Olguin et al., 2018), and the language group of participants (Olguin et al., 2019).

Neural data and speech properties can be analysed in a number of ways when testing for selective entrainment. Methods have included calculating cross-correlations across different channels and time points (Olguin et al., 2019; Olguin et al., 2018); computing the cross-correlation at different frequencies of the signal (Kubanek et al., 2013), and using the mTRF toolbox (Crosse et al., 2016) to integrate the inputs of neural and speech data and compute either a forward predictive correlation (TRF or temporal response function) or backward correlation (reconstruction score), both of which are widely accepted as robust indices of neural tracking (see Jessen et al., 2021 for a comparison of the methods).

In the neural studies presented here, I employed EEG to capture the neural encoding of attended and unattended speech envelopes in the groups of monolingual and bilingual children. I then used the mTRF toolbox (Crosse et al., 2016) to model the relationship between the speech envelopes and the neural data, and applied it in a backward direction to assess how well the attended and unattended speech envelopes could be reconstructed from the responses of the neuronal populations that encode them. The workings of the mTRF toolbox are explained in more detail in section 3.3.6.

3.3.3 The use of EEG in this research

3.3.4 Procedure

For the neural experiments, EEG was recorded using a child-sized 64-channel electrode net (Electrical Geodesics Inc., Eugene, OR, USA), connected to Netstation software. Conductive gel was applied to the electrodes to maximise connectivity and reduce interference. Impedances were checked during the gelling process and the experiment only proceeded when all impedances were under 100 Ω. The stimuli were played through foam-tipped earphones in the pre-allocated part-randomised order. During the presentation of the stimuli, voltages were recorded at a sampling rate of 500 Hz. The raw data were then pre-processed in MATLAB: EEGLAB Toolbox (Delorme & Makeig, 2004) before using them as an input to the mTRF toolbox.

3.3.5 Preprocessing

The EEG data were imported, cleaned and prepared for the toolbox using the following 10 step pre-processing pipeline:

1) Raw data was imported to EEGLAB; channels 61-64 (located in muscular/facial areas) were removed, leaving data from 60 channels for processing. Data was filtered between 1-100Hz using zero-phase bandpass Hamming windowed FIR filters (transition band widths of 1Hz with cutoff frequencies at −6 dB) and down-sampled to 250 Hz.
2) Markers were inserted into the EEG data for each sentence onset in attended and unattended conditions. These were identified and inserted using the .mat file generated per participant, which listed the part-randomised order of story presentation; and the signal information from the story recordings, with the exact length of each sentence. These markers could not be added during acquisition, as the stories were played as continuous streams. Markers were inserted for individual sentences denoting status (A = Attended, U = Unattended), Block Number (1 or 2), Condition (A-D for Conditions 1-4) and sentence number (1:60). For example, the 30^{th} sentence in the Block 2 of the Latin story of Condition 3 was marked U2C30 – Unattended/Block 2/Condition 3/Sentence 30.
3) Bad channels were identified via probability and kurtosis if they were 5 SD away from the mean kurtosis and 3 SD from the mean power spectrum and marked in red.
4) Independent Component Analysis (ICA) algorithm (EEGLAB) was run to identify components corresponding to artefacts (e.g. eye blinks) which contaminate data. The participants' age in these studies made the data especially vulnerable to artefacts from non-brain activity. The components identified by ICA were visually inspected, by reviewing topographies, spectral traits and time course, and bad components were removed manually from the data.
5) After ICA, epochs were extracted, starting at 200ms pre-onset of the sentence and ending at 2800ms post onset, resulting in 480 attended epochs and 360 unattended epochs per participant. This length of epoch was chosen so that, after allowing for epoch rejection, there would be a minimum threshold of five minutes of data per condition for input to the mTRF toolbox (as recommended by Jessen et al., 2019).

6) The bad channels identified in step 3) were interpolated, via spherical interpolation. This replaced missing data from faulty electrodes with estimates based on the activity and locations of surrounding electrodes.
7) After the bad channels were interpolated, sub-standard epochs were rejected with the *pop_autorej* function (EEGLAB), removing epochs with values outside a 3 SD of the probability and kurtosis thresholds.
8) The epoch rejection rate was calculated for both attended and unattended datasets in each condition and by group. In Experiment 1, this resulted in an overall epoch rejection of 16.33% for all participants' data (18.31% for monolinguals and 14.35% for bilinguals). In EEG Experiment 2 this was 15.96% overall (14.36% for monolinguals and 17.47% for bilinguals). This is consistent with epoch rejection rates for children of a similar age range (Barry et al., 2004; Picton et al., 2000).
9) Next, the EEG data, which had been recorded using the vertex (Cz) electrode as reference, were re-referenced to the average of all channels using the *pop_reref* function (EEGLAB). This process calculates the average of the signal across all electrodes and then subtracts it from the EEG signal at individual electrodes and timepoints. This ensures that the voltage at each electrode reflects what is unique to that location relative to all the other electrodes, independently of reference location (Nunez et al., 2006).
10) Finally, data were resampled to 100 Hz to reduce the computational load and match the speech envelope for processing in the mTRF toolbox.

Following this process, the EEG data from all participants were entered into the subsequent mTRF analysis to be cross-validated with the corresponding speech envelopes.

3.3.6 mTRF

Neural tracking of the stimulus envelopes was computed using multivariate temporal response functions, as implemented in the mTRF toolbox (Crosse et al., 2016).

TRF can be considered as a filter that describes the linear transformation of the ongoing stimulus to the ongoing neural response. This approach uses linear regression to model the relationship between each speech input and the signal at each EEG channel (Di Liberto et al., 2015). The inputs to the calculation of the TRF model in the toolbox are the stimulus (in this case the normalised speech envelope), response (normalised EEG data), minimum and maximum time lags, sampling rate and a series of ridge parameters or smoothing constants (as detailed in Crosse, Di Liberto, Bednar, & Lalor, 2016).

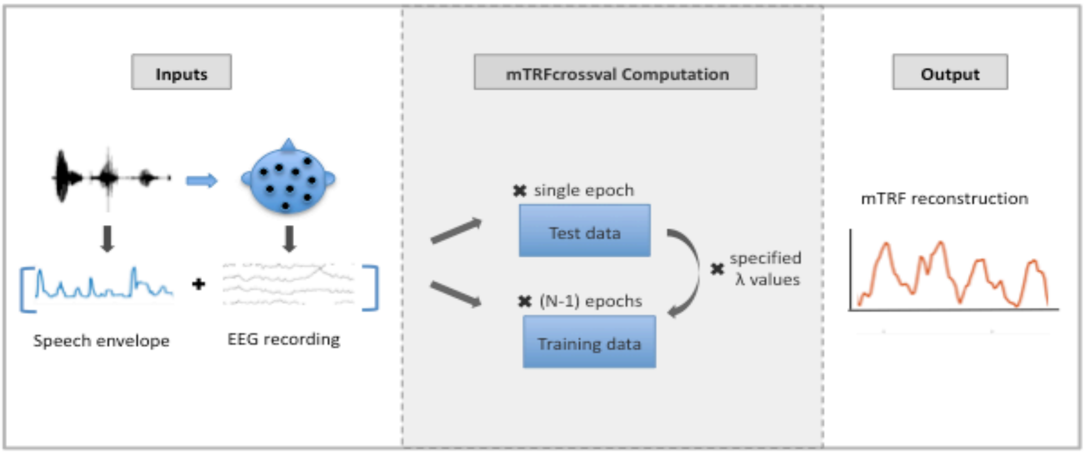
The model is then used to either "predict" the ongoing brain response from the stimulus (the forward or encoding model); or "reconstruct" features of the stimulus from the EEG data (backward or decoding model) and this reconstruction is compared to the original stimulus, resulting in a reconstruction accuracy score (Pearson's correlation, r). The forward model is analogous to regularised linear regression; the backward model (reconstruction) has the advantage of mapping all available neural data simultaneously across all channels and is therefore particularly suited to multi-channel systems such as EEG. The prediction and reconstruction accuracy scores computed by the forward and backward models are widely accepted as measures of encoding accuracy, both generally (Power et al., 2012), for children (Power et al., 2016; Jessen et al., 2019; Kalashnikova et al., 2018), and across modalities (O'Sullivan et al., 2017), and are consistent with other computations of neural tracking. The mTRF technique is especially appropriate for natural speech (Broderick et al., 2018; Ding & Simon, 2014), a stimulus which is more ecologically valid than artificial, contrived stimuli (Hamilton & Huth, 2020; Huk et al., 2018; Matusz et al., 2018).

For the purpose of these experiments, I chose to measure stimulus reconstruction accuracy (backward model). The backward model is arguably preferable to both the forward model and traditional cross-correlation approaches (Crosse et al., 2016) as it uses information from all EEG channels simultaneously to reconstruct the speech envelope, calibrating the relative influence of different channels so that informative channels receive greater weights than those which provide less data, and dividing out any autocovariance between channels. This way, even stimulus features that are not explicitly encoded in the neural response in a one-to-one mapping may be inferred from correlated input features that are encoded, which would not be the case using direct correlation to the raw signal. The inputs to the calculation of the TRF models were the stimulus (normalised speech envelope), response (normalised EEG data), minimum and maximum time lags (0 and 250ms), sampling rate (100 Hz) and a series of ridge regression parameters (12 λ values: 1×10^{-3}:1×10^{8}).

To calculate the models, I created matrices of EEG data and matching stimuli for each attended and unattended epoch per condition per participant per group. The size of the matrices corresponded to the number of viable epochs per condition (minimum 100 for a single condition in each participant). Decoder weights over time lags from 0 to 250ms were calculated using the cross validation (mTRFcrossval) function. The cross validation uses a 'leave-one-out' computation which first fits individual models to every trial for each specified λ, then excludes one trial at a time ('test set') while averaging the others across models ('training set'). The averaged model from the training set is then convolved with the test set to generate a stimulus reconstruction. In each model, this was done in rotation with each trial serving once as the 'test set', repeated across all 12 λ values. Figure 2 illustrates the computation of the mTRF model.

Figure 2

Stimulus reconstruction using the mTRF toolbox



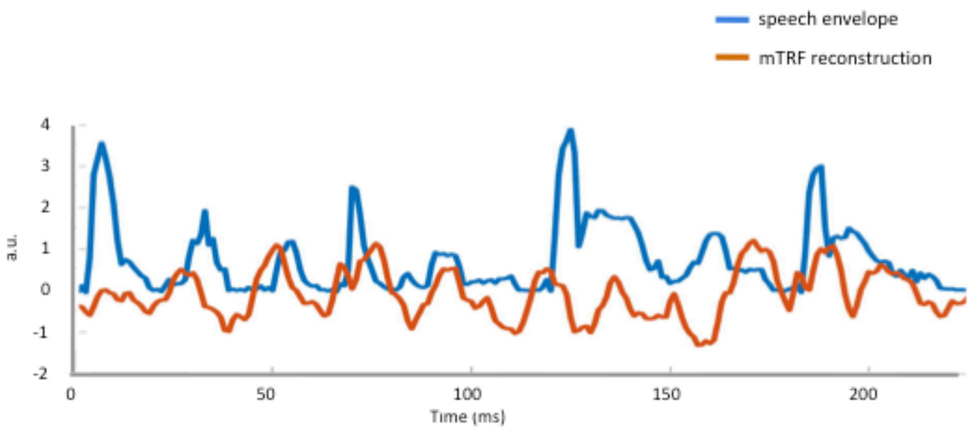
Note: mTRF stimulus reconstruction: A backwards mTRF decoding model was fit separately to the speech envelope of each of trials for each participant, using a leave-one-out cross-validation procedure. This generated a reconstruction of each speech envelope that was validated against the original stimulus envelope.

Each reconstruction was then validated against the original stimulus, resulting in 12 reconstruction accuracy scores (Pearson's r) per stimulus, with the *r* value at the optimal λ (identified as that which yields the highest overall *r*-value across epochs) taken. This optimal lambda value selection mitigated against the potential overfitting of the TRF model.

Figure 3 illustrates the outcome of reconstruction for a sample sentence '*This cat was getting skinnier and skinnier*'.

Figure 3

Reconstruction from a sample sentence



Note: The blue line shows the speech envelope from one trial of the original stimulus. The orange line is the estimate of the envelope reconstructed by the decoder. The reconstruction accuracy score (r) is a measure of the correlation between the original (blue) and reconstructed speech envelope (orange). Resulting r values per sentence per condition per participant were used in statistical analyses.

The reconstruction accuracy scores for each cell of the matrices (corresponding epochs and speech envelopes) were then compared across groups, attention status and condition using linear mixed-effect models (Baayen et al., 2008) as implemented in the lme4 R package (Bates et al., 2014). The step function in the lmerTest package (Kuznetsova et al., 2017) was used to arrive at the best-fitting model. The Satterthwaite approximation (Satterthwaite, 1946) was used for degrees of freedom. Significant p-values are reported in the results section at $p<.05$. All post-hoc tests were FDR corrected for multiple comparisons.

3.3.7 Speech envelopes

Speech envelopes were calculated from the .wav files of the recorded transcripts, using the Hilbert2 function in EEGLAB, downsampled to 100 Hz to match the data and normalised using *nt_normcol* (Noisetools http://audition.ens.fr/adc/NoiseTools/). They were then used to cross-validate with the EEG data in the mTRF toolbox.

3.4 Dual task

3.4.1 Overview

The dual task paradigm extends the selective attention demands made in one modality from a single task, and puts extra pressure on overall attentional capacity by making simultaneous demands in another, different, task. Research into the impact of dual tasks on performance can reveal fundamental aspects on the mechanisms and limitations of attentional processing, such as the consistent psychological refractory period (PRP), the delay generated when performing two tasks simultaneously. This delay is attributed to the need to execute both tasks' demands with a limited-capacity processor (Kahnemann, 1973), which can only process a restricted amount of information at any given point (Broadbent, 1965; Clark & Dukas, 2003). In a dual-task design, the tasks presented can be in the same or different modalities and often include perceptual-motor tasks, which have the advantage of precise measurement of reaction times per experimental trial, showing differences in milliseconds as the processing load increases. Typically, either two RT tasks are presented simultaneously, or a motor response task combined with a separate demand on cognitive processing, for example a working memory task. In all versions of a dual task paradigm, the two tasks are defined as independent, with distinct goals and separate measurements.

In the dual task paradigm for the behavioural experiments used here, participants were required to perform tasks which competed for their attention in two modalities: visual and auditory. The primary task was an edited version of the dichotic listening task used in the previous EEG experiment. In contrast to previous experiments however, the auditory task, which retained its varying levels of interference, was now presented in conjunction with a visual distractor task, creating a hybrid paradigm, with increased cognitive demands, and whose dual modality was consistent with a theory of central processing (Koch et al., 2018).

The visual distractor task was a continuous stimulus-response task, adapted from the T.O.V.A. (Test of Variables of Attention) task, a computerised fixed-interval continuous performance test that assesses inhibition and vigilance (Greenberg & Waldmant, 1993). Participants were asked to perform the task in front of a computer screen with a keyboard, whilst wearing headphones connected to the computer audio. The visual task demanded either a positive response (pressing the space bar), or inhibition of response (not pressing the space bar), to a stimulus on a screen. All behavioural experiments consisted of five conditions. The first condition (control) only tested the visual modality, without the concurrent auditory task. The next condition placed an additional load on the participant by requiring them to concentrate on a story in English streamed into one side of their headphones, whilst still performing the visual task, and answer comprehension questions on the story after the trial. The three subsequent conditions further increased the attentional load by requiring the participant to ignore a distractor story or stream, whilst listening to a target story in English, and simultaneously performing the visual task (T.O.V.A.). The details of the dichotic listening task are in section 3.2.

3.4.2 The visual task (T.O.V.A.)

The visual task was prepared and presented in Psytoolkit (Stoet, 2010; 'Stoet, 2017) . The task required pressing the SPACE bar as quickly as possible when the cartoon picture of a dog appeared at the top of the screen. If the dog appeared at the bottom of the screen, the participant was instructed to ignore and wait for the next presentation. Each dog image was on the screen for a maximum of 2000ms. If the SPACE bar was pressed correctly, the reaction time was recorded and the next trial began immediately. If the participant failed to press the SPACE bar when the dog appeared at the top of the screen (error of omission), the trial was recorded as a target error. If the participant incorrectly pressed the SPACE bar when the dog was at the bottom of the screen (error of commission), the reaction time was recorded, the trial was coded as a distractor error, and the next stimulus appeared immediately. The duration of the visual task was designed to align with that of the audio task.

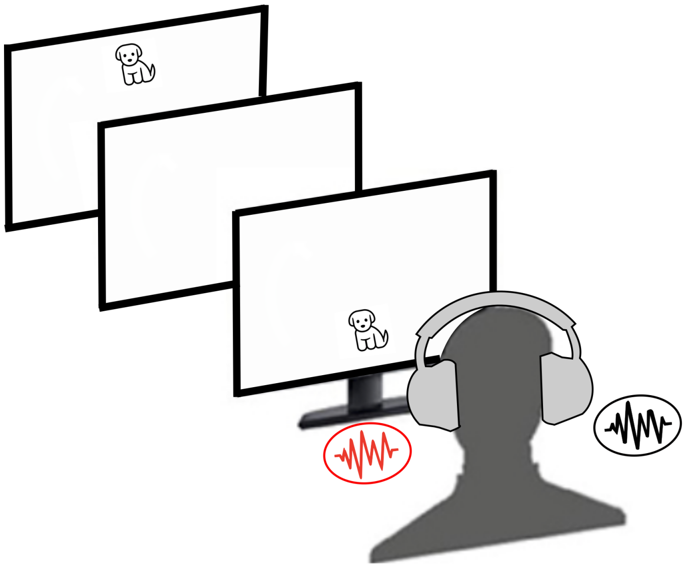
The ratio of target:non-target stimulus was coded to be 1:3 with the 24 targets and 72 non-targets appearing in a random order in each round. These 96 visual stimuli, with correct responses, and a 500ms break between presentations, aligned with the 3.3 min length of the auditory stimulus per condition. If, however, a participant completed the visual task before the end of the auditory stream, the experiment randomly presented extra stimuli in the same 1:3 ratio until the story and condition ended.

In the first condition, the participant only performed the visual task (‘Control’). There was a brief explanation of the task and practice session (which could be repeated, if the participant needed), then the first condition began while there was silence in the headphones. From the second condition onwards, the visual task was repeated in exactly the same way, but in a random order, while the auditory task was also presented.

Figure 4 illustrates the T.O.V.A. procedure for this study and how it was combined with the auditory task.

Figure 4

T.O.V.A. Experimental Procedure



Note: Stimuli were presented randomly in a target:non-target ratio of 1:3 for a maximum of 2000ms. A blank screen appeared for 500ms in between presentations. A picture of the dog at the top of the screen was the target requiring a response within 2000ms. A presentation of the dog at the bottom of the screen was the distractor requiring an inhibition of response for 2000ms. Condition 1 was the control condition, in which the participant only performed the visual task. From Condition 2 onwards, participants were instructed to listen to a story in one ear (which alternated between rounds), whilst also responding to the visual task. . In Conditions 3-5 the participant was instructed to attend to the target story in one ear and ignore a distractor stream in the other ear, whilst also responding to the visual task. After the auditory and visual tasks ended, the participant answered 10 comprehension questions about the target story.

Chapter 4: Experiment 1

4.1 Introduction

One of the key concepts presented in Introduction chapter was the importance of selective attention in the development of cognition and educational outcomes. Selective attention has been proposed as one of the key foundational skills for children's academic success (Stevens & Bavelier, 2012; Hampton Wray et al., 2017), due to its influence on factors such as inhibitory control (Reck & Hund, 2011), working memory (Veer et al., 2017), speech (L. B. Astheimer & Sanders, 2012), metalinguistic skills (L. Astheimer et al., 2014) and arithmetic (Moll et al., 2015). Thus any influences on this fundamental developmental process have the potential to be highly significant.

Selective attention, like many other executive functions, is subject to substantial individual differences (Hunt et al., 1989; Ruff et al., 1998). Nevertheless, there is consensus that there are multiple factors that can also influence its development across a group level (Mezzacappa, 2004), ranging from biological characteristics, such as age (Plude et al., 1994), or preterm birth (van de Weijer-Bergsma et al., 2008; Mulder et al., 2009); and environmental factors which are correlated both with a negative impact, such as lower SES (Hampton Wray et al., 2017; Stevens, Lauinger, & Neville, 2009; Isbell, Wray, & Neville, 2016; Karns, Isbell, Giuliano, & Neville, 2015; D'Angiulli, Herdman, Stapells, & Hertzman, 2008); or are regarded as a positive influence, such as musical experience (Benz et al., 2016; Kasuya-Ueba et al., 2020).

Another such factor that has been linked to modifications to selective attention in children is bilingualism. This is due to the fact that learning and using multiple languages is a major processing demand for the cognitive system, with evidence showing that bilingual language use leads to parallel activation and competition between the two languages, requiring the speaker to selectively select one and inhibit the other (Green, 1998; Costa et al., 2008; Bialystok, 2015; see Chapter 2 for neural evidence substantiating this theory). The bilingual neurocognitive system accommodates these additional processing demands by modifying and adapting the underlying neural and functional architecture, as evidenced by a large number of studies in both children and adults (Filippi et al., 2011; Archila-Suerte et al., 2018; Pliatsikas et al., 2020). Importantly, effects of bilingualism on aspects of neurocognitive processing have been observed from very early on, with data showing differences between monolingual and bilingual infants as young as 4-6 months old (Comishen et al., 2019; Nacar Garcia et al., 2018) as well as in older children (Barac et al., 2016; Arredondo et al., 2017).

However, the nature of these adaptive changes is still not entirely clear and is the subject of vigorous debate. One widely held view is that the increased processing demands arising from bilingual language use lead to enhanced capacity for selective attention, resulting in better performance for bilingual children on selective attention tasks (Bialystok, 2017; Poulin-Dubois et al., 2011). However this view has also been challenged, with a number of reports either not finding evidence for enhanced performance in bilinguals (Antón et al., 2014; Duñabeitia et al., 2014; Paap & Greenberg, 2013) or arguing that they can be accounted for by variables other than bilingual experience, such as working memory (Namazi & Thordardottir, 2010), or are only discernible in specific contexts (Paap et al., 2015).

Furthermore, using primarily behavioural studies to test for the neurocognitive effects of bilingualism is proving to be inadequate. There is ambiguity about whether the tests measure the executive functions they claim: separate studies either use different tests (e.g., Simon, Stroop, ANT and flanker) to measure the same function; or the same task (e.g., Stroop) to measure different functions, with inconsistent results (Paap, Johnson, & Sawi, 2015; Valian, 2015a). This ambivalence has been highlighted by neural studies showing that the same behaviours can arise from multiple cognitive processes. For example, an analysis of fMRI data (Ali et al., 2010) found that different brain areas were activated for the Stroop (left head of caudate) and the Simon task (prefrontal areas and left globus pallidus); both of which are considered to be tasks of controlled attention. A comparison of auditory and visual Stroop (Roberts & Hall, 2008) showed different areas of brain activation for the management of conflict in each domain. Similarly, when comparing bilingual performance, separate studies using a switching (Garbin et al., 2010) and flanker tasks (Abutalebi et al., 2012) generated activation in different brain areas.

Notably, several neuroimaging studies have identified neural differences between monolinguals and bilinguals even when behavioural outcomes are comparable on the same tasks (Bialystok et al., 2005; Kousaie & Phillips, 2012; Luk et al., 2010; Olguin et al., 2019). These apparently incompatible results suggest that the neuroadaptive changes from bilingualism might develop in order to enable bilingual children and adults to recruit mental resources differently (Kroll & Bialystok, 2013) to achieve comparable performance. This shifts the debate from bilingualism itself creating advantages or disadvantages, to an exploration of bilinguals' different "constellation of skills" (Hoff et al., 2012) which manifest in neuroplastic changes, and are more subtle than what most behavioural tests to date have elicited.

One such exploration was a study investigating neural and behavioural responses of monolinguals and bilinguals in a selective attention task (Olguin et al., 2019). The researchers compared behavioural performance and the neural encoding of attended and unattended spoken narratives in monolingual and bilingual adults. Participants were instructed to listen to a story in their native language, while ignoring different types of linguistic interference presented in the other ear. The results showed that, even though the respondents' comprehension scores were the same, there were significant differences in the pattern of neural encoding of the attended streams between the monolingual and the bilingual group.

With this is mind, a somewhat different interpretation of the mechanisms of neurocognitive adaptations to selective attention in bilingualism might be that they emerge in order to enable bilingual speakers to achieve and maintain optimal behavioural performance under the increased processing demands of bilingualism. Importantly, this compensation for the more complex processing environment is achieved in the context of a finite selective attention capacity. As discussed in the Introduction chapter, this account acknowledges that attention is ultimately limited such that the cognitive system can only process a restricted amount of information at any given point (Broadbent, 1965; Clark & Dukas, 2003), and that selective attention might also require processing capacity itself (Johnston & Heinz, 1978; Kahneman, 1973). In the bilingual context this could mean that the process of selecting the target language and inhibiting the non-target one will itself utilise some of the existing attentional resources (Wickens, 2007). This would then impact on the remaining attentional resources such that they need to be economised in order to support optimal task completion. This view builds on, and extends, the hypothesis that bilingual control processes themselves adapt to the recurrent processing demands placed upon them, as proposed in the adaptive control hypothesis (Green & Abutalebi, 2013; Abutalebi & Green, 2016), and while it does not preclude the possibility that this may lead to greater flexibility in the usage of the residual capacity, it shifts the focus from the often-inconsistent behavioural comparisons to the patterns of modification and adaptation in the underlying neural and functional architecture. Critically however, this account also gives rise to a different set of predictions about the patterns of these underlying adaptations. In particular, instead of assuming an overall enhancement in neural indices of attentional processing for bilinguals compared to monolinguals, this view predicts no increase - or possibly even a slight reduction - combined with their different distribution as determined by the requirements of the task at hand.

To date, studies exploring the above possibilities have focused primarily on adult samples. It is therefore unclear what the developmental trajectory of these neuroplastic modifications might be, and to what extent they affect the mechanisms of selective attention in bilingual children. One possibility is that the demands of competition and inhibition between co-activated languages reconfigure the patterns of attentional processes right from the onset ("Perceptual Wedge Hypothesis", Petitto et al., 2012), such that the effects can be clearly discerned by the time children can respond to selective attention tasks. Alternatively, these modifications might have a protracted maturation dependent on exposure to the demands of bilingualism, in which case they would be much more evident in adults than in children.

This chapter's experiment (EEG Experiment 1) therefore aimed to explore how the demands of bilingualism modify the neural mechanisms of selective attention in children. Building on the existing data from Olguin et al. (2019), the aim of EEG Experiment 1 was to establish if bilingual and monolingual children also demonstrate the differential neural encoding of the speech envelope in the face of different distractors; and consider the implications of resultant behavioural and neural indices in the context of theories of enhanced bilingual selective attention (Bialystok, 2017) and constraints on bilingual neural resource (Wickens, 2007).

4.2 Current study

To dissociate between the alternatives presented in the Introduction, EEG Experiment 1 explored how bilingualism modulates attentional processing in children through assessing the neural encoding of attended and unattended speech envelopes in monolingual and bilingual listeners aged 7-12. The neural encoding of speech envelopes is a well-established method for investigating attentional processing. According to the 'selective entrainment hypothesis' (Zion Golumbic et al., 2013; Giraud & Poeppel, 2012b), attention causes low-frequency neural oscillations to entrain to the temporal envelope of speech. Supporting this, there is a large body of evidence confirming robust correlation between attended speech envelopes and neural activity (Aiken & Picton, 2008; Di Liberto et al., 2018; Mesgarani & Chang, 2012; Olguin et al., 2018) and showing that the neural encoding of speech envelopes plays an important role for speech intelligibility in both adults (Obleser & Kayser, 2019) and children (Power et al., 2016; Ríos-López et al., 2020). The current study thus employed EEG to capture the neural encoding of attended speech envelopes in monolingual and bilingual children. Linear regression as implemented in the mTRF toolbox (Crosse et al., 2016) was used to model the relationship between the speech signal and the neural data, and applied it in a backward direction to assess how well the attended and unattended speech envelopes could be reconstructed from the responses of the neuronal populations that encode them (see Methods chapter for more details). The accuracy of speech envelope reconstructions from the EEG data was assessed by comparing the reconstructions to the original speech envelopes, resulting in reconstruction accuracy scores (Pearson's r) - where the higher r value signifies that more stimulus-relevant information was encoded in the EEG signal and the better model could be created, leading to a better reconstruction. Reconstruction scores calculated this way are widely accepted as measures of neural encoding in children (Power et al., 2016; Kalashnikova et al., 2018) and are consistent with other computations of cortical tracking (Sassenhagen, 2019). Another feature of the reconstruction method is that it maps all available neural data simultaneously and is therefore specifically suited to multi-channel systems such as EEG. The mTRF technique has also been shown to be particularly suitable for natural speech (Di Liberto et al., 2018; Broderick et al., 2018), and thus highly appropriate for the streams of spoken narratives used in the design of this experiment.

Another important consideration for investigation into the ways bilingualism shapes selective attention in children is the trajectory of selective attention development. As described in the Introduction chapter, although auditory selective attention is sufficiently developed by age 4 to respond to auditory dichotic tasks (Stevens & Bavelier, 2012; Hampton Wray et al., 2017), an older age range is recommended due to younger children's high variability in performance (Sanders et al., 2006; Takio et al., 2009). Auditory selective attention typically stabilises from age 7 upwards (Gomes et al., 2007; Jones et al., 2015). Given these considerations, participants in the age range of 7-12 were recruited for this experiment, as this age range not only represents a developmental plateau for selective attention in childhood, but is also likely to generate relatively stable effects whilst ensuring that children can reliably perform the selective attention task element.

To investigate whether and how bilingualism modifies the neural mechanisms of selective attention in children, the current experiment used a dichotic listening task, the origins of which (Cherry, 1953) are explained in the Introduction chapter. Following the design used previously for adults (Olguin et al., 2019), children were presented with two competing narratives simultaneously and instructed to attend to one while ignoring the other. The nature of the competing stream was manipulated across four different conditions to create perceptual or linguistic interference. The first condition was 'Single Talker', a control condition where children attended to a narrative presented in one ear, with no interference presented in the other ear. This allowed us to establish the extent of attentional encoding in monolingual and bilingual listeners at baseline (i.e., without any interference present). In the second condition, children attended to a narrative in English presented in the attended ear while ignoring another English story presented in the unattended ear (English–English condition). In the third condition, children attended to a narrative in English while ignoring a narrative in Latin, a language unknown to them (English–Latin condition). These two conditions therefore tested attentional encoding in the context of linguistic interference, where the known language distractor (English) could be expected to interfere more strongly with the attended stream than the language that children cannot process for meaning (Latin). In the fourth condition, the interfering stream was Musical Rain (MuR), a stream derived from speech that is closely matched to the acoustic properties of speech, but does not trigger speech percept and is therefore expected to only engage low-level acoustic processing (English–MuR condition). Another key feature of this design was that participants were instructed to listen to the attended stream for comprehension, a task that children in this age group were expected to able to do without difficultly. Based on the existing adult data (Olguin et al., 2019) it was also expected that there would be no significant difference between the ability of monolingual and bilingual listeners to perform the task. By equating on behavioural performance, this approach enabled a focus on the patterns of modification of the mechanisms that underpin selective attention, rather than performance per se.

The set of conditions described above allowed the study to investigate whether bilingualism modifies the neural correlates of selective attention in children, and to assess directly the predictions of the two hypothesised mechanisms of this modification which were presented earlier. Following the existing evidence (Olguin et al., 2019; Di Liberto et al., 2018; Mesgarani & Chang, 2012; Olguin et al., 2018), it was assumed that attention would modulate the neural encoding of speech envelope in both monolingual and bilingual children, with the type of distractor probably further influencing the strength of the encoding of the attended stream. Critically however, it was also assumed that the way different distractors influence attentional encoding might differ between the groups. According to the hypothesis that bilingual experience leads to general enhancement of attentional processing, results would be expected to show an overall increase in reconstruction accuracy scores for bilingual compared to monolingual children. Specifically, while the overall *pattern* of effects might be similar in the two groups – with distractors narrated in a language likely causing stronger interference than the non-linguistic distractor and the Single Talker condition - all these markers of attentional encoding would be expected to be enhanced in the bilingual group. On the other hand however, there might be no discernible increase, or even a decrease in the indices of attentional encoding in bilingual children, reflecting the hypothesis that language selection and inhibition themselves might draw on the existing attentional capacity, restricting the resources available to track the speech envelope. In addition and more importantly, this could lead to a modification of the encoding patterns across conditions in bilinguals, suggesting that the remaining attentional capacity would have been distributed to maximise this finite resource and meet the task requirements in the context of increased processing demands of bilingualism.

4.3 Materials and method

4.3.1 Participants

48 typically-developing children aged 7-12 were tested, comparable to the sample size of similar EEG studies on children (Di Liberto et al., 2018; Power et al., 2016; Kalashnikova et al., 2018; Stevens et al., 2009). They were split into two categories: bilingual (n=24, sixteen males, age M=9.3 yr, SD=1.83) and monolingual (n=24, thirteen males, age M=9.6 yr, SD=1.48), which were matched groupwise on mean and distribution of age (t=.54, *p*=.59). All participants were healthy with no history of hearing problems or neurological disorder. 43 were right-handed, with four of the left-handed children being monolingual and one bilingual. All participants' parents completed a language history questionnaire, which provided an overview of children's exposure to languages. As confirmed by the questionnaire, all monolingual participants were native speakers of English, with no significant exposure to other languages. The participants in the bilingual group all had a similar profile: the language they first learnt was not English, and they used this language at home on a daily basis. They were however fluent and highly proficient in English, following English-speaking curriculum at school, and with native-like English conversation skills comparable to their monolingual peers. The second languages spoken were Afrikaans, French, Finnish, Greek, Hindi, Hungarian, Igbo, Japanese, Lithuanian, Mandarin, Polish and Turkish. Additionally, two children spoke a third language proficiently (French and Spanish), and one spoke a total of four languages other than English proficiently (Arabic, French, Hebrew and Spanish). Children were recruited via posters, social media, and word of mouth. Parental education information was collected as an indication of SES, a well-documented influence on selective attention in children (Stevens et al., 2009) and modulator of the cognitive effects of bilingualism (Naeem et al., 2018). The majority of participants' parents (87.2%) were educated to degree level or higher, and the groups were not significantly different on this approximation of SES (bilinguals M=2.56, SD=.52; monolinguals M=2.35, SD=.79; Mann-Whitney U=259, p =.53).

The study was approved by the Cambridge Psychology Research Ethics Committee, and performed in accordance with relevant guidelines and regulations. Prior to the testing session, parents and children were given detailed information on the aims of the project and what to expect from the session. Upon arrival, informed consent was given by parents signing a consent form and the children an assent form. They were told they could withdraw from the study at any time.

1.3.2 Design

The experiment consisted of four conditions (Table 1). In each condition, children were attending to a story in English in one ear. Condition 1 had no interference in the other ear ('Single Talker'). In the other three conditions children were also presented with a distractor in the other ear, which they were instructed to ignore. The nature of the distractor varied, from a different story in English ('English-English'), to a story in a language unknown to children ('English-Latin') and non-linguistic acoustic interference ('English-Musical Rain').

Table 1

Experimental Conditions

Condition	***Attended stream***	***Interference***
1. Single Talker	English story 1	No interference
2. English-English	English story 2	English story 5
3. English-Latin	English story 3	Latin story
4. English-MuR	English story 4	Musical Rain (acoustic stream)

4.3.3 Target streams

The target stories for the attended ear were four children's stories in English specifically aimed at this age group, taken from online resource storynory.com. All stories were transcribed into 120 sentences each, with each sentence lasting approximately 3 seconds in length. Each target story was then split into 2 blocks and children attended to the first half in either the left or right ear (randomly assigned), with interference in the other, and then swapped ears for Block 2. Each block (half of a story) consisted of 60 sentences, with all 60 sentences concatenated with a 300ms gap between them to create a single block lasting 3.3 minutes. Block 1 was always the first half of the target story and Block 2 the second half. Gender of the speaker was kept the same for all stories (same female voice for all target stories, different female voice for interference), to reduce segregation strategies based on talker's gender (Brungart & Simpson, 2007). All stories' volumes were normalised to ensure equivalent average amplitude.

4.3.4 Distractor streams

There was no interference in Condition 1, to provide a baseline against which to compare different levels of distractor. The interference in Condition 2 was a fifth children's story in English sourced from storynory.com, adapted in the same way as the target stories and recorded by a second female native English speaker (i.e., different from the female narrator of the target stories). For the unknown language interference in Condition 3, Latin was chosen as a non-artificial language, which would almost certainly be unknown to the participants. The narrative was sourced from teaching resource *Ritchie's Fabulae Faciles* and was recorded by a native English female who was a postgraduate Classics student at the University of Cambridge.

The acoustic interference of Musical Rain used in Condition 4 was identical in length, root mean squared level and long-term spectrotemporal distribution of energy to the target story in Condition 4, but did not trigger a speech percept (Uppenkamp et al., 2006). It was generated in MATLAB by extracting temporal envelopes of the target sentences and filling them with 10ms fragments of synthesised vowels jittered in frequency and periodicity. The resulting stream was described by participants as "the sound of a jug pouring water".

Instructions were recorded by the same female speaker of the target stories. These were played before each block in the target ear, telling the child*: "This is your right/left ear. Please listen carefully to the story in this ear, on your right/left side, and ignore the story or sound in the other ear".*

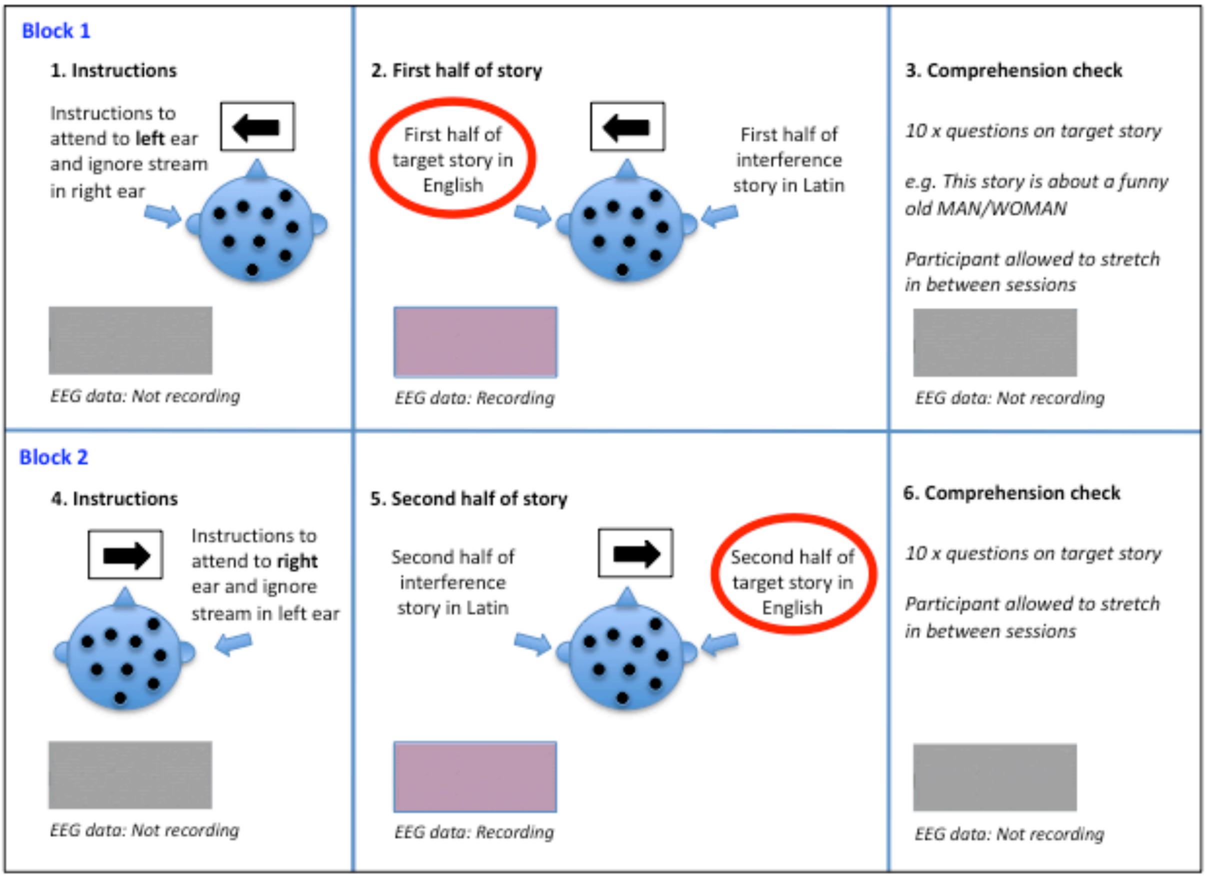
4.3.5 Procedure

The participants had a practice session of listening to an English story in both the left and the right ear while ignoring a distracting English story in the other ear, in order to familiarise themselves with the dichotic listening paradigm. After practice, they were asked to summarise the target story to check they could hear correctly and understood the instructions to attend to one ear at a time. The task itself took 45-60 minutes across the four conditions. Children first heard Block 1 of Condition 1 (Single Talker) followed by 10 comprehension questions. They then listened to Block 2 of Condition 1 (Single Talker), again followed by 10 comprehension questions. Each block was preceded by the recorded instructions in the relevant (target) ear. This procedure was repeated for the other three conditions, which were presented in a random order. Children were instructed to stay as still as possible while the stories were playing and were allowed to stretch, yawn etc. during the comprehension breaks.

Comprehension questions consisted of simple sentences to check understanding of each story (for example: *'This story is about a funny old MAN/WOMAN'*), and children pointed or verbally confirmed which option they thought was correct. The children did not receive feedback on their responses. At the end of the experiment children were presented with a certificate of completion and compensation for their time. Figure 5 is an illustration of the procedure of the dichotic listening task in Condition 3.

Figure 5

Dichotic listening task procedure for EEG Experiment 1



4.3.6 Data collection and preprocessing

EEG was recorded using a 64-channel electrode net (Electrical Geodesics Inc., Eugene, OR, USA), connected to Netstation software. The stimuli were played through foam-tipped earphones in the pre-allocated part-randomised order. All data were pre-processed in MATLAB: EEGLAB Toolbox (Delorme & Makeig, 2004). Channels 61-64 (located in muscular/facial areas) were removed, leaving data from 60 channels for processing. Data was filtered between 1-100Hz using zero-phase bandpass Hamming windowed FIR filters (transition band widths of 1Hz with cutoff frequencies at −6 dB) and down-sampled to 250 Hz. Bad channels were identified via probability and kurtosis and were interpolated (via spherical interpolation) if they were 5 SD away from the mean kurtosis and 3 SD from the mean power spectrum.

Independent Component Analysis (ICA) algorithm (EEGLAB) was conducted to identify components corresponding to artefacts (e.g. eye blinks). These were visually inspected and bad components removed from the data. After ICA, epochs were extracted, starting at 200ms pre-onset of the sentence and ending at 2800ms post onset. This length of epoch was chosen so that, after allowing for epoch rejection, there would be a minimum threshold of five minutes of data per condition for input to the mTRF toolbox (Jessen et al., 2019). After the bad channels were interpolated, bad epochs were rejected with the *pop_autorej* function (EEGLab), removing epochs with values outside a 3*SD* of the probability and kurtosis thresholds. This resulted in an overall epoch rejection of 16.33% for all participants' data (18.31% for monolinguals and 14.35% for bilinguals). By condition, epoch rejection was 14.67% in Single Talker, 19.68% in English-English, 12.77% in English-Latin and 17.36% in English-MuR datasets. Next, data were re-referenced to the average of all channels and finally resampled to 100 Hz to reduce the computational load. Following this process, the EEG data from all 48 participants were entered into the subsequent mTRF analysis.

4.3.7 Speech envelopes

Speech envelopes were calculated using the Hilbert2 function in EEGLAB, downsampled to 100HZ to match the data and normalised using *nt_normcol* (Noisetools http://audition.ens.fr/adc/NoiseTools/).

4.3.8 Analyses

Neural tracking of the stimulus envelopes was computed using multivariate temporal response functions, as implemented in the mTRF toolbox (Crosse et al., 2016). As explained in the Methods chapter, TRF uses linear regression to model the relationship between speech input and signal at each EEG channel. The backward model (reconstruction) was used, which has the advantage of mapping all available neural data simultaneously across all channels, calibrating their relative influence so that informative channels receive greater weights than those which provide less data, and dividing out any autocovariance between channels. This way, even stimulus features that are not explicitly encoded in the neural response in a one-to-one mapping may be inferred from correlated input features that are encoded, which would not be the case using direct correlation to the raw signal. The inputs to the calculation of the TRF models were the stimulus (normalised speech envelope), response (normalised EEG data), minimum and maximum time lags, sampling rate and a series of ridge regression parameters (λ). To calculate the models, I created matrices of EEG data and matching stimuli for each attended and unattended condition per participant per group. The size of the matrices corresponded to the number of viable epochs per condition (minimum 100 for a single condition in each participant). Decoder weights over time lags from 0 to 250ms were calculated using the cross validation (mTRFcrossval) function. The cross validation uses a 'leave-one-out' computation which first fits individual models to every trial for each specified λ, then excludes one trial at a time ('test set') while averaging the others across models ('training set'). The averaged model from the training set is then convolved with the test set to generate a stimulus reconstruction. In each model, this was done in rotation with each trial serving once as the 'test set', repeated across all λ values (12 λ values, 1×10^{-3}:1×10^{8}). Each reconstruction was then validated against the original stimulus, resulting in 12 reconstruction accuracy scores (Pearson's r) per stimulus, with the *r* value at the optimal λ (identified as that which yields the highest overall *r*-value across epochs) taken. This optimal lambda value selection mitigated against the potential overfitting of the TRF model. The reconstruction accuracy scores were then compared across groups, attention status and condition using linear mixed-effect models (Baayen et al., 2008) as implemented in the lme4 R package (Bates et al., 2014). To arrive at the best-fitting model, the step function in the lmerTest package (Kuznetsova et al., 2017) was used. The Satterthwaite approximation (Satterthwaite, 1946) was used for degrees of freedom. Significant p-values are reported at $p<.05$. All post-hoc tests were FDR corrected for multiple comparisons. Figures 2 and 3 in the Methods chapter illustrate the procedure of mTRF model computation, and the outcome of reconstruction for a sample sentence.

4.4 Results

4.4.1 Behavioural comprehension scores

Children from both groups performed the task equally well, with overall comprehension scores of 98.1% in the monolingual group, and 98.7% in the bilingual group. A summary of comprehension scores and standard deviations are shown in Table 2 and Figure 6.

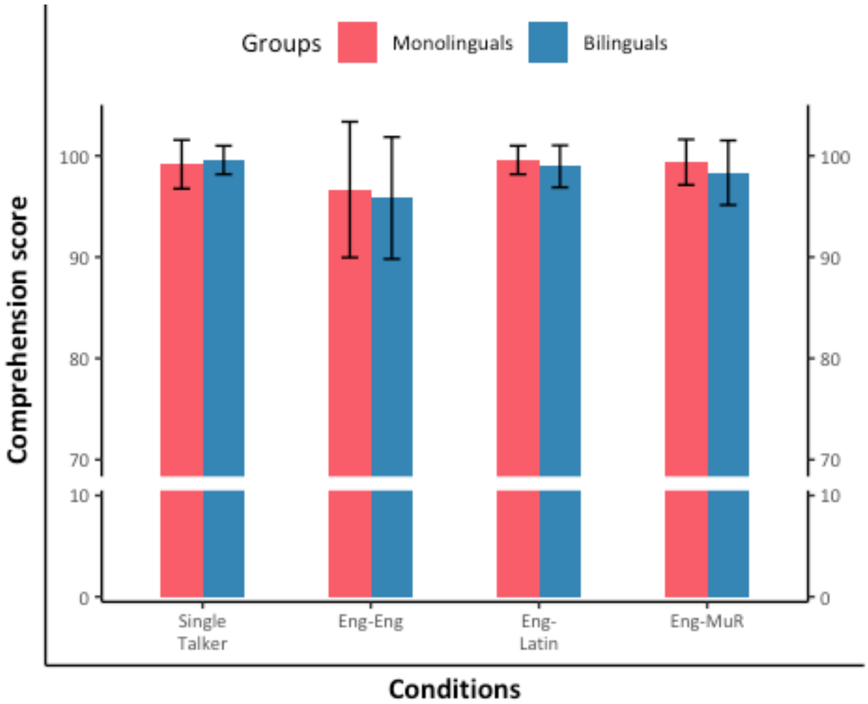
Table 2

Comprehension scores and standard deviation by condition and group

Condition	*Monolinguals*	*Bilinguals*
Single Talker	99.6 (1.41)	99.2 (2.41)
English-English	95.8 (6.02)	96.7 (6.7)
English-Latin	98.8 (2.66)	99.6 (1.41)
English-MuR	98.3 (3.18)	99.4 (2.24)
Overall across conditions	98.1% (3.92)	98.7% (3.92)

Figure 6

Comprehension scores and standard deviation by condition and group



To test for any differences between the groups' comprehension scores, the raw scores were first converted to binary correct/incorrect and then a glmer model from the binomial family in R was run, with binary scores as the dependent variable, and factors of group (two levels: monolingual, bilingual), condition (four levels: Single Talker, English-English, English-Latin and English-MuR) and their interaction, in addition to participant age, socio-economic status (SES) plus subjects as a random effect. The results showed that the only significant factor was condition [X^2 (1, N = 48) = 17.3, p = .00061] and there was no difference in comprehension by group nor condition:group interaction. Pairwise tests on participants' scores per condition, using t tests, revealed that the only condition across groups that differed from the others was Condition 2, English-English, as per Table 3 below:

Table 3

T tests for comprehension scores between conditions in EEG Experiment 1

Condition A	**Condition B**	**t**	***p***	***d***
1. Single Talker	**2. English-English**	**3.27**	**<.01**	**.67**
1. Single Talker	3. English-Latin	.27	.79	.056
1. Single Talker	4. English-MuR	1.06	.44	.22
2. English-English	**3. English-Latin**	**-3.19**	**<.01**	**-.65**
2. English-English	**4. English-MuR**	**-2.62**	**<.05**	**-.53**
3. English-Latin	4. English-MuR	.88	.46	.18

In addition to the frequentist approach, comprehension scores were also analysed using a Bayesian independent sample t-test and repeated measures ANOVA in JASP (version 0.13), where the null was defined as a group effect of 0, with a Cauchy prior width set to 0.707. The Bayes factor from the t test of overall comprehension scores indicated anecdotal evidence for the null hypothesis (BF10=.378), suggesting comparable performance between the groups. A Bayesian repeated measures ANOVA with default priors and the factors of group and condition, with covariate of age, identified extreme evidence for an effect of condition (BF10=2248). In a subsequent best model assuming the effect of condition, there was extreme evidence for the null hypothesis of the factor of group (BF10=.000124). This indicates that, once the participants' variation by condition is taken into account, the Bayes factor provides extreme support for the claim that the groups performed equivalently in the comprehension task.

These results show comparable performance of monolingual and bilingual children in the behavioural comprehension task, with the performance in both groups suffering in the English-English condition relative to the other conditions. The comprehension scores for both groups in the English-English condition were lower than in any other part of the task, indicating most interference in this condition. This substantiates reports by participants in both groups that they found the interference in English the most difficult.

4.4.2 EEG Data

4.4.3 The effects of attention on speech reconstruction accuracy

In the analysis of the neural data, datapoints more than 1.5 interquartile ranges above the upper quartile or below the lower quartile were removed as outliers, excluding 170 datapoints (0.5% of the total). Visual inspection of residual plots did not reveal any obvious deviations from normality. The first analysis of the neural data aimed to test the robustness of the paradigm, by establishing whether attention modulated speech reconstruction accuracy in children. The lmer model included the three conditions where both attended and unattended narratives were presented to the participants (English-English, English-Latin and English-MuR); thus excluding the condition where there was no interference (Single Talker). The dependent variable was reconstruction accuracy score (r), and the fixed factors were group (two levels, monolingual, bilingual), attention (two levels, attended and unattended) and condition (three levels), and the interactions between them. Participant age and parental SES were also included as predictors, and subjects and items as crossed random effects. Results showed a significant effect of attention [$F(1,712.8)=46.53$, $p<.001$, $\eta^2=.06$]; a significant effect of condition [$F(2, 720.6)=59.3$, $p<.001$, $\eta^2=.14$] and a significant interaction between condition and attention [$F(2, 710)=5.4$, $p<.01$, $\eta^2=.01$] as well as between condition and group [$F(2, 28096.1)=7.4$, $p<.001$, $\eta^2=.005$]. Pairwise comparisons confirmed that the attended stream EEG data showed on average higher stimulus reconstruction accuracy than the unattended ones, with the difference between them significant overall [$r_{attd}=.057$, $r_{unattd}=.040$, $t=8.79$, $p<.001$, $d=.10$] and in each condition separately [English-English $r_{attd}=.047$, $r_{unattd}=.032$, $t=4.21$, $p<.001$, $d=.09$; English-Latin $r_{attd}=.053$, $r_{unattd}=.026$, $t=8.39$, $p<.001$, $d=.17$; English-MuR $r_{attd}=.071$, $r_{unattd}=.062$, $t=2.38$, $p<.05$, $d=.05$]. They confirm that attention improves reconstruction accuracy of spoken narratives in children, replicating similar results in the literature.

The next analysis tested whether the same general pattern holds in monolingual and bilingual groups separately. In *monolinguals*, a model including attention (two levels, attended and unattended), condition (three levels) and their interaction, participant age, parental SES, plus subjects and items as crossed random effects showed significant effects of attention [F(1, 706.03)=29.5, p<.001; η^2=.04] and condition [F(2, 718.01)=55.28, p<.001; η^2=.13]. In *bilinguals*, the equivalent model showed a significant effect of attention [F(1, 731.19)=29.03, p<.001, η^2=.04], condition [F(2, 731.52)=21.44, p<.001, η^2=.06], and their interaction [F(2, 724.01)=4.66, p<.01, η^2=.01]. Pairwise comparisons confirmed that in both groups attended streams were reconstructed more accurately than unattended streams in each condition separately, other than in the English-MuR condition in bilinguals. Table 4 and Figure 7 show attended and unattended reconstruction accuracy scores, and results of t tests between the attended and unattended results, by group and condition.

Table 4

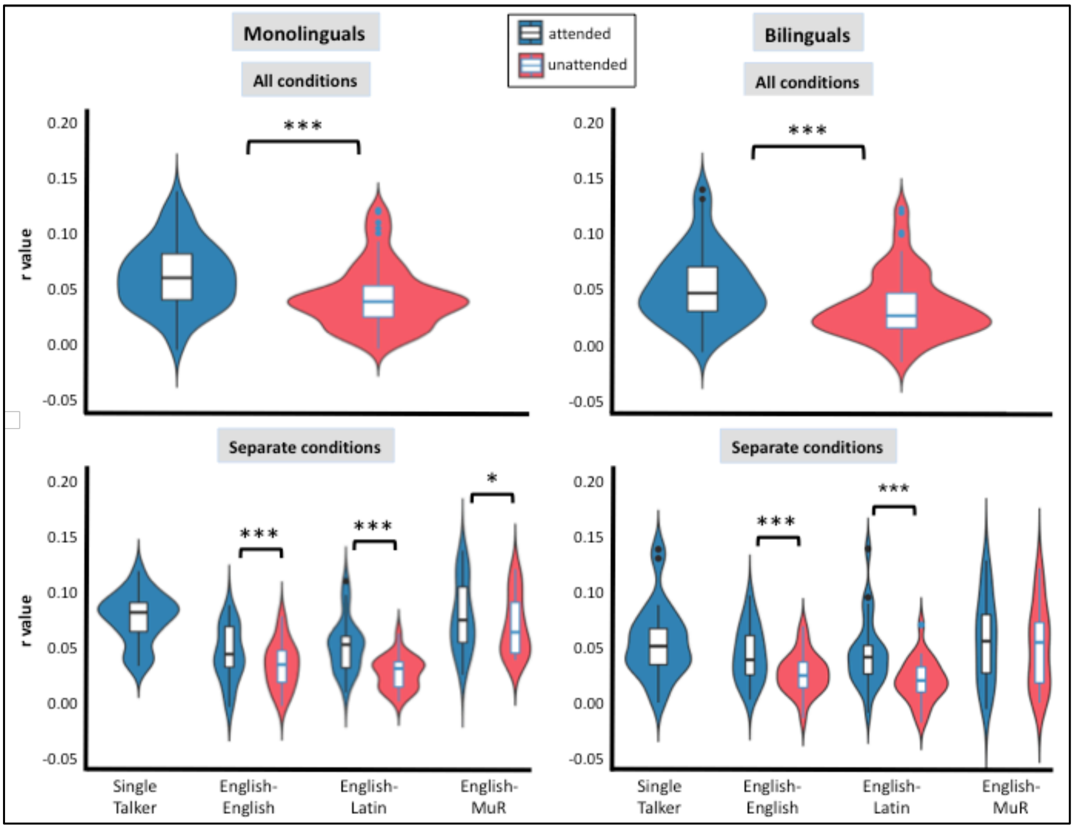
Reconstruction accuracy scores (r) by condition and group

	Monolinguals					*Bilinguals*				
Condition	*Attd*	*Unattd*	*t*	*P*	*d*	*Attd*	*Unattd*	*t*	*p*	*d*
Single Talker	.075					.06				
English–English	.048	.036	2.59	<.05	.08	.045	.029	3.29	<.01	.1
English-Latin	.055	.028	5.99	<.001	.17	.051	.025	5.87	<.001	.16
English-MuR	.085	.073	2.45	<.05	.07	.059	.054	.99	ns	.03
Overall across conditions	.066	.045	6.36	<.001	.11	.054	.036	6.01	<.001	.1

Attd=attended stream, Unattd=unattended stream

Figure 7

Attended and unattended reconstruction accuracy scores (r) by condition and group



Note: Results show robust effects of attention on the reconstruction accuracy of speech envelopes, with higher reconstruction accuracy for the attended than for the unattended envelopes in both groups

4.4.4 Reconstruction accuracy of attended streams in monolinguals and bilinguals

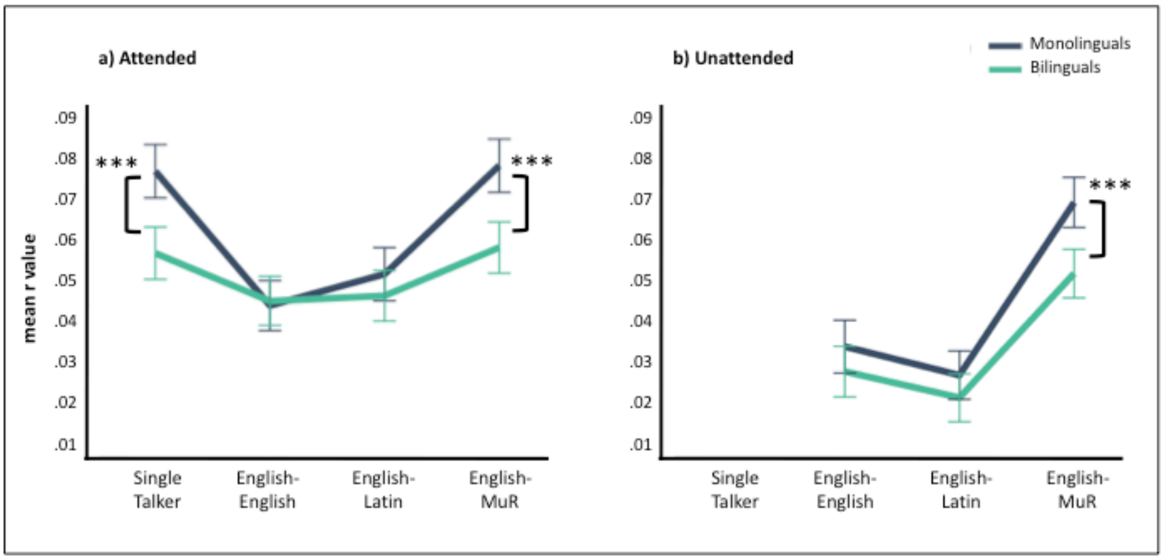
A key question driving this research was to establish whether bilingualism modulates the neural encoding of attended speech envelopes in children; and what pattern does this modulation follow. The next set of analyses therefore asked whether monolingual and bilingual groups differ in reconstruction accuracy of attended streams across conditions. To this end a model was run that included attended condition (four levels, Single Talker, English-English, English-Latin, English-MuR), group (monolingual, bilingual) and their interaction, participant age, parental SES, plus subjects and items as crossed random effects. The results showed that the only significant predictors were condition [F(3, 483.2)=13.63, *p*<.001, η2=.08] and group by condition interaction [F(3, 18283.7)=3.59, *p*<.05, η2=.005].

To explore what was driving this interaction, the next analysis investigated the patterns of reconstruction across attended conditions in each group separately. In *monolinguals*, a model with four levels of attended condition, participant age, parental SES, and subjects and items as random effects, showed a significant effect of condition [F(3,481.02)=15.1, *p*<.001, η^2=.09] only, with the post-hoc tests showing significantly higher encoding in the Single Talker condition than in the English-English and English-Latin conditions [t=5.49, *p*<.001, *d*=.16, and t=4.07, *p*<.001, *d*=.19 respectively], and significantly higher encoding in the English-MuR than the English-English and English-Latin conditions [t=-7.44, *p*<.001, *d*=-.22; and t=-6.04, *p*<.001, *d*=-.18 respectively]. There was a trend of stronger encoding in the Single Talker than in the English-MuR condition [t=-2.01, *p*=.054]; but no difference between the English-English and English-Latin conditions [t=-1.41, *p*=.16]. The equivalent analysis in *bilinguals* showed a comparable, but much reduced pattern of differences between conditions, with a significant effect of condition [F(3,491.09)=4.03, *p*<.01, η^2=.02] reflecting weaker encoding in the English-English condition compared to the Single Talker and English-MuR conditions [t=3.05, *p*<.05, *d*=.09; and t=-2.81, *p*<.05, *d*=-.08 respectively]. No other differences emerged in the bilingual group, implying that the type of interference significantly modulated attentional encoding in monolinguals but had an attenuated effect in bilinguals, comparable to the results seen in adults (Olguin et al., 2019).

To confirm that monolinguals indeed encoded attended stream envelopes more strongly than bilinguals in some of the conditions, the next analysis directly compared the reconstruction accuracy between the groups in each attended condition separately. These pairwise comparisons for individual conditions showed significantly higher attentional encoding in monolinguals than in bilinguals in the Single Talker and English-MuR conditions [t=3.12, *p*<.01, *d*=.09; and t=5.32, *p*<.001, *d*=.16; respectively], but no difference between the groups in the two language interference conditions [English-English t=.74, *p*=.46; English-Latin t=.83, *p*=.46]. Hence, even if the attentional encoding in the language interference conditions in bilinguals was comparable to that seen in monolinguals, the significantly weaker encoding of the Single Talker and the English-MuR conditions in this group has resulted in the overall much flatter pattern of results across conditions in bilinguals (Figure 8). In other words, the key underlying variable behind the differences between the two groups appears to be the strength of attentional encoding in conditions of weak or no interference. These differences are illustrated in Figure 8.

Figure 8

Between-group differences in reconstruction accuracy scores per condition



Note: Summary of the pattern of results for (a) attended streams, and (b) unattended streams. Error bars represent 95% CI.

4.4.5 Reconstruction accuracy of unattended streams in monolinguals and bilinguals

Following the same approach as used in the analyses of the attended streams, an equivalent model was run with unattended conditions (three levels, English-English, English-Latin, English-MuR), group (monolingual, bilingual) and their interaction, participant age, parental SES, and subjects and items as random effects. The results showed a significant main effect of condition [$F(2, 355.68)=46.44$, $p<.001$, $\eta^2=.21$], but no main effect of group, and no interaction between group and condition. Further analyses confirmed that both groups showed the same pattern on differences across the three unattended conditions, with the unattended acoustic interference (MuR) showing more encoding and higher reconstruction accuracy than the two unattended languages distractors (English, Latin). For monolinguals, the results of the pairwise t-tests were $t=7.64$, $p<.001$, $d=.22$ for English-MuR vs English-English comparison, and $t=9.85$, $p<.001$, $d=.29$ for English-MuR vs English-Latin comparison. For bilinguals they were $t=5.55$, $p<.001$, $d=.16$ and $t= 6.62$, $p<.001$, $d=.18$ respectively. Neither group showed a significant difference in reconstruction accuracy for the unattended envelopes between the English-English and English-Latin conditions. The patterns between groups for unattended reconstruction accuracy scores across conditions were therefore equivalent.

Finally, the between group comparisons showed a significantly higher encoding of unattended envelopes in the English-MuR condition for monolinguals compared to bilinguals [$t=4.05$, $p <.001$, $d=.11$]. These results are summarised in Figure 8 (line chart above).

In sum, the results revealed that monolingual children modulated the accuracy of attended stimulus reconstruction as a function of the type of interference, with natural language distractors (English, Latin) most strongly interfering with the reconstruction of the attended stream. In contrast, bilingual children showed weaker differentiation in the encoding of attended speech across conditions. The key factor driving these between-group differences appears to be the strength of encoding in conditions of little or no interference (Single Talker, English-MuR), with significantly stronger encoding in monolinguals than in bilinguals here. Monolingual and bilingual children showed comparable patterns of reconstruction accuracy of unattended speech.

4.5 Discussion

Building on the substantial evidence that learning and using multiple languages modulates selective attention in children (Barac et al., 2014), the current experiment investigated the mechanisms that drive this modification. Using a dichotic listening task, I assessed the patterns of responses to different types of interference in monolingual and bilingual children aged 7-12; comparing their behavioural comprehension scores and their cortical tracking of attended and unattended speech envelopes. Despite equivalent behavioural performance, clear differences emerged in the way monolinguals and bilinguals encoded attended speech, confirming that the processing demands of bilingualism shape the supporting neurocognitive architecture (Green & Abutalebi, 2013). Most important however was the observation that, instead of enhanced attentional capacity, these neuroadaptive modifications appear to reflect its redistribution, arguably aimed at economising the available resources to support optimal behavioural performance. I discuss these results in more detail below.

In terms of behavioural comprehension scores, the results clearly showed that all children performed the task equally well, and were able to process the attended stories for meaning. This aligns with the general pattern observed in dichotic listening studies that the information presented to the attended ear can usually be processed with very few errors (Cherry, 1953; Treisman, 1969). Importantly however, data showed no difference in the pattern of comprehension scores between monolingual and bilingual children, with both groups achieving high comprehension scores across the board, but finding the English-English condition most difficult. Similar to the arguments already made in the literature (Paap et al., 2015), this finding that both groups achieved equivalent high-level performance can be taken to imply that any modification to the underlying neural mechanisms in the bilingual group could be considered as adaptation aimed at supporting such performance, made necessary by the increased processing demands of the bilingual environment.

The analysis of the neural data focused on reconstruction accuracy of attended and unattended speech envelopes from the EEG data as the index of attentional encoding. As reviewed in the Introduction, it has been well-established in both children and adults that cortical activity encodes the temporal envelope of speech, synchronising to its slow amplitude modulations (Poeppel & Assaneo, 2020; Lalor & Foxe, 2010). Selective attention robustly influences these synchronisations, with the results showing preferential tracking of the attended stream over the ignored one (Rimmele et al., 2015; Horton et al., 2014). These synchronisations between the auditory signal and the neural data were typically investigated by assessing their linear relationship using cross-correlation or forward modelling; however here a backward 'stimulus reconstruction' approach was used. This approach has been gaining increased popularity in the recent literature (Power et al., 2016; Kalashnikova et al., 2018; Jessen et al., 2019; Attaheri et al., 2020) as it offers advantages such as providing increased sensitivity to signal differences between highly correlated EEG channels (Crosse et al., 2016).

Consistent with the existing evidence (Rimmele et al., 2015; Horton et al., 2013; Ding & Simon, 2012) the results in this experiment showed a robust effect of attention, with higher reconstruction accuracy scores consistently seen for the attended than for the unattended envelopes in both groups. Given that reconstruction scores reflect how much stimulus-relevant information is encoded in the EEG signal and how well this can be modelled, these results imply that attended streams were encoded more strongly than the unattended streams. Also consistent with the existing data (Olguin et al., 2018; Brungart & Simpson, 2007; Hawley et al., 2004), there was evidence that the type of interference influenced attentional processing; with language distractors (English and Latin) reducing reconstruction accuracy of the attended envelopes more strongly than the less interfering distractors (Single Talker and English-MuR conditions). This is arguably because attentional selection between competing streams of information can be achieved either on the basis of lower-level sensory differences between them, or based on higher-level syntactic and semantic information - with the latter argued to occur later and require more processing capacity (Johnston & Heinz, 1978; Bronkhorst, 2015). The separation between the two streams in the language distractor conditions is more likely to require this latter type of processing; more robustly impacting on the attentional capacity available for the processing of attended stream in these conditions. Alternatively, this pattern of results might be explained in terms of increased difficulty of auditory object formation and selection in the language distractor conditions (Shinn-Cunningham, 2008); where the similarity between the attended and the unattended streams might cause them to be perceived as a unified auditory object, thus resulting in poorer sensitivity to the content of the attended target stream.

In relation to the account of early vs. late selective processing, these results support the multimode theory of attention (Johnston & Heinz, 1978), an approach that integrates the early and late accounts and incorporates capacity constraints. This theory proposes that target information is selected at the level of sensory analysis by early modes of attention but not until after semantic analysis by late modes. Thus along the continuum of different attention modes from early mode to late mode, attended information and unattended information can be differentiated at different depths, consistent with the results in this thesis. Experiment 1 indicated that the weakest encoding of the attended stream occurred in the English-English condition. In this condition, the children were presented with two simultaneous stories that could not be dissociated based on intelligibility or some low-level sensory differences (as was the case in the other conditions). The low reconstruction accuracy scores indicated that in this condition both attended and unattended inputs were processed equivalently and arguably only dissociated after they had undergone some degree of semantic encoding and analysis. Therefore, in the English-English condition the unattended semantic information was dissociated from the attended information further up the processing stream compared to the conditions with non-linguistic interference, which used up more attentional capacity and left fewer resources for encoding the attended stream. This is consistent with the multimode theory of selective attention, which states that semantic processing happens later up the selective attention stream and requires more effort (Johnston & Heinz, 1978). The English-English condition therefore also created the greatest interference, consistent with reports that the participants found it the most difficult condition.

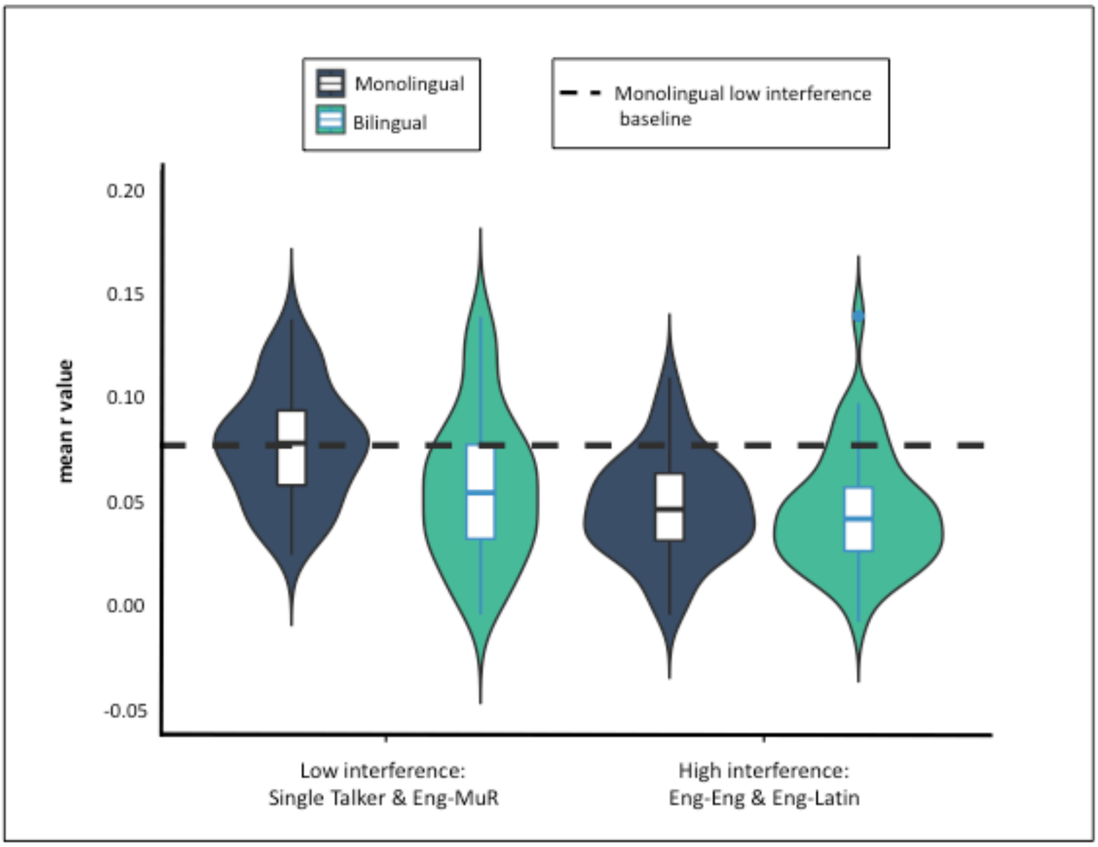
The key finding of this study, however, was that the attentional encoding across conditions differed between the monolingual and the bilingual children. In the monolingual group, results revealed a prominent contrast between the conditions with low or no interference and the language interference conditions; yet this effect was markedly attenuated in the bilingual group (Figure 8). The differential patterns of encoding in monolingual and bilingual listeners observed here replicates the results found in adults (Olguin et al., 2019), adding further support to the hypothesis that bilingualism modifies the neural mechanisms of selective attention across the lifespan (Comishen et al., 2019; Krizman et al., 2014; Garbin et al., 2010). At the start of this chapter, two accounts were presented that might explain the possible mechanisms of this modification. The first was that the need for constant management and inhibition of competing languages in bilinguals enhances their capacity for selective attention, resulting in better performance and increased attentional control (Bialystok, 2015). The second was that these demands of selection and inhibition will themselves utilise some of the existing attentional resources, which might impact on the available attentional capacity and require that the remaining resources are optimised in order to achieve full task performance. The results in this experiment showed no evidence for the enhanced attentional capacity, behaviourally or neurally, in the bilingual group. In contrast there was statistically significant weaker neural encoding in bilinguals overall for both attended conditions (r_{attd}=.054 for bilinguals vs r_{attd}=.066 for monolinguals; t(18660)=-4.81, *p*<.001,*d*=-.070) and unattended conditions (r_{unattd}=.036 for bilinguals vs r_{unattd}=.045 for monolinguals; t(14784)=3.43, *p*<.001, *d*=-.056), and significantly weaker reconstruction in attended conditions of low or no interference in bilingual compared to monolingual children, lending support to the second proposition.

The observed indication of reduced cortical encoding overall in bilinguals is not without a precedent, with examples of reduced neural activity during selective attention tasks most commonly seen in the cortical areas associated with conflict processing. For instance, functional imaging during a Flanker task performed by bilinguals and monolinguals (Abutalebi et al., 2012) revealed significantly lower patterns of activation in the anterior cingulate cortex (ACC) for bilinguals, leading the authors to conclude that 'bilinguals…resolve cognitive conflicts with less neural resource'. A similar fMRI study of a Stroop-like switching task (Garbin et al., 2010) also found that monolinguals activated the ACC during the task, whereas bilinguals did not. An ERP study tracking bilingual and monolinguals' neural responses during a variety of selective attention tasks (Kousaie & Phillips, 2012), predicted superior performance (greater accuracy and faster reaction times) and larger N2 amplitudes for bilinguals relative to monolinguals. On the contrary, behaviour was equivalent between the two groups; and the monolingual group exhibited larger N2 amplitudes than the bilingual group during the Stroop task. The Simon task also elicited the 'unexpected and surprising' result that monolinguals demonstrated larger P3 amplitudes than bilinguals. Furthermore, higher ERN amplitudes for bilinguals than monolinguals in the final Flanker task, which would usually be interpreted as evidence of enhanced cognitive control, were due to a longer tail for incongruent trials, indicating a prolonged post-response conflict and slower recovery for bilinguals in these trials. Taken together, this evidence supports the hypothesis that different configurations of the underlying neurofunctional architecture can support equivalent behavioural performance, with these different configurations reflecting different processing demands presented to the system over time. This functional plasticity, also known as degeneracy in the scientific literature (Green et al., 2006; Mason et al., 2015; Navarro-Torres et al., 2021) is a common feature in biological systems, allowing flexible adaptation to changing environments. Hence, while the findings reveal that the management of competing languages draws on attentional resources in bilingual children, they do not show any adverse effects on performance – the outcome is primarily indicative of the modifications to the underlying processing networks that are aimed at supporting performance. In fact, as mentioned in the Introduction, these results could be interpreted as showing increased flexibility in the usage of the available resources in bilingual children, enabling them to do 'more with less'.

Turning to the more specific pattern of reduced cortical tracking of the attended speech envelope in bilinguals observed, where this was most prominent in the Single Talker and English–MuR conditions – the two conditions with weakest interference, and thus requiring least effort to comprehend the attended steam. Figure 9 demonstrates this by combining the low-interference (Single Talker and MuR) conditions and high-interference (English and Latin) and then plotting the groups side by side. The monolingual and bilingual participants are comparable in the high-interference conditions, but there is a clear difference between the groups in the low-interference conditions, especially when the monolinguals' low-interference is plotted (the dashed line) as a baseline reference.

Figure 9

Differences in combined low-interference and high-interference conditions



One hypothesis is that this directly results from the need to economise the available attentional capacity in order to support optimal behavioural performance. To understand this, it is again necessary to recall that behavioural comprehension scores were equivalent between the groups for all conditions. Yet, achieving optimal behavioural performance is not equally demanding across different conditions, and can arguably be more easily accomplished with reduced attentional resources in the conditions that are less taxing for the processing system. It can therefore be assumed that this reduction in cortical tracking in the conditions of weak or no interference in bilinguals arises because it can be most easily accommodated while still retaining full behavioural performance. In contrast, reductions of attentional encoding in conditions with stronger interference (English-English and English-Latin) would likely lead to diminished performance compared to the monolingual group.

Whilst tentative, this interpretation aligns with evidence from research into the mechanisms of adaptive neural plasticity, which suggest that 'experiences contributing to mastery over environmental challenges modulate neural responses in ways that enhance optimal performance' (Lambert et al., 2019).

The final set of findings to address concerns the pattern of reconstruction accuracy scores seen for the unattended streams. Here results showed that, in both groups, the unattended MuR stream was significantly better reconstructed than the unattended Latin and English stories. In addition, the MuR encoding was stronger in the monolingual than in the bilingual group. Both of these findings might be explained by the same mechanisms discussed above, with the selection between competing streams being less demanding for the MuR distractor and for monolinguals, thus impacting least on processing capacity available for encoding. However, it is more likely that the strong MuR encoding reflects the fact that the unattended MuR envelopes used in the experiment were generated from the same narratives that the participants were presented with as target stories in their attended ear. Given that the MuR envelope largely preserves the spatio-temporal features of the source utterance, it is unsurprising that there is a high degree of similarity between the envelope reconstruction scores for attended and unattended steams in the English-MuR condition. Despite this, the results showed that the attended steam was more strongly encoded than the unattended steams (significantly so in the monolingual group), adding further evidence that attention significantly influences the neural encoding of speech envelope (Ding & Simon, 2012).

In sum, EEG Experiment 1 investigated the mechanisms underlying the modification of selective attention in bilingual children. The data showed no evidence for the enhanced attentional capacity in the bilingual group. Instead, equivalent behavioural performance was observed, coupled with a modified pattern of neural encoding that was most prominent in conditions of weak or no interference. These data are interpreted as showing that the available resources are economised to support optimal behavioural performance; potentially suggesting increased flexibility of their usage in response to the demands of bilingual language processing. Subsequent experiments in the next chapters explore the limitations of this adaptation of attentional resource; and investigate to what extent these findings generalise beyond the language domain by using non-linguistic distractors.

Chapter 5: Experiment 2

5.1 Introduction

The previous chapter described a study in which bilingual children's reconstruction scores, an index of attention, were generally lower and flatter than those of monolingual children. Their behavioural comprehension scores were equivalent, however. This supports three of the suggested consequences of bilingualism on selective attention discussed in the Introduction. First, that bilingualism triggers modifications to the neural correlates of selective attention, evidenced in the differential scores and patterns of reconstruction accuracy between monolinguals and bilinguals performing the dichotic listening task, and consistent with evidence that bilingualism shapes brain structure and processing across the lifespan (in childhood: Jasińska & Petitto, 2013; Archila-Suerte et al., 2018; Pliatsikas et al., 2020; into adulthood: Bialystok et al., 2005; Mechelli et al., 2004; Filippi et al., 2011 and old age: Luk et al., 2011; Abutalebi et al., 2015; Frutos-Lucas et al., 2020).

The second conclusion is that these neural adaptations emerge in order to support optimal performance, as seen in the equivalent behaviour (comprehension scores) in both groups. This result replicates other studies which have observed neural differences between monolinguals and bilinguals even when the groups display equivalent behavioural performance (Bialystok et al., 2005; Kousaie & Phillips, 2012; Olguin et al., 2019), lending support to the hypothesis that bilingualism creates a degenerate system (Green et al., 2006; Mason et al., 2015; Navarro-Torres et al., 2021), in which differences in functional structure can lead to the same output.

Furthermore, the pattern of neural responses in bilinguals in the EEG study specifically revealed lower indices of attention. This suggests that the third conclusion to be drawn is that the processing demands of bilingualism draw on some of the attentional resources (Wickens, 2007) of an attentional processor of finite capacity (Kahneman, 1973; Broadbent, 1965; Clark & Dukas, 2003). This results in lower indices of attention but, as seen in Chapter 4, does not have a negative impact on performance.

This supports the view that typically attentional systems are flexible enough to accommodate parallel processing demands and maintain performance as long as total capacity is not exceeded (Moray, 1967). Thus the increased processing load from an additional language would decrease overall capacity (Dornic, 1980), but, in the context of a primary task, still leave enough bandwidth for optimal performance. This would explain why, as shown in Chapter 4, bilinguals accomplish single behavioural tasks with no apparent loss of performance relative to monolinguals. Indeed, an alternative interpretation of the neurocognitive adaptations of selective attention in bilingualism might be that they emerge precisely in order to enable bilinguals to overcome the consumption of attentional resources and achieve and maintain optimal (equivalent) behavioural performance in the context of standard selective attention tasks.

This raises the following question: what are the limitations of this bandwidth in the context of bilingualism and selective attention tasks? One way of investigating this is to increase the attentional load in a dual-task paradigm. Research shows that any attentional system, despite being flexible enough to accommodate parallel processing when attentional demands are not excessive (Hunt et al., 1989; Moray, 1967), has limitations on the processing of simultaneous tasks (Gopher, 1986). Multiple tasks make demands on different mechanisms, each with its own capacity (Navon & Gopher, 1979), leading to a processing pipeline of prioritization of competing demands (Janssen & Brumby, 2010) and allocation of attentional resources to overcome the resultant attentional bottleneck (Pashler, 1994; Schubert, 1999), as described in the multiple resource theory framework (Wickens, 2008).

Studies into the impact of dual tasks on performance can reveal fundamental aspects on the mechanisms and limitations of attentional processing. Contrary to many examples of “multitasking” in daily life (such as driving and maintaining a conversation) being achieved without noticeable deterioration of performance, researchers have found that the dual task paradigm in an experimental setting consistently results in a psychological refractory period (PRP), the delay generated when performing two tasks simultaneously (Telford, 1931; Vince, 1949; Welford, 1952; Pashler & Johnston, 1998; Osman & Moore, 1993; Schubert, 2008). This delay is again attributed to the need to execute both tasks’ demands with a limited-capacity processor (Kahnemann, 1973), which can only process a restricted amount of information at any given point (Broadbent, 1965; Clark & Dukas, 2003). Parallels have been drawn between the allocation of attentional resources in dual tasks and models of information processing, resulting in models such as multiple resource theory (Wickens, 2008), which provide a theoretical framework of the prioritisation of tasks.

Thus the aim of the current study was to test the impact of adding a secondary task to a primary selective attention task, specifically on the performance of bilinguals who were assumed to have more constrained attentional capacity. In spite of the long-standing premise that typical performance is limited under competing task demands (Treisman, 1969; Mowbray, 1954), the interaction between these limitations and bilingualism has been less clear cut. On the one hand, there have been studies which show a protective effect of bilingualism, through reduced deterioration relative to monolinguals in performance, when managing competing tasks (Janic et al., 2020; Telner et al., 2008) compared to baseline performance in a single (control) task. These studies used a visual search (Janic et al., 2020) and driving simulation (Telner et al., 2008) as the primary tasks and counting backwards or verbal tasks as the secondary or distractor task. Another combination of tasks, memory recall and switching (Sörman et al., 2017), has suggested a more nuanced effect of bilingualism. Using this paradigm, a longitudinal study investigating the dual-task costs of encoding and retrieval of a list of words while performing a simultaneous card sorting task found lower costs for bilinguals in one condition only (encoding + retrieval + card-sorting) and this finding was not consistent across age groups.

A series of complementary behavioural studies (Bialystok et al., 2006; Bialystok, 2011) have investigated the effect of dual tasks in different modalities for monolingual and bilingual groups, using semantic categorisation tasks across visual and auditory domains. In the first (Bialystok et al., 2006), two semantic categorisations were required (of letters/numbers or animals/musical instruments) for both visual and auditory stimuli. Both age groups (younger and older adults) showed a bilingual advantage in one section only of the visual task; but not for an alternative version of the visual task, nor in the auditory task. In the second study (Bialystok, 2011), two groups of 8 year olds performed one of the semantic categorisation tasks in two modalities simultaneously and the only difference between the groups was the accuracy, but not response time, in the categorisation of the visual stimuli. The above point to a slight bilingual advantage in the visual domain for dual tasks across modalities.

However, a separate study (Fernandes et al., 2007) of younger and older adults, combining memory recall of spoken words with a visual distraction task using semantically similar or unconnected words to the primary task, found that bilingual participants in both groups performed significantly worse in all the conditions (no distraction and distraction with both connected and unconnected words). The authors attributed this bilingual limitation to the task's dependency on lexical access, which might advantage monolinguals who have a larger vocabulary in their primary (only) language.

Given the inconsistent results of previous studies of the effect of bilingualism on behavioural performance of competing tasks, several precautions were taken when designing the dual task for the study in this chapter. Firstly, the tasks selected for this study were not explicitly dependent on lexical access/semantic retrieval/vocabulary. Secondly, their combined attentional load varied throughout progressive rounds in order to isolate and identify attentional resource constraints.

Thirdly, tasks that were used were across different modalities, in order to minimise perceptual masking and resource similarity for each of the dual tasks (Rollins & Hendricks, 1980). The neural mechanisms for selective attention tasks in different modalities are clearly dissociated in imaging studies (Shomstein & Yantis, 2004), as would be expected. Furthermore, the neural patterns differ between single selective tasks in either modality and the areas recruited to perform in a divided bimodal task (J. A. Johnson & Zatorre, 2006), which, in addition to recruiting the associated sensory cortical areas, also uses an area of the prefrontal cortex. This suggests the recruitment of additional resource to prioritise and juggle the demands of the two competing tasks in different domains, and is consistent with accounts that a limited-capacity system draws on central – as well as task specific - control processes to manage competing demands (Lien et al., 2008).

Finally, to prevent motor response interference, the response mechanisms also differed by task (timed motor response throughout the visual task; untimed multiple choice selection at the end of the auditory task).

The primary task was an edited version of the dichotic listening task used in the EEG experiment, which again featured varying levels of interference (Olguin et al., 2018, Phelps et al, 2022) to be inhibited in order to attend to the target story. This was presented in combination with a simple visual distractor task: a version of the T.O.V.A. (Test of Variables of Attention) task, a computerised fixed-interval continuous performance test that assesses inhibition and vigilance (Greenberg & Waldmant, 1993). Details of the T.O.V.A. are presented in the Methods chapter.

Of primary interest was the prioritisation of the tasks and subsequent performance for different groups of monolingual and bilingual participants. With this in mind, the dual task was deliberately designed so that the listening task would take priority over the visual task in conditions of divided attention. Interest was sustained within each round of the listening task by using stories which were unpredictable and entertaining. Additionally, each round used a different narrative as the target story, and presented different levels of interference in the non-attending ear, adding variety and a range of difficulty across the whole task. In contrast, the visual (T.O.V.A.) task was repetitive and simple within each round; and the same stimuli were presented in a random order for each of the conditions. Finally, in the dichotic listening task, participants were instructed explicitly to listen carefully in order to answer comprehension questions at the end of each round; in each of the visual tasks there was neither feedback nor performance assessment.

The prediction was that the demands of this dual task would reveal any effects of second language inhibition on overall attentional capacity, by showing the relative performance and prioritisation of the visual and auditory tasks in all groups and across different levels of difficulty/attentional load. The study was replicated across three groups: two age groups (children and adults), and with the adult group split by language experience. The motivation for recruiting different age groups was twofold: firstly, to confirm whether the inconsistent effect across age groups using a dual-task paradigm seen in previous studies would be replicated (Sörman et al., 2017); and secondly to see if the lack of differentiation between monolingual and bilingual adults' performance noted in a single-task paradigm, attributed to ceiling cognitive capabilities (Bialystok et al., 2005; Valian, 2015b), would also emerge in a dual-task design. The variable of language experience on adults' responses was included after noting inconsistencies in the literature on bilinguals' performance in selective attention tasks dependent on language exposure and age of acquisition (Prior & Gollan, 2011; Luk, Sa, et al., 2011; Pelham & Abrams, 2014; Shi, 2010; Mayo et al., 1997; Swain & Cummins, 1979; Linck et al., 2008). Thus, the dual-task paradigm was used on a sample of school-age children and on young adults with different bilingual profiles, and results compared.

5.2 Materials and method

The experiment was conducted on three groups of participants: monolingual and bilingual children aged 7-12 (Study 1) and adults aged 18-45 with differing second language exposure (Studies 2 and 3). All studies were approved by the Cambridge

Psychology Research Ethics Committee, and performed in accordance with relevant guidelines and regulations.

5.2.1 Study 1 Participants

80 typically-developing children aged 7-12 were tested. They were split into two categories: bilingual (n=40, twenty two males, mean age 9.7 yrs, SD 1.39) and monolingual (n=40, twenty five males, mean age 10.4 yrs, SD 1.64). The recruitment process checked that all participants were healthy with no history of hearing problems or neurological disorder. All participants' parents completed a language history questionnaire, which provided an overview of children's exposure to languages. As confirmed by the questionnaire, all monolingual participants were native speakers of English, with no significant exposure to other languages. The participants in the bilingual group all had a similar profile: they all had one or more parents whose first language was not English, and they used this language at home on a daily basis. The average age of acquisition for the language other than English was 0.1 years (age 0 for 38 participants, age 2 for two participants). All children were also fluent in English, being resident in the UK, and following English-speaking curriculum at school. The average age of acquisition for English was 0.3 years (from birth for 32 participants, age 1 for five participants, age 2 for two participants, age 3 for one participant). The languages spoken by the bilinguals in addition to English were Creole, French, German, Greek, Gujarati, Hungarian, Japanese, Italian, Portuguese, Russian, Spanish and Swedish. Additionally, six children spoke a third language proficiently (French, Japanese, Italian and Urdu). Children were recruited via their parents, who responded to posters on social media, and word of mouth. The monolingual children were marginally older on average than the bilingual group [10.4 vs 9.7 yr respectively, $t(76)=2.06$, $p=.043$], and age was included as a predictor in all analyses. Parental education information was collected as an indication of SES, a well-documented influence on selective attention in children (Stevens et al., 2009). The majority of participants' parents (79.2%) were educated to degree level or higher, and the groups were not significantly different following a Mann-Whitney U

test on this approximation of SES [bilinguals M=2.34, SD=.66; monolinguals M=2.09, SD=.69; W=608.5, p = .085].

5.2.2 Study 2 Participants

89 adults were recruited via the online platform Prolific (https://www.prolific.co/) and tested, of whom five were rejected after initial quality checks (see details of rejection criteria in Analyses section). This left 84 adults whose data were included in Study 2. They were split into a bilingual group (n=42, six males, mean age 27.4 yrs, SD 5.95) and monolingual (n=42, fifteen males, mean age 28.9, SD 7.29). All participants were neurotypical with no history of hearing problems or neurological disorder. Participants completed a language questionnaire on age of acquisition, proficiency and daily usage of their languages. All monolingual participants were recruited as native speakers of English with no fluency in other languages. All bilingual participants were residents in the UK; fluent and highly proficient English speakers (average English proficiency = 9.3/10, SD .96); and using English on a daily basis (average English use = 73%, SD 24.9), but with a language other than English as their native language. The native languages spoken by the bilingual participants were Afrikaans, Bengali, Danish, Farsi, Filipino, Finnish, French, Galician, Greek, Gujarati, Hindi, Igbo, Indonesian, Italian, Konkani, Latvian, Lithuanian, Malayalam, Persian, Polish, Portuguese, Romanian, Russian, Scots, Spanish, Turkish and Welsh. As well as English as a second language, the majority of participants spoke a third language proficiently (Albanian, Catalan, Dutch, French, German, Hindi, Icelandic, Italian, Japanese, Russian, Russian Sign Language, Spanish, Tamil, Telegu, Urdu and Xhosa), several a fourth (Annang, French, Italian, Polish, Portuguese, Spanish, Swedish) and one a fifth (Japanese). The monolingual and bilingual participants were matched on age [t(78.9)=1.01, p=.32, d=.22]. Highest level of education was collected as an indication of SES, and the groups were comparable on this approximation [monolinguals M=1.5, SD=.59, bilinguals M=1.81, SD=.74; W=685, p=.053].

5.2.3 Study 3 Participants

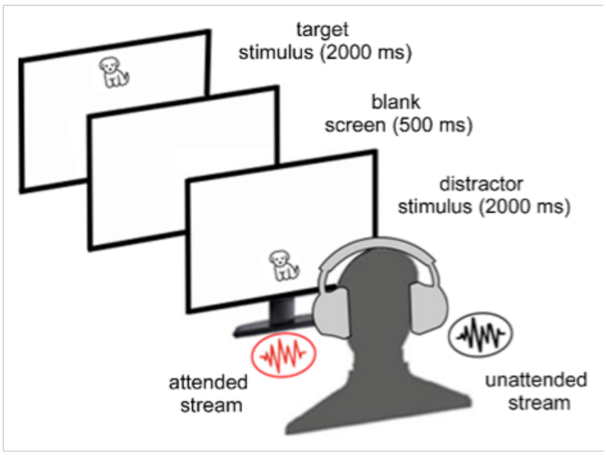
60 adults were recruited via the online platform Prolific (https://www.prolific.co/) and tested, of whom two (one monolingual and one bilingual) were rejected after initial quality checks (see details of rejection criteria in Analyses section). This left 58 adults whose data were included in Study 3. They were split into a bilingual group (n=29, eighteen males, mean age 28.5 yrs, SD 7.72) and monolingual (n=29, fourteen males, mean age 28.9, SD 7.29), who were matched on age [$t(54.9)=1.31$, $p=.194$, $d=.345$]. Highest level of education was collected as an indication of SES, and the groups were comparable on this approximation [bilinguals M=1.77, SD=.612, monolinguals M=2.04, SD=.649; W=359.5, $p=.157$]. All participants were neurotypical with no history of hearing problems or neurological disorder. Participants completed a language questionnaire on age of acquisition, proficiency and daily usage of their languages. All monolingual participants were recruited as native speakers of English with no fluency in other languages. All bilingual participants were screened as bilingual and proficient in English as well as another language, but there was no specification that they were to be residents in the UK. As the experiment was an online study that could be completed anywhere in the world, this less stringent set of criteria for the bilingual participants resulted in more variation in language background and daily exposure. English was used less frequently on average for the bilinguals in Study 3 than in the bilingual group recruited for Study 2 (Study 3: self-reported mean English use 33.6%, SD 26.9) but they were all still proficient English speakers (self-reported mean for English proficiency was 8.66/10, SD 1.28). The native languages spoken by the bilingual participants were Estonian, Italian, Polish, Portuguese, Slovenian, Spanish and Swedish. As well as English as a second language, the majority of participants spoke a third language proficiently (French, Galician, German, Italian, Japanese, Polish, Spanish and Turkish), and six spoke a fourth language (Chinese, French and Spanish). Due to the substantial difference in second language use, the bilinguals in adult groups from now on will be referred to as high-exposure for Study 2 and low-exposure for Study 3.

5.2.4 Design

In this dual task paradigm, participants were required to perform tasks simultaneously in two modalities: auditory and visual (Figure 10). The visual task demanded pressing the space bar in response to a pre-specified target image on the screen. The auditory task employed a dichotic listening paradigm (an edited version of the one used in Experiment 1), where participants were asked to concentrate on a story in English played in one ear, while ignoring a distractor steam presented in the other ear. The distractor stream was manipulated to create different levels of interference, from purely acoustic to linguistic. This created a total of five conditions, which are summarised in Table 5.

Figure 10

Dual task procedure



Note. Participants were instructed to attend to a story in one ear and ignore a distractor stream in the other ear, whilst also responding to a visual task. The distractor streams were manipulated to create different levels of interference. In the visual task, a picture of a dog at the top of the screen was the target, while a picture of a dog at the bottom of the screen was the distractor. Visual stimuli were presented in a target:non-target ratio of 1:3. After each block of the audio-visual task participants answered 10 comprehension questions about the target story.

In the first condition ('Control'), the participant only performed the visual task. From Condition 2 onwards, the participants were also presented with the dichotic listening task, and asked to attend to a target story in English in one ear. Condition 2 had no interference in the other ear ('Single Talker'). In the remaining three conditions participants also heard a distractor in the other ear, which they were instructed to ignore. In Condition 3 the distractor was a different story in English ('English-English'). The distractor in Condition 4 was a story in a language unknown to them ('English-Latin'). The distractor in Condition 5 was non-linguistic acoustic interference ('English-Musical Rain').

Table 5

Experimental conditions

Condition	Visual task	Auditory task	
		Attended stream	**Interference**
1. Control	sustained attention	None	None
2. Single Talker	sustained attention	English story 1, block 1	None
3. English-English	sustained attention	English story 1, block 2	Different story in English
4. English-Latin	sustained attention	English story 2, block 1	Story in unknown language (Latin)
5. English-MuR	sustained attention	English story 2, block 2	Acoustic interference (Musical Rain)

The target stories for the attended ear were two children's stories in English, taken from online resource storynory.com. Both stories were transcribed into 120 sentences each, with each sentence lasting approximately 3 seconds in length. The sound files were then uploaded to the experiment on Psytoolkit. Each target story was then split into 2 blocks and participants attended to the first half in the left ear with any interference in the right ear, and then the target and interference in the right and left ears respectively for Block 2. Each block (half of a story) consisted of 60 sentences, with all 60 sentences concatenated with a 300ms gap between them to create a single block lasting 3.3 minutes. Latin was chosen as the interference in Condition 4 as a non-artificial language which would almost certainly be unknown to the participants. Gender of the speaker was kept the same for all stories (same female voice for all target stories, different female voice for English interference), to reduce segregation strategies based on talker's gender (Brungart & Simpson, 2007). All stories' volumes were normalised to ensure equivalent average amplitude. The non-linguistic interference of Musical Rain in Condition 5 was identical in length, root mean squared level and long-term spectrotemporal distribution of energy to another source story, but did not trigger a speech percept (Uppenkamp et al., 2006). It was generated in MATLAB by extracting temporal envelopes of the target sentences and filling them with 10ms fragments of synthesised vowels jittered in frequency and periodicity. Instructions were recorded by the same female speaker of the target stories. These were played before each block in the target ear, telling the participant*: "This is your right/left ear. Please listen carefully to the story in this ear, on your right/left side, and ignore the story or sound in the other ear".*

After each block had finished, a screen appeared with ten comprehension questions in multiple-choice format. Comprehension questions consisted of simple written sentences to check understanding of each story (for example: *'This story is about a BEGGAR/SHEPHERD'*), and participants selected which option they thought was correct by clicking a box next to the response. Participants did not receive feedback on their responses. After completing the comprehension questions, a screen appeared introducing the next condition.

Visual task: The task required pressing the SPACE bar as quickly as possible when the cartoon picture of a dog appeared at the top of the screen. If the dog appeared at the bottom of the screen, the participant was instructed to ignore and wait for the next presentation. Each dog image was on the screen for a maximum of 2000ms. If the SPACE bar was pressed correctly, the reaction time was recorded and the next trial began immediately. If the participant failed to press the SPACE bar when the dog appeared at the top of the screen (error of omission), the trial was recorded as a target error. If the participant incorrectly pressed the SPACE bar when the dog was at the bottom of the screen (error of commission), the reaction time was recorded, the trial was coded as a distractor error, and the next stimulus appeared immediately.

The ratio of target:non-target stimulus was coded to be 1:3 with the 24 targets and 72 non-targets appearing in a random order in each round. These 96 visual stimuli, with correct responses, aligned with the 200s length of the auditory stimulus per block. If, however, a participant completed the visual task before the end of the auditory stream, the experiment presented extra stimuli in the same 1:3 ratio until the story and condition ended.

There was a brief explanation of the task and practice session (which could be repeated, if the participant needed), then the first condition began while there was silence in the headphones. From the second condition onwards, the visual task was repeated in exactly the same way, while the auditory task was also presented.

Participants' responses from the visual task and comprehension answers were collated in Psytoolkit and downloaded for analysis.

5.2.5 Study 1 (children): Procedure

Prior to the testing session, parents and children were given detailed information on the aims of the project and what to expect from the session. Once they had agreed to participate, parents were sent a link to the Psytoolkit landing page for the study. This page contained another short explanation of the experiment and a sound check for the headphones to ensure they were connected to the computer audio and at an acceptable volume. Parents then completed a consent form, confirming informed consent. Parents also completed a short background questionnaire on the child, indicating age, language history and approximation of SES (parental highest educational level). Then the child watched a short video explaining the rules of both tasks in child-appropriate language. The visual "looking" task was called "Spot the Dog" and the auditory task was renamed "the listening task". Before starting the experiment, children were reminded that they could withdraw from the study at any time. If they were happy to proceed, the experiment started with the press of a key.

The children had a practice session of performing the visual task, with indications of correct and incorrect responses, and the opportunity to repeat the practice as many times as needed to familiarise themselves with the task. They were then invited to start the first condition (visual only) with the press of a key. After each condition, there was a "Well done!" page explaining that the round (condition) was complete, and an instruction to press a key to resume, allowing children to take a break if they so wished between tasks. The key press led to a new set of instructions explaining the "rules" of the next condition. For example, the instruction before Condition 4 stated: "In this fourth round, you will listen to the story in your left ear while continuing the experiment. Keep playing 'Spot the Dog' and listen closely to the story in your LEFT ear. Ignore any distracting sounds in your right ear."

After finishing Condition 5, children were given a completion code to show their parent. The parent emailed the code to the researcher who issued a £5 Amazon e-voucher as compensation. The study duration from the landing page to the end of Condition 5 took approximately 30-45 minutes.

5.2.6 Studies 2 and 3 (adults): Procedure

In both adult studies, eligible participants were given access to an introductory page on Prolific, which explained the aims and design of the study. A link took them to landing page for the study on Psytoolkit. Here, they read more detailed instructions, performed a headphone audio check, and ticked an informed consent form. They then completed the background questionnaire, asking details of sex, age, educational background and details of language proficiency.

Participants had a practice session of performing the visual task, with indications of correct and incorrect answers, and the opportunity to repeat the practice as many times as needed to familiarise themselves with the task. They were then invited to start the first condition (visual only) with the press of a key. After each condition, there was a page explaining that the round (condition) was complete, and an instruction to press a key to resume, allowing participants to take a break if they so wished between tasks. The key press led to a new set of instructions explaining the "rules" of the next condition. For example, the instruction before Condition 4 stated: "In this fourth round, you will listen to the story in your left ear while continuing the experiment."

After finishing Condition 5, participants were redirected to Prolific to claim compensation of £3.50. The study duration from the landing page to the end of Condition 5 took approximately 25 minutes. The adults' average duration was shorter than the children's because they did not watch an explanatory video or have a pause during the handover from parent to child between the explanatory landing page with consent form and background questionnaire (completed by the parent), and the experiment (performed by the child).

5.3 All studies: Analyses

5.3.1 Dichotic listening task

At the end of each block participants answered 10 comprehension questions about the attended narrative, where they had to choose between true and false options (e.g., 'This story is about a QUEEN/KING'). Correct answers were coded as 1 and errors as 0, and their probability across groups and conditions was modelled using a glmer function from the binomial family in R (Boeck et al., 2011).

5.3.2 Visual task

Reaction times and error rates were recorded. As an initial quality check, all outlier reaction times under 200ms and over 1500ms were eliminated. The remaining correct target reaction times were then log transformed to eliminate skew and datapoints more than 1.5 interquartile ranges above the upper quartile or below the lower quartile were removed as outliers. This resulted in exclusion of 129/8860 datapoints (1.5% of the total) in Study 1 (children), 302/9724 datapoints (3.1% of the total) in Study 2 (high-exposure bilingual adults) and 237/6742 datapoints (3.52% of the total) in Study 3 (low-exposure bilingual adults). Error rates were calculated per participant, including both missing the target (not pressing the space bar when the target was presented) and incorrect detection of targets (pressing the space bar when the target was not presented), thus all 40000 trials were included. The initial quality check of total error rates did not identify any children in Study 1 whose error score exceeded the normal range for attention task in that age group [the maximum error rate identified was 10%; normal range in neurotypical children aged 6-13 performing the task is 0.8%-14% according to Greenberg & Waldmant (1993)], hence the data of all 80 children were included in the analyses. In Study 2 (high-exposure bilingual adults), a check of total error rate identified two monolingual and two bilingual participants whose total error rates significantly exceeded 3SD of the mean; likely indicating that they did not attend to the task as instructed. One further monolingual participant's language questionnaire revealed proficiency in a second language, acquired in adulthood. The data of these five participants were excluded, leaving 84 participants' data for further analysis. In Study 3 (low-exposure bilinguals), a check of the total error rate identified two participants (one monolingual and one bilingual) whose error rates were significantly higher than 3SD of the mean and they were excluded, leaving 58 participants' data for analysis.

The reaction times of correct target responses, total error rates (omission and commission) and comprehension scores were then compared across groups and conditions using linear mixed-effect models (Baayen et al., 2008) as implemented in the lme4 R package (Bates et al., 2014). To arrive at the best-fitting model, the step function in the lmerTest package (Kuznetsova et al., 2017) was applied. The Satterthwaite approximation (Satterthwaite, 1946) was used for degrees of freedom. Significant p-values are reported at $p<.05$. All post-hoc tests were FDR corrected for multiple comparisons.

5.4 Results

5.4.1 Study 1 (children)

Auditory task: Children from both groups performed the task equally well, with overall comprehension scores of 97% in the monolingual group, and 98.6% in the bilingual group. A model was used to test whether the probability of making an error differed across groups and conditions, with categorical response accuracy as the dependent variable, fixed effects of group (two levels: monolingual, bilingual), condition (four levels: Single Talker, English-Latin, English-English and English-MuR) and their interaction, participant age and parental socio-economic status (SES); and participants as a random intercept. The results showed that age was a significant predictor [X^2 (1, N = 80) = 13, p = .00031] and condition showed significance overall [X^2 (3, N = 80) = 9.46, p = .024] but there was no difference in comprehension by group nor condition:group interaction (all p>.1), confirming that both groups performed the auditory task equally well. Pairwise tests on all participants' scores per condition, using t tests, revealed no significant differences between individual conditions.

In addition to the frequentist approach, comprehension scores were also analysed using a Bayesian independent sample t-test and repeated measures ANOVA in JASP (version 0.13), where the null was defined as a group effect of 0, with a Cauchy prior width set to 0.707. The Bayes factor showed anecdotal evidence for the null hypothesis (no group effect) in an independent samples t-test (BF_{10}=.601). A subsequent Bayesian repeated measures ANOVA with default priors, incorporating group, condition and age as a covariate, suggested there was very strong evidence for the null hypothesis in the factor of group (BF_{10}=.03). This indicates that, once the factors of condition, age and group are taken into account, the Bayes factor provides very strong support for the claim that the groups performed equivalently in the comprehension task.

A summary of comprehension scores and standard deviations for children is shown in Table 6 and Figure 11.

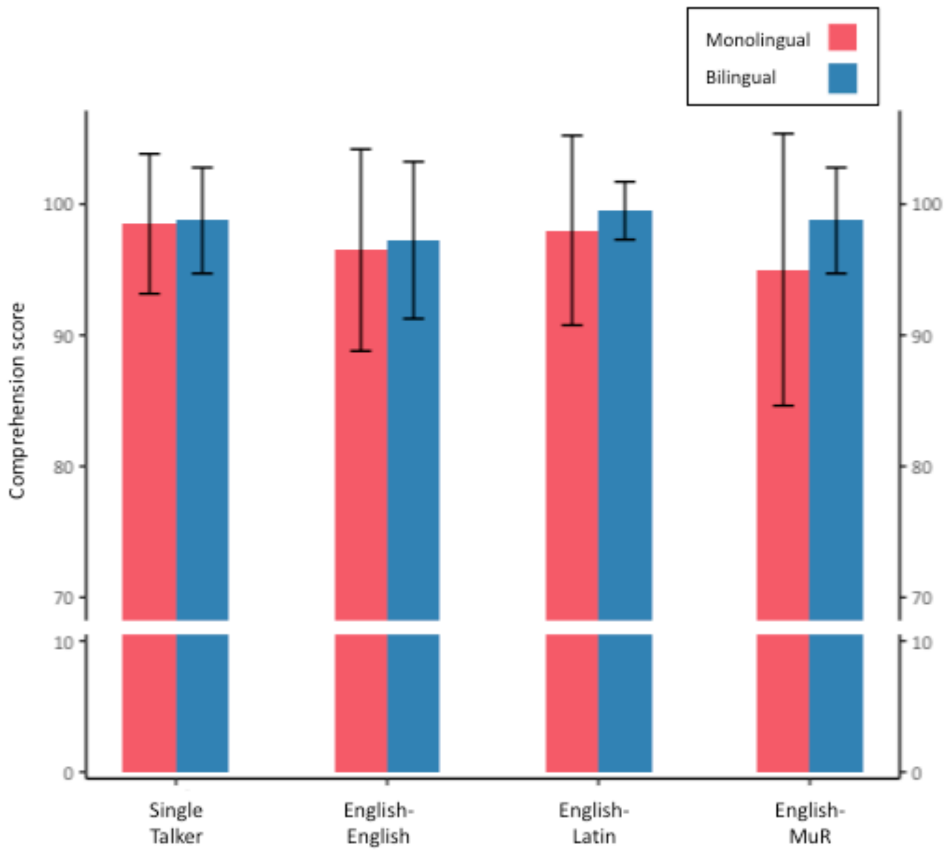
Table 6

Study 1 (Children): Percentage correct comprehension scores by group and condition

Condition	Monolinguals	Bilinguals
1. Control	n/a	n/a
2. Single Talker	98.5 (5.3)	98.8 (4.0)
3. English-English	96.5 (7.7)	97.2 (5.9)
4. English-Latin	98 (7.2)	99.5 (2.2)
5. English-MuR	95 (10.4)	98.8 (4.0)

Figure 11

Study 1 (Children): Percentage correct comprehension scores by group and condition



Results from the visual task:

The first analysis of response times aimed to test if performance varied by group or across different attentional loads of the auditory conditions. The first model included all five conditions (Condition 1: visual only; Condition 2: visual + Single Talker; Condition 3: visual + English–English; Condition 4: visual + English–Latin; Condition 5: visual + English–Musical Rain). The dependent variable was log-transformed reaction times (log RTs), and the fixed factors were group (two levels, monolingual, bilingual), condition (five levels), and the interactions between them. Participant age and parental SES were also included as predictors, and subjects as crossed random effects. Results showed a significant effect of condition [$F(4,8645.6)=26.62$, $p<.001$, $\eta_p^2=.01$]; age [$F(1,77)=24.19$, $p<.001$, $\eta_p^2=.24$]; and a significant interaction between condition and group [$F(4,8645.6)=5.38$, $p<.001$, $\eta_p^2=.0025$].

Pairwise comparisons confirmed that the bilingual group's log response times were slower than the monolingual group's in all conditions except Condition 1 (visual task only). Condition 1 showed equivalent performance between the groups [$t=-1.79$, $p=.37$, $d=-.084$], but there was a significant difference between the groups' performance from Condition 2 onwards, with the difference most significant in Conditions 3 – 5 (visual + auditory interference conditions), which are arguably the conditions that demand most attentional resource. A summary of response times by condition, standard deviations and the log-transformed differences between groups are shown in Table 7 and Figure 12.

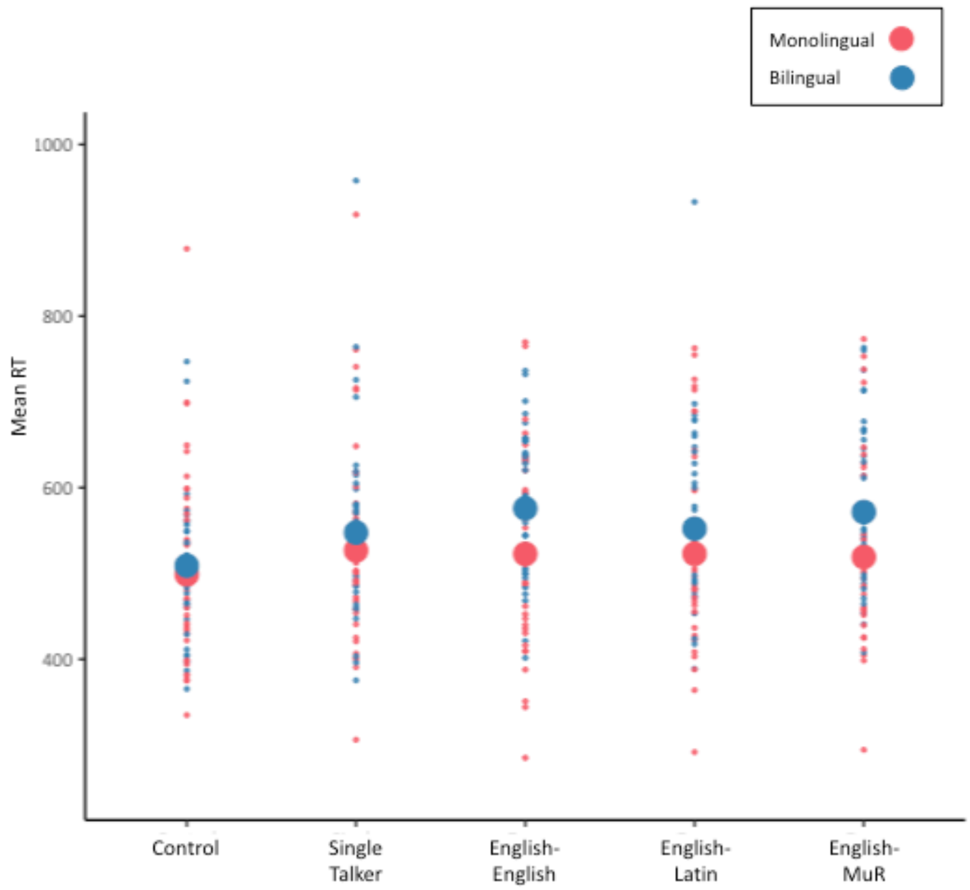
Table 7

Study 1 (Children): Reaction times (SD) in ms and t tests between groups' log-transformed scores

Condition	Monolingual RT (ms)	Bilingual RT (ms)	t	*p*	*d*
1. Control	499 (182)	509 (179)	-1.79	.37	-.084
2. Single Talker	**527 (192)**	**548 (185)**	**-3.10**	**<.01**	**-.148**
3. English-English	**523 (199)**	**576 (200)**	**-6.53**	**<.001**	**-.317**
4. English-Latin	**523 (194)**	**552 (186)**	**-4.20**	**<.001**	**-.202**
5. English-MuR	**519 (182)**	**572 (193)**	**-6.65**	**<.001**	**-.318**

Figure 12

Study 1 (Children): Mean RT times by group and condition



The next analysis examined the patterns of RT responses in monolingual and bilingual groups separately. In *monolinguals*, a model, with log RTs as the dependent variable, which included condition (five levels) as a fixed factor, participant age and parental SES as predictors, and subjects as crossed random effects, showed significant effects of condition [F(4, 4416.6)=5.6, p<.001, η_p^2=.005] and age [F(1, 38)=13.47, p<.001, η_p^2=.26]. Post hoc t tests revealed that the only condition significantly different from the rest was Condition 1 (visual only), which had a significantly faster reaction time than each of the auditory conditions. None of the dual task conditions (Conditions 2-5) was significantly different from another. (See Table 8 for summary of post hoc t test results).

Table 8

Study 1 (Children): Differences in conditions for monolinguals

Condition A	**Condition B**	**t**	***p***	***d***
1. Control	**2. Single Talker**	**-3.5**	**<.01**	**-.16**
1. Control	**3. English-English**	**-2.72**	**<.05**	**-.13**
1. Control	**4. English-Latin**	**-2.83**	**<.05**	**-.13**
1. Control	**5. English-MuR**	**-2.86**	**<.05**	**-.13**
2. Single Talker	3. English-English	.72	.77	.03
2. Single Talker	4. English-Latin	.62	.77	.03
2. Single Talker	5. English-MuR	.69	.77	.03
3. English-English	4. English-Latin	-.1	.96	-.005
3. English-English	5. English-MuR	-.05	.96	-.002
4. English-Latin	5. English-MuR	.06	.96	.003

In *bilinguals*, the equivalent model showed a significant effect of condition [F(4, 4229)=26.1, p<.001, η_p^2=.02], and age [F(1, 37.9)=9.98, p<.01, η_p^2=.21]. However, post hoc t tests revealed a more uneven performance across conditions than in the monolingual participants, with reaction times in stronger interference conditions significantly slower than both Control and Single Talker conditions – see Table 9 for full set of comparisons.

Table 9

Study 1 (Children): Differences in conditions for bilinguals

Condition A	Condition B	t	*p*	*d*
1. Control	**2. Single Talker**	**-5.1**	**<.001**	**-.24**
1. Control	**3. English-English**	**-7.92**	**<.001**	**-.39**
1. Control	**4. English-Latin**	**-5.63**	**<.001**	**-.27**
1. Control	**5. English-MuR**	**-7.93**	**<.001**	**-.38**
2. Single Talker	**3. English-English**	**-3.01**	**<.01**	**-.15**
2. Single Talker	4. English-Latin	-.55	.64	.12
2. Single Talker	**5. English-MuR**	**-2.84**	**<.01**	**-.15**
3. English-English	**4. English-Latin**	**2.47**	**<.05**	**.12**
3. English-English	5. English-MuR	.27	.79	.01
4. English-Latin	**5.English-MuR**	**-2.28**	**<.05**	**-.11**

Errors: The total error rate was 1.9% for monolinguals and 2.07% for bilinguals, which was not statistically significant [t(77.7)=-.36, *p*=.72]. Because of too few data points, of target and distractor errors across all trials (762/40000), no further error analyses were run.

5.4.2 Study 2 (high-exposure bilingual adults)

Auditory task: Similar to the results from Study 1, adults from both groups performed the task equally well, with overall comprehension scores of 98.4% in the monolingual group, and 98.5% in the bilingual group. A model with categorical response accuracy as the dependent variable; group (monolingual, bilingual), condition (Single Talker, English-English, English-Latin and English-MuR) and their interaction, age and socio-economic status (SES) as fixed effects, and participant as random intercept, indicated that the only significant factor was condition [X^2 (3, *N* =

84) = 10.9, p = .012]. Post hoc t tests revealed that this overall effect was driven by higher scores in the Single Talker condition than English-English [$t(111)=2.4$, $p<.05$, $d=.37$]; as well as higher in the English-Latin than English-English [$t(105)=3.08$, $p<.05$, $d=.48$); and higher in English-Latin than English-Musical Rain [$t(106)=2.39$, $p<.05$, $d=.37$). However, again there were no effects of group or group by condition interaction. These results indicate comparable performance of monolingual and bilingual adults in the behavioural auditory task, with similar patterns of performance in both groups across all four auditory conditions.

This was further supported by Bayesian analysis, which showed moderate support for the null hypothesis of group in an independent samples t-test (BF_{10}=.232). Additionally, a repeated measures ANOVA identified moderate evidence for an effect of condition (BF_{10}=6.4). In a subsequent best model assuming the effect of condition, there was very strong evidence for the null hypothesis in the factor of group (BF_{10}=.022), i.e., very strong support for the conclusion that the groups performed equivalently.

A summary of comprehension scores, standard deviations and their differences between groups for Study 2 are shown in Table 10 and Figure 13.

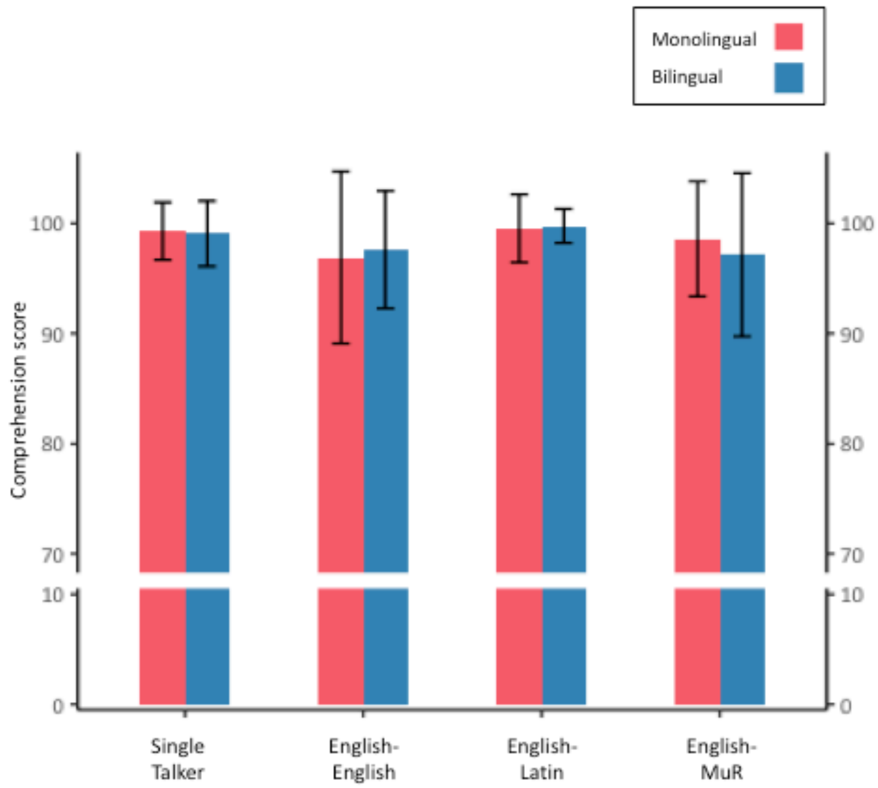
Table 10

Study 2 (High-exposure bilinguals): Percentage correct comprehension scores

Condition	**Monolinguals**	**Bilinguals**
1. Control	n/a	n/a
2. Single Talker	99.3 (2.6)	99 (3)
3. English-English	96.9 (7.8)	97.6 (5.3)
4. English-Latin	99.5 (3.1)	99.8 (1.5)
5. English-MuR	98.6 (5.2)	97.1 (7.4)

Figure 13

Study 2 (High-exposure bilinguals): Percentage correct comprehension scores



Results from the visual task:

The first analysis of response times aimed to test if performance varied by group or across the increased attentional load of the auditory conditions. The first model included all five conditions (visual only; visual + Single Talker; visual + English–English; visual + English–Latin; and visual + English–Musical Rain). The dependent variable was log-transformed reaction times (log RTs), and the fixed factors were group (two levels, monolingual, bilingual), condition (five levels), and the interactions between them. Participant age and SES were also included as predictors, and subjects as crossed random effects.

Results showed a significant effect of condition [$F(4,9334.5)=23.4$, $p<.001$, $\eta_p^2=.0099$] but no Condition*Group interaction, suggesting that the same pattern of responses across conditions held across both groups. Post hoc t tests showed that the visual only condition (1) was significantly faster than each of the auditory conditions and Condition 2 (Single Talker) was also significantly faster overall than Condition 5. All other conditions were equivalent when averaged across groups.

Table 11

Study 2 (High-exposure bilinguals): Differences in conditions for all participants

Condition A	**Condition B**	**t**	***p***	***d***
1. Control	**2. Single Talker**	**-4.45**	**<.001**	**-.14**
1. Control	**3. English-English**	**-5.62**	**<.001**	**-.18**
1. Control	**4. English-Latin**	**-6.16**	**<.001**	**-.2**
1. Control	**5. English-MuR**	**-7.02**	**<.001**	**-.23**
2. Single Talker	3. English-English	-1.86	.11	
2. Single Talker	4. English-Latin	-1.2	.29	
2. Single Talker	**5. English-MuR**	**-2.59**	**<.05**	**-.08**
3. English-English	4. English-Latin	.68	.51	
3. English-English	5. English-MuR	-.66	.51	
4. English-Latin	5. English-MuR	-1.38	.24	

Despite a numerical trend for slower RTs in bilinguals overall and in each condition separately, Group also did not emerge as a significant predictor of RTs. A summary of response times by condition and standard deviations are shown in Table 12 and Figure 14.

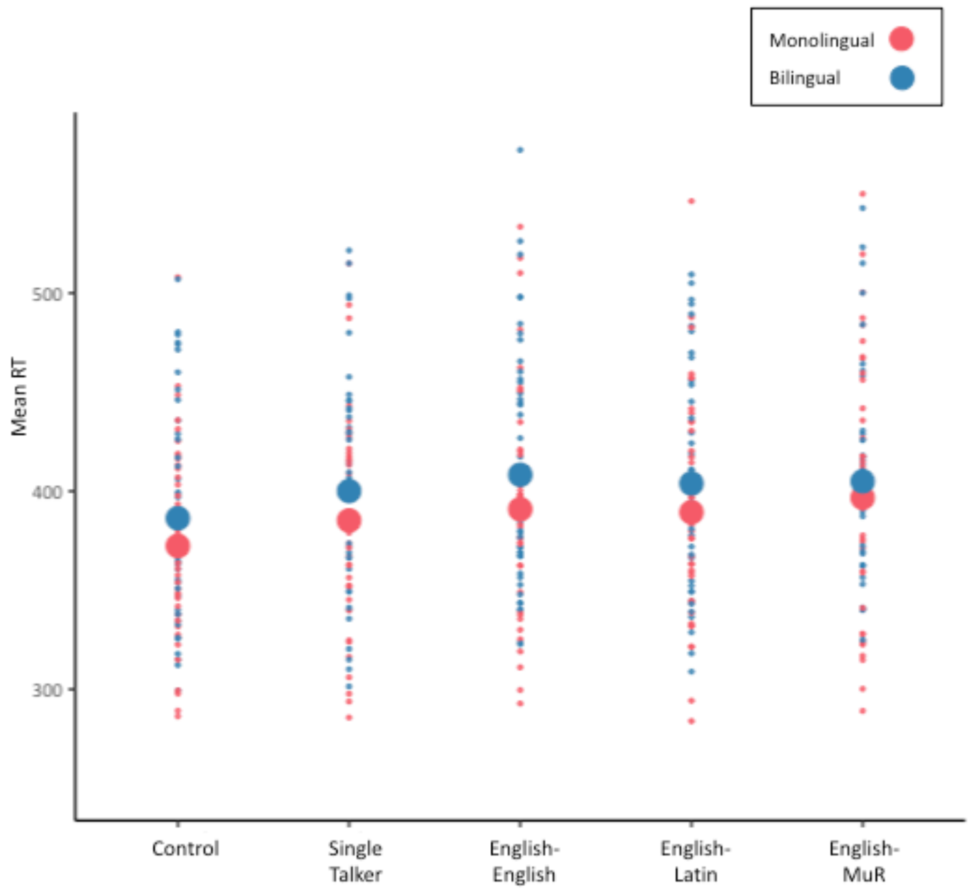
Table 12

Study 2 (High-exposure bilinguals): Reaction times (SD) in ms between groups' log-transformed scores

Condition	Monolingual RT (ms)	Bilingual RT (ms)
1. Control	372 (89.8)	386 (95.1)
2. Single Talker	385 (95.6)	400 (98.7)
3. English-English	391 (98.6)	408 (110)
4. English-Latin	389 (95.6)	404 (106)
5. English-MuR	397 (105)	405 (98.1)

Figure 14

Study 2 (High-exposure bilinguals): Mean RT times by group and condition



Following the analyses strategy used in Study 1 (children), the next analysis examined the patterns of responses in monolingual and bilingual groups separately. In *monolinguals*, a model, with log RTs as the dependent variable, which included condition (five levels) as a fixed factor, participant age and SES as predictors, and subjects as crossed random effects, showed a significant effect of condition [F(4, 4697.2)=14, p<.001, η_p^2=.01].

Post hoc t tests revealed that Condition 1 (visual only) had a significantly faster reaction time than each of the auditory conditions. In addition, Single Talker (Condition 2) was significantly faster than Condition 5 (Eng-MuR).

Table 13

Study 2 (Adults with high-exposure bilinguals): Differences in conditions for monolinguals

Condition A	Condition B	t	*p*	*d*
1. Control	**2. Single Talker**	**-3.12**	**<.01**	**-.14**
1. Control	**3. English-English**	**-4.29**	**<.001**	**-.2**
1. Control	**4. English-Latin**	**-4.19**	**<.001**	**-.19**
1. Control	**5. English-MuR**	**-5.38**	**<.001**	**-.25**
2. Single Talker	3. English-English	-1.23	.31	-.057
2. Single Talker	4. English-Latin	-1.06	.32	-.048
2. Single Talker	**5. English-MuR**	**-2.35**	**<.05**	**-.11**
3. English-English	4. English-Latin	.199	.84	.0093
3. English-English	5. English-MuR	-1.1	.32	-.051
4. English-Latin	5. English-MuR	-1.32	.31	-.061

In *bilinguals*, the equivalent model showed a significant effect of condition [F(4,4633)=10.07, p<.001, η_p^2=.0086]. Post hoc t tests revealed that the bilinguals showed a similarly significant difference to the monolingual group between Condition 1 (visual only) and all the other conditions, but not between any of the dual conditions.

Table 14

Study 2 (High-exposure bilinguals): Differences in conditions for bilinguals

Condition A	Condition B	t	*p*	*d*
1. Control	**2. Single Talker**	**-3.23**	**<.01**	**-.15**
1. Control	**3. English-English**	**-4.42**	**<.001**	**-.21**
1. Control	**4. English-Latin**	**-3.75**	**<.001**	**-.17**
1. Control	**5. English-MuR**	**-4.54**	**<.001**	**-.21**
2. Single Talker	3. English-English	-1.33	.35	-.062
2. Single Talker	4. English-Latin	-.58	.62	-.027
2. Single Talker	5. English-MuR	-1.25	.35	-.058
3. English-English	4. English-Latin	.75	.62	.035
3. English-English	5. English-MuR	.15	.88	.007
4. English-Latin	5. English-MuR	-.64	.62	-.029

Errors: The total error rate was .66% for monolinguals and .59% for bilinguals, which was not statistically significant [t(81.5)=-.51, *p*=.61]. As a result of too few data points across all trials (250/40000), no further error analyses were run.

5.4.3 Study 3 (low-exposure bilingual adults)

Auditory task: Consistent with the results from Studies 1 and 2, adults from both language groups performed the task equally well, with overall comprehension scores of 99.1% in the monolingual group, and 97.5% in the bilingual group. A model with categorical response accuracy as the dependent variable; group (monolingual, bilingual), condition (Single Talker, English-English, English-Latin and English-MuR) and their interaction, age and socio-economic status (SES) as fixed effects, and participant as random intercept, showed no effects of condition, group or group by condition interaction. These results indicate comparable performance of monolingual and bilingual adults in the behavioural auditory task, with equivalent performance in both groups across all four auditory conditions.

This was further supported by Bayesian analysis, which showed anecdotal support for the null hypothesis of group in an independent samples t-test (BF_{10}=.807). A subsequent repeated measures ANOVA including the factors of group, condition and covariate of age also found anecdotal evidence for the null hypothesis in the factor of group (BF_{10}=.65), i.e., anecdotal support for the conclusion that the groups performed equivalently.

A summary of comprehension scores, standard deviations and their differences between groups for Study 3 are shown in Table 15 and Figure 15.

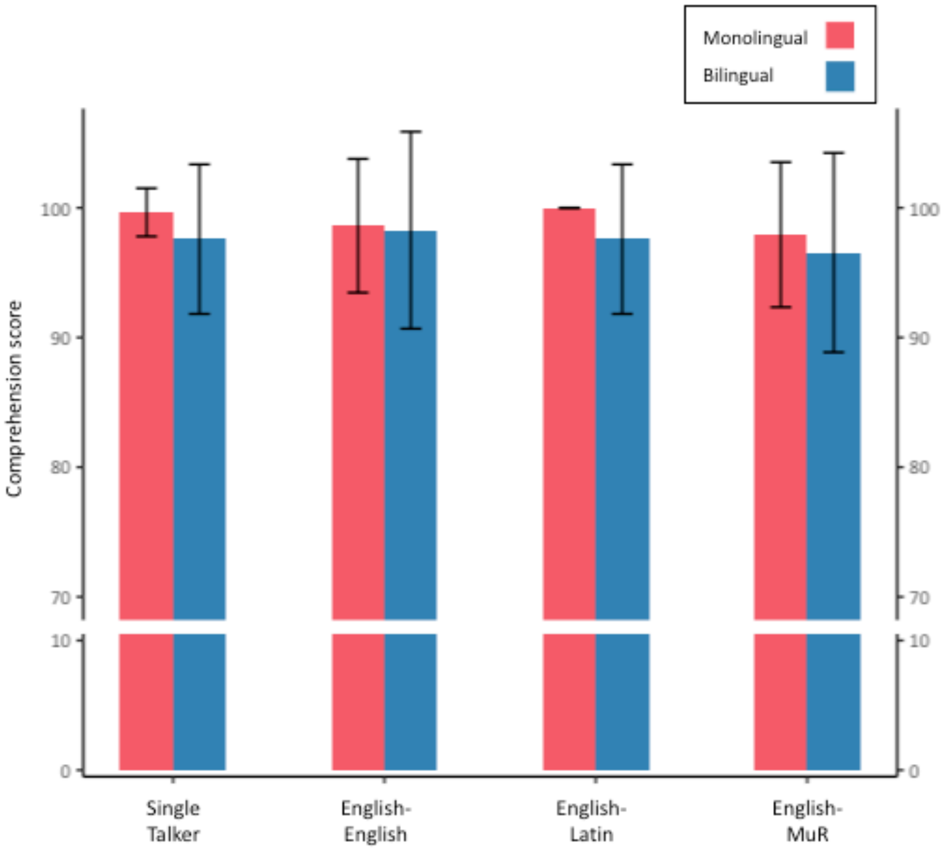
Table 15

Study 3 (Low-exposure bilinguals): Percentage correct comprehension scores

Condition	Monolinguals	Bilinguals
1. Control	n/a	n/a
2. Single Talker	99.7 (1.86)	97.6 (5.77)
3. English-English	98.6 (5.16)	98.3 (7.59)
4. English-Latin	100 (0)	97.6 (5.77)
5. English-MuR	97.9 (5.59)	96.6 (7.69)

Figure 15

Study 3 (Low-exposure bilinguals): Percentage correct comprehension scores



Results from the visual task:

As in the previous two studies, the first analysis of response times aimed to test if performance varied by group or with the addition of the increased attentional load of the auditory conditions. The first model included all five conditions (visual only; visual + Single Talker; visual + English–English; visual + English–Latin; and visual + English–Musical Rain). The dependent variable was log-transformed reaction times (log RTs), and the fixed factors were group (two levels, monolingual, bilingual), condition (five levels), and the interactions between them. Participant age and SES were also included as predictors, and subjects as crossed random effects. Results replicated the pattern that emerged from the equivalent model for children in Study 1: there was a significant effect of condition [$F(4,6439.3)=7.04$, $p<.001$, $\eta_p^2=.044$]; age [$F(1,54.8)=4.16$, $p<.05$, $\eta_p^2=.07$]; and a significant interaction between condition and group [$F(4,6439.3)=3.32$, $p<.01$, $\eta_p^2=.0021$].

Pairwise comparisons confirmed that the bilingual group's log response times were equivalent to the monolingual group's in all conditions except Condition 5 (English-MuR), in which the monolinguals were significantly slower than the bilinguals [t=3.37, *p*<.01, *d*=.188]. A summary of response times by condition, standard deviations and the log-transformed differences between groups are shown in Table 16 and Figure 16.

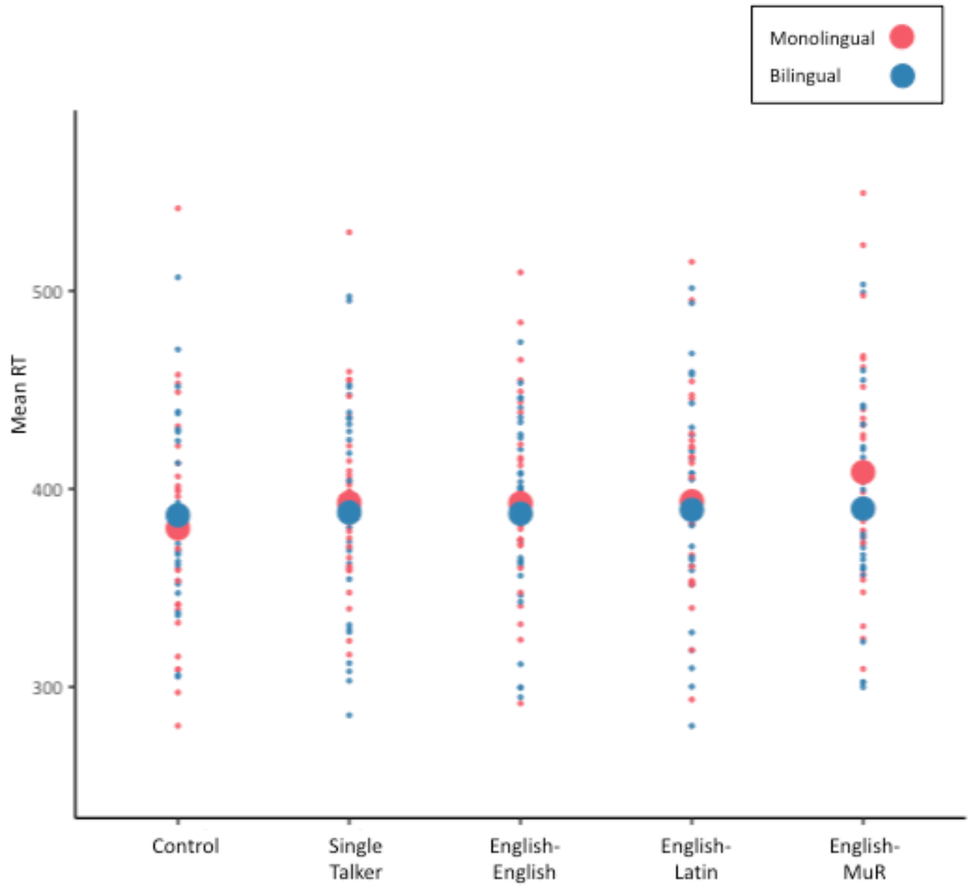
Table 16

Study 3 (Low-exposure bilinguals): Reaction times (SD) in ms and t tests between groups' log-transformed scores

Condition	Monolingual RT (ms)	Bilingual RT (ms)	t	*p*	*d*
1. Control	380 (95.1)	387 (93.7)	-1.5	.135	-.08
2. Single Talker	393 (92.0)	388 (96.5)	1.3	.193	.072
3. English-English	393 (92.6)	388 (95.3)	1.19	.236	.067
4. English-Latin	394 (92.4)	389 (95.4)	1.10	.272	.061
5. English-MuR	**408 (102)**	**390 (94.2)**	**3.37**	**<.01**	**.188**

Figure 16

Study 3 (Low-exposure bilinguals): Mean RT times by group and condition



The next analysis examined the patterns of RT responses in monolingual and bilingual groups separately. In *monolinguals*, a model, with log RTs as the dependent variable, which included condition (five levels) as a fixed factor, participant age and SES as predictors, and subjects as crossed random effects, showed a significant effect of condition [$F(4, 3226.1)=9.9$, $p<.001$, $\eta_p^2=.01$] and age [$F(1, 26.8)=5.59$, $p<.05$, $\eta_p^2=.17$].

Post hoc t tests revealed that Condition 1 (visual only) had a significantly faster reaction time than each of the auditory conditions. In addition, English-Musical Rain (Condition 5) was significantly slower than all the other conditions.

Table 17

Study 3 (Adults with low-exposure bilinguals): Differences in conditions for monolinguals

Condition A	Condition B	t	*p*	*d*
1. Control	**2. Single Talker**	**-2.99**	**<.01**	**-.17**
1. Control	**3. English-English**	**-2.78**	**<.05**	**-.15**
1. Control	**4. English-Latin**	**-3.09**	**<.01**	**-.17**
1. Control	**5. English-MuR**	**-5.43**	**<.001**	**-.3**
2. Single Talker	3. English-English	.15	.9	.0083
2. Single Talker	4. English-Latin	-.13	.9	-.0069
2. Single Talker	**5. English-MuR**	**-2.71**	**<.05**	**-.15**
3. English-English	4. English-Latin	-.27	.9	-.015
3. English-English	**5. English-MuR**	**-2.79**	**<.05**	**-.16**
4. English-Latin	**5. English-MuR**	**-2.57**	**<.05**	**-.14**

In *bilinguals*, the equivalent model showed no significant effect of condition or age. Post hoc t tests revealed that there were no significant differences between the bilinguals' log RTs in any conditions, even in the Control Condition 1 (visual only).

Errors: The total error rate was .54% for monolinguals and .49% for bilinguals, which was not statistically significant [t(224)=-.35, *p*=.73]. Because of too few data points (200/40000) no further error analyses were run.

5.5 Comparisons between studies

The final set of analyses combined the visual RT data across the three studies, in order to directly compare the performance of monolingual and bilingual participants across the two age groups, and by language exposure in the two adult cohorts. The first analysis explored trends across age groups for monolinguals and bilinguals separately.

5.5.1 Analysis by age: Comparison of visual data across Studies 1, 2 and 3

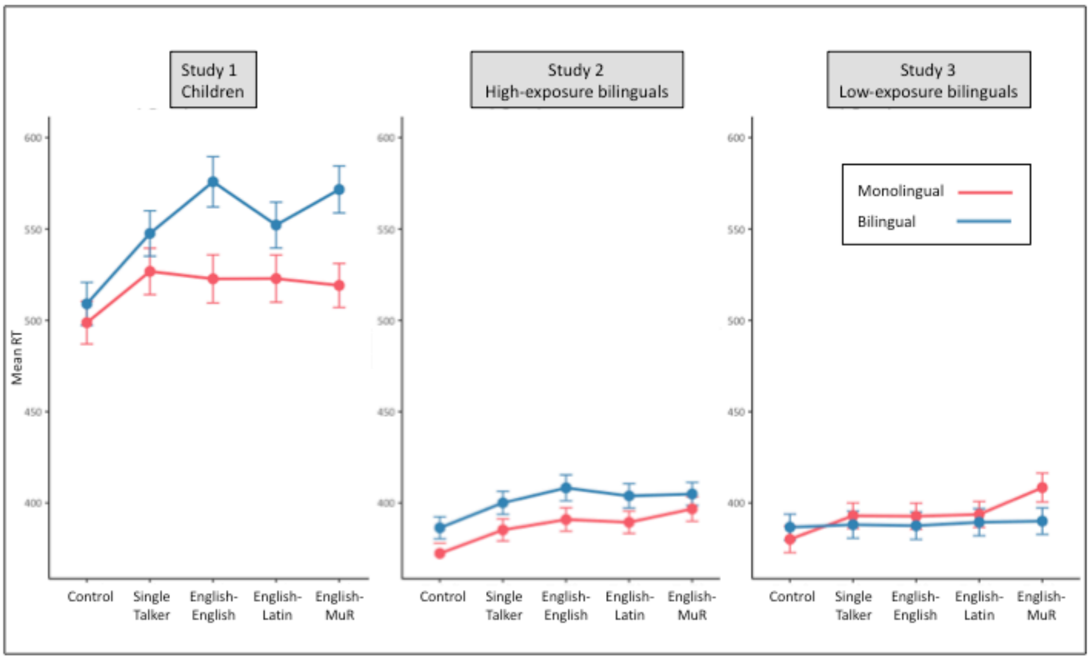
Due to the RTs in children being slower than in either cohort of adults, age group (Study) was expected to be a significant predictor of RTs in both monolingual and bilingual groups. Condition was also expected to be a significant predictor in both groups, reflecting the finding that the Control condition was consistently faster than other conditions in all previous analyses. The key question was therefore whether Study and Condition would interact in either monolingual or bilingual groups, suggesting a differential pattern of responses in children and adult participants.

In monolinguals, a model included fixed factors of study (children, high-exposure adults, low-exposure adults), condition (five levels) and their interaction, participant age and SES; and participant as random intercept. Results showed that both study [$F(2,107.8)=37.58$, $p<.001$, $\eta_p^2=.41$] and condition [$F(4,12347.6)=22.68$, $p<.001$, $\eta_p^2=.0073$] were significant predictors, but there was no interaction between them, indicating that all monolingual groups responded comparably to all five conditions, and that the two adult groups of monolinguals, while faster than the Study 1 monolinguals (as to be expected), did not vary in their pattern of response to the visual task relative to monolingual children. This is consistent with the previous analysis of patterns in the monolinguals for each study, which found that in all three studies Condition 1 (control, visual only) was significantly faster than every other condition, demonstrating a robust PRP effect (psychological refractory period, or psychological delay incurred when processing a dual task relative to a single task). This result corroborates the literature on dual tasks, which has established that the PRP is a consistent outcome of the cognitive processing of multiple tasks simultaneously (Pashler, 1994; Welford, 1952; Osman & Moore, 1993; Strobach et al., 2015).

In bilinguals, the equivalent model also revealed that study [$F(2,107.8)=76.75$, $p<.001$, $\eta_p^2=.59$] and condition [$F(4,12075.1)=26.83$, $p<.001$, $\eta_p^2=.0088$] were significant predictors, but there was also additional robust interaction between the two [$F(8,12075.1)=7.38$, $p<.001$, $\eta_p^2=.0049$]. Previous posthoc tests had already established that there were differences in the patterns of responses by the bilinguals of the different studies. To summarise: 1) in Study 1 (children) the Control Condition 1 was significantly faster than all the other conditions; and additionally Single Talker and English-Latin were both significantly faster than the English-English and English-Musical Rain conditions; 2) in Study 2 (high-exposure bilinguals), Control Condition 1 was significantly faster than all the auditory conditions (2-4), which were equivalent; and 3) in Study 3 (low-exposure bilinguals) there were no significant differences between the bilinguals' log RTs in any conditions. Figure 17 displays a summary of mean RTs for bilinguals across all studies, groups and conditions, clearly showing that responses of bilingual children were disproportionately affected by interference conditions 3-5 relative to any of the other language or age groups.

Figure 17

Patterns of RTs across conditions for Studies 1, 2 and 3



Additional posthoc tests, comparing the bilingual groups against each other, by study and by condition, showed that not only were the reaction times from Study 1 (children) significantly slower than the bilingual adults in Studies 2 and 3 (all $p<.001$) with large effect sizes (d ranging from .89-1.29) – as to be expected – but there were also significant differences between the bilingual adults in Studies 2 and 3 in every condition except Condition 1 (Control). This brings us to the next comparison: between the two adult groups, to see the effect of differential bilingual language experience.

5.5.2 Analysis of adult language groups: Comparison of data across Studies 2 and 3

As seen above, the adult bilinguals from studies 2 and 3 not only differed from the children (Study 1) but also from each other (details in Table 18 below). This warrants further investigation. The groups of bilinguals also varied slightly in how they compared to their monolingual counterparts (the monolinguals and bilinguals in Study 2 were equivalent in the model; the groups in Study 3 were different and posthoc tests revealed that this was due to the Study 3 monolinguals having significantly slower (higher) RTs in Condition 5 (English-Musical Rain).

Before focusing on the adult bilingual participants in each study, let us first turn to the monolinguals and establish if they are equivalent and therefore a reliable comparator in each study.

Analysis across adult monolinguals in Studies 2 and 3

Demographically, the monolinguals across the two adult studies were equivalent by age (Study 2: mean=28.9 yrs, SD=7.29; Study 3: mean=31.0 yrs, SD=6.69; $t(63.5)=-1.27$, $p=.21$, $d=-.301$); but not by SES, measured by level of education, in which the monolinguals in Study 3 scored higher (Study 2: mean=1.5, SD=.595; Study 3: mean=2.03, SD=.626; W=364.5, $p=<.01$). A model of comprehension scores of monolinguals across the two studies, with categorical response accuracy as the dependent variable; study (2, 3), condition (Single Talker, English-English, English-Latin and English-MuR) and their interaction, age and socio-economic status (SES) as fixed effects, and participant as random intercept, showed condition as the only significant factor [X^2 (1, N = 71) = 11.04, p = .012], caused by a slight drop in performance in Condition 3, but none of study or study by condition interaction. These results indicate comparable performance of monolingual adults across studies 2 and 3 in the behavioural auditory task, with equivalent performance in both studies across all four auditory conditions (including slightly lower scores in Condition 3 for both studies equally).

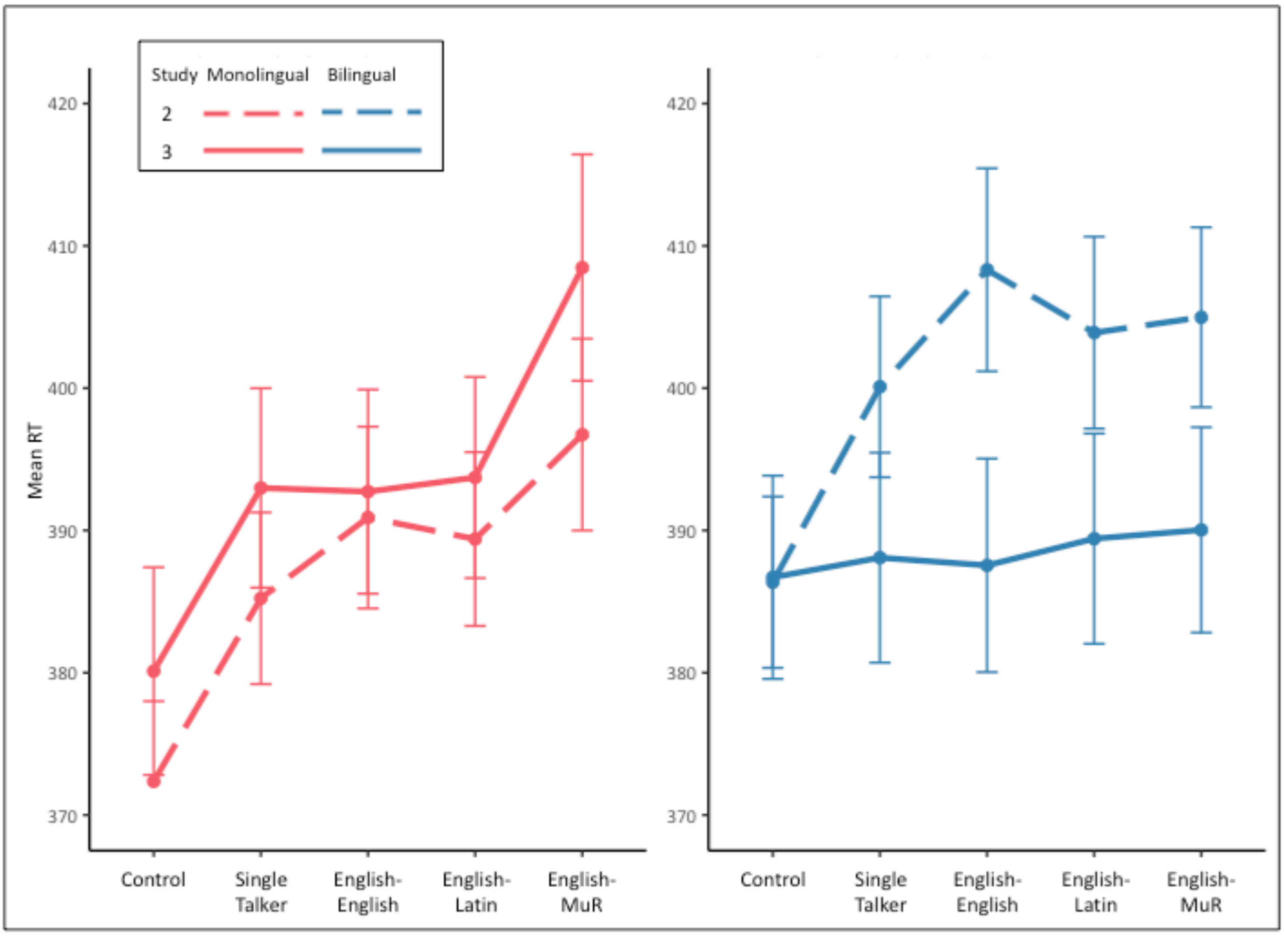
In addition, Bayesian analysis in JASP (version 0.13) showed moderate evidence for the null effect of experimental group in an independent samples t-test of overall comprehension scores (BF_{10}=.32). A subsequent Bayesian repeated measures ANVOA, including the factors of experimental group and condition, and age as a covariate, identified anecdotal evidence for an effect of condition (BF_{10}=1.32) and a best model assuming the effect of condition showed moderate evidence for the null effect of experimental group (BF_{10}=.156). This supports the conclusion that there was no statistical difference in the monolingual adults' comprehension scores across Studies 2 and 3.

Analysis of the two monolingual groups on the visual task with log-transformed reaction times (log RTs) as the dependent variable, and fixed factors of study (two levels, 2, 3), condition (five levels), and the interactions between them, participant age and SES as predictors, and subjects as crossed random effects; found a significant effect of condition [$F(4,7927.3)=22.8$, $p<.001$, $\eta_p^2=.01$]; but no effect of study nor interaction between study and condition. Despite the difference in the groups' SES scores, there was also no effect of SES in the model. Post hoc t tests found no significant differences between monolinguals in each study in any condition.

In fact, a version of Figure 17 shown in Figure 18 below, focusing on Studies 2 and 3 only, shows that the monolingual groups' pattern of scores across conditions is remarkably similar.

Figure 18

Patterns of monolingual and bilingual RTs across conditions in Studies 2 and 3

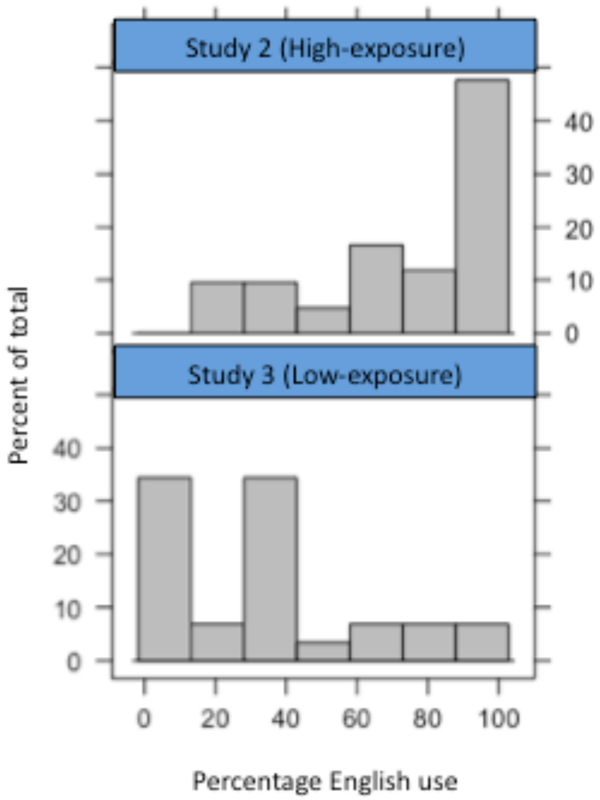


Analysis across adult bilinguals in Studies 2 and 3

Demographically, the bilinguals across the two adult studies were equivalent by age (Study 2: mean=27.4 yrs, SD=5.95; Study 3: mean=28.5 yrs, SD=7.72; $t(50)=-.643$, $p=.523$, $d=-.16$); and by SES, measured by level of education (Study 2: mean=1.81, SD=.74; Study 3: mean=1.77, SD=.61; $W=457$, $p=.945$). Where they did differ, however, was in language background. The language questionnaire captured their age of acquisition (AoA), proficiency in their second language (English), and percentage of the time the participants estimated they used each of their languages, including their native language and English. The AoA of each of the groups was not significantly different (Study 2: mean=6.21 yrs, SD=6.86; Study 3: mean=6.64 yrs, SD=2.5; $t(44.9)=-.33$, $p=.74$, $d=-.077$), but the bilinguals in the two studies were different on scores of proficiency out of a maximum of 10 (Study 2: mean=9.31, SD=.96; Study 3: mean=8.66, SD=1.28; $t(51.1)=2.28$, $p<.05$, $d=.59$) and their self-assessment of English usage (Study 2: mean=73%, SD=24.9; Study 3: mean=33.6%, SD=26.9; $t(57.2)=6.26$, $p<.001$, $d=1.53$). The difference in English usage was the most evident and Figure 19 shows the different distributions in the two studies.

Figure 19

Percentage of English used regularly by bilinguals in Studies 2 and 3



Note. The question in the language questionnaire was: Please list the approximate percentage of the time you are using each language (please include your native language too). The figure above represents the percentage each group scored for their use of English specifically

It is important to note that even though the self-reported proficiency score for bilinguals in Study 3 was significantly lower than the score for Study 2, this did not negatively impact comprehension scores, which were equivalent for the two groups of bilinguals across studies. A model of comprehension scores of bilinguals across the two studies, with categorical response accuracy as the dependent variable; study (2, 3), condition (Single Talker, English-English, English-Latin and English-MuR) and their interaction, age and socio-economic status (SES) as fixed effects, and participant as random intercept, showed an effect of condition [X^2 (1, N = 71) = 8.59, p = .035] but none of study or study by condition interaction. These results indicate comparable performance of bilingual adults across Studies 2 and 3 in the behavioural auditory task, with no loss of performance due to proficiency.

This was supported by Bayesian analysis, which showed anecdotal evidence for the null effect of group in both an independent samples t-test of overall comprehension scores (BF_{10}=.451), and a repeated measures ANOVA, with factors of group, condition and age as a covariate (BF_{10}=.339).

For the analysis of the visual task, a model of log reaction times of bilinguals across the two studies, with RT as the dependent variable; study (2, 3), condition (Single Talker, English-English, English-Latin and English-MuR) and their interaction, age and socio-economic status (SES) as fixed effects, and participant as random intercept, showed an effect of condition [F(4, 7846.4) = 6, p<.001, η_p^2 =.0031]; and a study*condition interaction [F(4, 7846.4) = 3, p<.05, η_p^2=.0015]. The post hoc t tests revealed significant differences in all conditions except Control (Condition 1, visual only).

Table 18

Comparison of bilinguals' scores in Studies 2 (High-exposure bilinguals) and 3 (Low-exposure bilinguals) by condition

Condition	Study 2 (high-exposure bilinguals)	Study 3 (low-exposure bilinguals)	t	*p*	*d*
1. Control	386 (95.1)	387 (93.7)	-.134	8.93	-.007
2. Single Talker	**400 (98.7)**	**388 (96.5)**	**2.56**	**<.05**	**.132**
3. English-English	**408 (110)**	**388 (95.3)**	**3.73**	**<.001**	**.19**
4. English-Latin	**404 (106)**	**389 (95.4)**	**2.74**	**<.01**	**.14**
5. English-MuR	**405 (98.1)**	**390 (94.2)**	**3.23**	**<.01**	**.16**

These results from the visual task indicate more differences between the bilinguals in Studies 2 and 3 with different language exposure, than between either of them and their monolingual counterparts within the studies. All these results are discussed below.

5.6 Discussion

The results of the previous study (EEG Experiment 1, described in Chapter 4), with a lower and flatter pattern of neural attentional indices in bilinguals despite equivalent behavioural scores, support the proposition that the inhibition of the non-target language in bilinguals does not affect performance on primary tasks, but does lead to a reduction of overall capacity (Dornic, 1980). The purpose of the Studies described above was to explore the consequences of increasing the processing demands, to investigate if bilinguals' optimised performance in spite of constrained capacity (or the ability to "do more with less"), has limitations in the context of dual tasks. Therefore, increasing the processing demands in a controlled way in a dual task, would establish if there were any indicators of additional interference in the bilingual group as well as the expected PRP (psychological refractory period, or well-documented delay as a result of simultaneous task processing) for all participants as a result of the “central bottleneck” (Pashler, 1994).

The new behavioural task was designed by adding a secondary task to the dichotic listening task from EEG study 1, which additionally varied the attentional load during the study. The prediction was that bilinguals, with reduced attentional capacity due to managing their additional language processing demands, would need to prioritise and economise their responses to competing task demands, relative to monolingual participants, to maintain task performance and that this would affect performance in the secondary task.

Performance was measured on two tasks: a dichotic listening task with comprehension scores as an performance indicator; and a visual T.O.V.A. task in which both accuracy, through errors of commission and omission, and speed of response, through response times were tracked. The study was conducted on three groups spanning age ranges and language experience, with one group of school-age children (Study 1, age range 7-12), and two groups of adults (Studies 2 and 3, age range 18-45), who were differentiated by exposure to English. Study 2 recruited a high-exposure bilingual group and Study 3 a low-exposure bilingual group, as well as monolingual adults in the same age range.

The results showed equivalent performance in the auditory (primary) task between monolingual and bilingual participants, across all three studies. For the visual (T.O.V.A.) task, accuracy, measured by error rates, was extremely high and equivalent between monolingual and bilingual participants, in all studies.

Reaction times in the visual (secondary) task, however, showed key differences between conditions, age groups and language groups. These are summarised and discussed below.

Firstly, there was an expected PRP effect from the addition of the auditory task to the Control condition of the visual task only. Condition 1 (Control, visual only) was significantly faster for all groups of participants across all three studies, confirming a robust psychological refractory period (PRP), the delay generated when performing two tasks simultaneously, consistent with the literature (Pashler, 1994; Telford, 1931; Vince, 1949; Welford, 1952; Pashler & Johnston, 1998; Osman & Moore, 1993; Schubert, 2008).

5.6.1 Differences between monolingual and bilingual children

The results from Study 1 revealed that bilingual children's reaction times were significantly slower relative to monolingual children's in all the dual-interference conditions (Conditions 2-5). The only exception was the Control Condition 1, which comprised the visual task only, in which the groups were equivalent. This result suggests that, as the attentional load increased through multiple tasks, bilingual children's performance was not affected uniformly across tasks and conditions. Rather, the processing system in bilingual children distributed resource in response to the tasks' demands, maintaining optimal performance in the task of higher priority, at the expense of resource to perform the secondary element. This account is consistent with the multimode theory of attention. In their dual task incorporating an auditory task and visual task measuring reaction times, Johnston & Heinz (1978) found that conditions of greater semantic processing in the auditory task generated slower reaction times in the visual task, thus demonstrating the limitation of attentional capacity and its effect of the processing of multiple tasks depending on auditory conditions. The Johnston & Heinz (1978) experiment did not investigate the additional impact of bilingualism, but their conclusion of longer reaction times equating to constraints on capacity is consistent with the results shown by bilingual children.

Thus for bilingual children a hierarchy was revealed in which comprehension of the auditory task and accuracy in the visual task were prioritised and optimal performance maintained. This budgeting of attentional resource left a deficit, relative to monolinguals, in speed in the visual task. I will discuss next whether this order of priority was consistent across age groups and language exposure from the results of the adult studies.

5.6.2 Differences between adult bilinguals in Studies 2 and 3

In spite of both adult groups of bilinguals showing comparable speed (or faster in the English-MuR condition in Study 3) to monolinguals in the conditions of dual interference, there still appeared to be significant differences between the bilinguals' reaction times across the adult studies. This was established after ensuring that the monolinguals across Studies were in fact equivalent. This difference held across every single dual interference condition, in which low-exposure bilinguals were significantly faster than high-exposure bilinguals. One possible interpretation here would be that the high-exposure bilinguals, resident in the UK and using their second language (English) on a daily basis, have greater parallel activation (Green, 1998) and hence processing load due to the second language (Wickens, 2007). Indeed, according to the adaptive control hypothesis (Green & Abutalebi, 2013), the language context in which processing demands – such as interference suppression and conflict monitoring – are highest is the dual-language context, i.e. the profile of the bilinguals in Study 2. The results from comparing the two groups of adult bilinguals suggest that the effect of maturation on selective attention proposed in the section above is enough to close any gap between monolingual and bilingual speakers; but that there is still some residual processing cost that, although it does not manifest when compared to monolinguals, is exposed in speed of response in relation to other bilinguals who do not face the same daily processing demands.

5.6.3 Difference between monolinguals and bilinguals across studies

The initial analysis for each study testing the effect of group, condition, age and SES on RTs, found a significant group:condition interaction for two of the studies: Study 1 (children) and Study 3 (low-exposure bilinguals). Post hoc tests revealed that in

Study 1 bilingual children had significantly slower reaction times in all conditions except the control (Condition 1). In Study 3 (low-exposure bilinguals), the only significantly different condition between the language groups was English-Musical Rain, in which bilinguals were significantly faster. Study 2 (high-exposure bilinguals) revealed no group:condition interaction in the model.

This arguably suggests a developmental trajectory for bilinguals revealed by a dual-task paradigm; in which apparent limitations of attentional resource, while still not impacting on the primary task, are shown in scores of the secondary task in conditions of dual interference in children; but that these effects on response times dissipate with maturation. This adds nuance to the previous discussion of degeneracy, indicating that, while behavioural performance on a primary task is indeed equivalent from childhood (as seen in Study 1 here and EEG Experiment 1 described in Chapter 4); attentional systems impacted by bilingualism may not reach parity under the increased demands of dual tasks, which extend the bandwidth of normal processing, until adulthood and thus maturation of the prefrontal cortex associated with selective attention processing (Giedd et al., 1999; Gogtay et al., 2004; Sowell et al., 2001; Tsujimoto, 2008).

5.6.4 Implications of the prioritisation of the tasks

The prioritisation of attentional resource in response to the auditory vs visual task, manifested by equivalence in all the groups and studies in the auditory comprehension scores and variability across age/language groups in the response times (but not accuracy) to the T.O.V.A., is plausibly a result of the paradigm used in this study. One explanation for the apparent hierarchy of response is that the auditory task was presented explicitly as the primary task. Another explanation is that the auditory task was also more varied and entertaining than the visual task, which was simple and repetitive, thus capturing more attention through content and presentation rather than through a directive. For the visual task, it is important to note that accuracy was not emphasised over speed in the instructions or practice.

[The manipulation of specific task instructions has been established as an influence on the outcome of the accuracy-speed tradeoff (Katsimpokis et al., 2020)]. Furthermore, any reaction time longer than 2000ms was deemed a "time out" and recorded as an error of omission, so the slower reaction times as a result of analysis were in the context of correct responses and within a time-limited window. Indeed, slower speeds for bilingual participants – especially younger ones – in the visual task are consistent with neural explanations of how a task using the speed-accuracy tradeoff is processed: the processing network progresses through a series of stages including noise filtering, integration and amplification of evidence, and choice selection (Standage et al., 2011), as well as motor control. In the case of a constrained processing capacity, it is plausible that these processing steps would take fractionally longer – but not be any less accurate.

5.6.5 The findings in the context of other studies

The results of a bilingual limitation in one element of the dual task in order to maintain optimal performance in the primary elements are at odds with some of the previous research investigating dual tasks and bilingualism, notably the studies combining a visual search with counting backwards (Janic et al., 2020) and driving simulation and verbal tasks (Telner et al., 2008). However, in those studies not only were different tasks used and assessed, but the computation of performance was based on the decrements of participants' scores, compared to their baseline score recorded in a control condition, rather than the absolute values analysed above. In order to compare like for like and following the method employed in these papers, decrement scores for each participant were calculated by subtracting each condition's normalised response times from the participant's mean response time in the Control condition (visual only, Condition 1). Comparing the decrements scores of monolinguals and bilingual participants in each study revealed a significant difference between the groups in the children only, consistent with the original results detailed above. Contrary to the previous studies using decrements (Janic et al., 2020; Telner et al., 2008), these showed that bilinguals' performance was more significantly affected than that of monolinguals in each of the dual conditions that required the inhibition of auditory interference. See Table 19 for results of decrement analysis in all three studies.

Table 19

Decrement t test results for Studies 1, 2 and 3 between monolinguals and bilinguals

Condition	***Study 1 (Children)***			***Study 2 (High-exposure bilinguals)***			***Study 3 (Low-exposure bilinguals)***		
	t	***p***	***d***	**t**	***p***	***d***	**t**	***p***	***d***
2. Single Talker	1.59	.11	.076	.17	.87	.0078	-2.17	**<.05**	-.12
3. English-English	4.16	**<.001**	.2	.13	.9	.0059	-2.22	**<.05**	-.13
4. English-Latin	3.06	**<.01**	15	-.34	.74	-.016	-1.75	.08	-.097
5. English-MuR	4.53	**<.001**	.22	-1.47	.14	-.068	-4.56	**<.001**	-.25

As seen in the above table, for the adult high exposure bilinguals study (Study 2), comparisons of decrement scores relative to the control task revealed no significant difference between monolinguals and bilinguals.

Finally, results of the decrement analysis for the adult study on low-exposure bilinguals (Study 3) showed not only a significant result for Condition 5 (English-MuR), consistent with the original results, but also significant difference between monolinguals and bilinguals in Single Talker (Condition 2) and English-English (Condition 3). These, like the Single Talker condition, indicated that bilinguals suffered less effect of PRP compared to the Control condition than monolinguals, in direct contrast to the results from children.

In sum, the use of decrement analysis as employed in other studies (Janic et al., 2020; Telner et al., 2008) did not change the overall conclusions that performance differed for the bilinguals in Study 1 (Children) relative to monolinguals; and this effect had been overcome or reversed by adulthood (Studies 2 and 3).

5.6.6 Conclusions

This set of studies investigated the effect of increased processing demands on bilingual performance across three groups. The data from Study 1 show that there is a process of economisation and prioritisation of elements of tasks in bilingual children, in this case concentrating the resources on comprehension of the auditory task and accuracy of the visual task, at the expense of speed in the visual task.

This results in limitations in speed in bilingual children's performance in the visual, but not accuracy of auditory, element of a dual task. This task, tapping two competing domains, deliberately increases attentional load beyond what can normally be accommodated in a flexible attentional processing system. Importantly, these speed limitations in the secondary task appear to recede, relative to monolinguals, by adulthood. Furthermore, analysis of adults with differing second language exposure has revealed differences in performance which are not discernible when comparing either group to monolingual peers.

In the context of the effects of bilingualism, this suggests that maturation of the selective attention system enables adaptation to accommodate the combined load of second language processing and competing task demands; resulting in optimal selective attention processing and performance in "extreme" tasks. It has already been established that behavioural performance is equivalent for children in a primary task, even when neural indices of attention are lower for bilingual than monolingual children (as in Chapter 4) supporting the view that modifications to the neurofunctional architecture as a consequence of bilingualism (Hayakawa & Marian, 2019) are aimed at supporting performance within the boundaries of typical demands on selective attention. The results here still indicate that behavioural performance is maintained for the primary element of a dual task (in this case, auditory), but differs for bilingual children when performing the secondary task element (in this case, visual). The assumption therefore is that the additional processing load of another language leads to constrained capacity, which triggers the need to economise and prioritise the demands of a task which extends beyond the bandwidth of a typical attentional load.

Critically, however, any bilingual difference relative to monolinguals in performance of the secondary task was no longer discernible in either of the adult groups. This suggests that, as the attentional system matures, bilinguals demonstrate degenerate behaviour (relative to monolinguals) not only in primary tasks but in secondary tasks as well. This, however, does not preclude some residual processing constraints, which although not large enough to differentiate bilinguals significantly from monolingual peers, emerge in indices of attentional processing (reaction times) when groups of bilinguals with different levels of language exposure are compared.

As an aside, one of these differences was that low-exposure bilinguals, as demonstrated in Figures 17 and 18, showed the overall fastest reaction times of all the language groups across all the studies. Perhaps this could be used as an incentive to promote learning a second language in an educational setting, to a reasonable degree of proficiency, which appears to yield benefits in selective attention tasks with multiple demands, without using the additional language every day.

Chapter 6: Experiment 3

6.1 Introduction

The final question was to what extent a difference observed in auditory selective attention patterns between monolinguals and bilinguals could be discerned in a non-linguistic domain. To this end, I replicated EEG Experiment 1 with the same demographics, and target stimuli but replaced the unattended streams with different levels of non-linguistic interference.

As discussed in Chapter 4, selective attention is a critical component of children's executive functioning, with strong evidence pointing to its influence on outcomes such as academic success (Stevens & Bavelier, 2012) and mitigation of environmental barriers such as lower SES (Hampton Wray et al., 2017; Isbell et al., 2016). Bilingualism, as a consequence of the habitual processing demands associated with managing an additional language (Green, 1998), has been shown to trigger neuroplastic adaptations not only in areas associated with language processing (Perani, 2005); but also in regions associated with more generalised selective attention, such as the anterior cingulate cortex (Abutalebi et al., 2012). This is consistent with the hypothesis that bilingualism causes adaptation to control processes associated with these regions. Furthermore, some researchers claim that these modifications not only affect behaviour in verbal selective attention tasks (Kaushanskaya et al., 2014), but also generalise to nonverbal selective attention tasks (Carlson & Meltzoff, 2008). This has motivated theoretical frameworks such as the Adaptive Control Hypothesis (Green & Abutalebi, 2013), which details the attentional control processes affected, and specifically proposes a framework for precise predictions about the performance of bilinguals on non-verbal tasks.

However, such proposals of adaptation to control processes, leading to modified behaviour in non-verbal tasks, are not universally accepted, with many studies finding no difference between the performance of bilinguals and monolinguals in non-verbal attention tasks (Hilchey & Klein, 2011; Morton & Harper, 2007). Importantly, this proposed – and contested – modification to non-verbal as well as verbal selective attention processing occurs while children's selective attention processes are still undergoing development in a prolonged period of maturation (see Lane & Pearson, 1982, for review).

Furthermore, even non-verbal selective attention tasks must be performed in the context of finite attentional capacity (Kahneman, 1973), in which the management of a second language has been proposed to be a constraint (Wickens, 2007). Therefore, it is plausible to assume that there is a similar economisation of residual capacity in order to maintain optimal behavioural performance, comparable to that observed for attentional processing in the verbal domain. This would also have implications for frameworks such as the Adaptive Control Hypothesis (Green & Abutalebi, 2013) by placing predictions of bilingual performance on non-verbal tasks in the context of a narrower bandwidth of attentional capacity.

As before, this does not preclude the possibility of a resulting greater flexibility, i.e., doing "more with less" in bilinguals, but shifts the focus from inconsistent behavioural comparisons on non-verbal tasks (von Bastian et al., 2016) to patterns of adaptation and economisation in the neural processing of such tasks. Indeed, one prediction would be that, as in EEG Experiment 1, neural indices would not point to an overall enhancement, but might show some reduction and reconfiguration, in the bilingual group's attentional processing of the task, using non-verbal unattended stimuli.

6.2 Current study

To establish if the patterns that emerged in EEG Experiment 1 also generalise to the non-linguistic domain, the current study again investigated the neural encoding of attended and unattended speech envelopes in monolingual and bilingual listeners aged 7-12. I used the same attended narratives (and their speech envelopes) as in the previous experiment, but substituted the unattended stimuli with non-linguistic streams. As established in the previous EEG experiment, neural encoding of speech envelopes is a proven method for investigating attentional processing. Evidence that there is a robust correlation between attended speech envelopes and neural activity (Aiken & Picton, 2008; Di Liberto et al., 2018; Mesgarani & Chang, 2012) underpins the selective entrainment hypothesis (Zion Golumbic et al., 2013) which proposes that this neural activity, or encoding, is essential for speech intelligibility in adults (Obleser & Kayser, 2019; Olguin et al., 2018) and children (Power et al., 2016; Ríos-López et al., 2020).

Following the design of EEG Experiment 1 described in Chapter 4, the current study employed EEG to capture the neural encoding of attended and unattended speech envelopes in monolingual and bilingual children. As before, linear regression as implemented in the mTRF toolbox (Crosse et al., 2016) was used to model the relationship between the speech signal and the neural data, and applied in a backward direction to assess how well the attended and unattended speech envelopes could be reconstructed from the responses of the neuronal populations that encode them (see Methods chapter for more details). The measure of correlation between the speech envelope and EEG signal was the reconstruction accuracy score computed by the mTRF toolbox for each matching sentence/EEG epoch per condition per participant, using all neural data simultaneously in a "leave-one-out" computation. This method of assessing correlation is not only suitable for multi-channel data such as EEG (O'Sullivan et al., 2015), but an established method for quantifying neural tracking in children (Power et al., 2016).

Although the mTRF technique has been shown to be particularly suitable for natural speech (Wong et al., 2018; Sassenhagen, 2019; Pasley et al., 2012) and differentiation of speech streams in the cocktail party design (Rimmele et al., 2015; Riecke et al., 2018; O'Sullivan et al., 2015), it is also suitable for sensory signals in general (Crosse et al., 2016), including non-speech streams (Crosse et al., 2021). Examples of studies tracking non-speech auditory stimuli include streams derived from linguistic stimuli such as unintelligible vocoded speech (Di Liberto et al., 2018), or individual syllables (Power et al., 2016) ; to auditory stimuli devoid of any linguistic input such as birdsong (Di Liberto et al., 2018), animal communication calls (Machens, 2004) and classical music (Di Liberto et al., 2020). The mTRF toolbox has even been used in conjunction with non-auditory stimuli, for example to track the response to motion and luminance of visual streams (Jessen et al., 2019).

As in the first EEG experiment, children were presented with two competing auditory stimuli simultaneously, and instructed to attend to one while ignoring the other. The nature of the competing stream was manipulated across four different conditions to create different types of non-linguistic interference. As in EEG Experiment 1, the first condition was 'Single Talker', a control condition where children attended to a narrative presented in one ear, with no interference presented in the other ear. This established a baseline measure for attentional encoding in monolingual and bilingual listeners, which could also be compared to the previous EEG Experiment 1 to assess equivalence of baseline responses.

The non-linguistic interference streams for the other three conditions were selected with the aim of providing naturalistic nonverbal distractors for the target sample of school-age children (age range 7-12) that they would plausibly hear in an everyday scenario. Thus in the second condition, children attended to a narrative in English presented in the attended ear while ignoring unintelligible multi-talker babble, recorded from children in a classroom, presented in the unattended ear (English–Babble condition). In the third condition, children attended to a narrative in English while ignoring a stream of typical road traffic noise (English–Traffic condition). In the fourth condition, the interfering stream was a simple melodic backing track (English–Music condition), of the genre used in television adverts, but with no lyrics, to avoid triggering a response to linguistic content.

As before, participants were instructed to listen to the attended stream for comprehension, a task that children in this age group had already performed without difficultly in EEG Experiment 1. Based on the previous experiment's comprehension results, it was also expected that there would be no significant difference between the ability of monolingual and bilingual listeners to perform the task. As before, by maintaining consistency in target (comprehension) narratives and behavioural performance, the focus was on the neural response patterns under new conditions of interference, rather than performance alone.

The set of conditions described above allowed an assessment of whether the patterns discerned in conditions of linguistic interference in EEG Experiment 1, also generalised to a study using non-linguistic unattended stimuli. To summarise the findings from EEG Experiment 1, results showed that attention modulated the neural encoding of speech envelope in both monolingual and bilingual children, with the type of distractor further influencing the strength of the encoding of the attended stream. Critically however, the way different distractors influenced attentional encoding differed between the groups. Bilingual reconstruction scores tended to be lower and flatter. Monolinguals showed substantial variability between conditions, with significantly higher attended reconstruction scores in conditions of reduced (Musical Rain) or no interference (Single Talker) relative to their reconstruction scores in the two other conditions of linguistic interference. These scores were also significantly higher than the bilinguals' reconstruction scores in the same (no or low interference) conditions.

This tendency for lower neural indices of selective attention in bilingual children – despite equivalent behavioural performance – supports the hypothesis that language selection and inhibition themselves draw on the existing attentional capacity (Wickens, 2007), restricting the resources available to track the speech envelope. Results from EEG Experiment 1 further indicate that the subsequent economisation of this restricted resource leads to a modification of the encoding patterns across conditions in bilinguals, leading to a redistribution of the residual attentional capacity to optimise the usage of this constrained resource and perform the task in the context of the increased processing demands of bilingualism.

4.3 Materials and method

4.3.1 Participants

45 typically-developing children aged 7-12 were tested. One child (bilingual) was excluded from analysis after achieving an outlier comprehension score more than seven standard deviations lower than the sample mean, after which there remained 44 participants across two groups: 22 bilingual children (seven males, age M=9.67 yr, SD=1.56) and 22 monolingual children (fourteen males, age M=10.1 yr, SD=1.56), which were matched groupwise on mean and distribution of age (t=.83, p=.41). All participants were healthy with no history of hearing problems or neurological disorder. 41 were right-handed, with two of the left-handed children being bilingual and one monolingual. All participants' parents completed a language history questionnaire, which provided an overview of children's exposure to languages. As confirmed by the questionnaire, all monolingual participants were native speakers of English, with no significant exposure to other languages. The participants in the bilingual group all had a similar profile: the language they first learnt was not English, and they used this language at home on a daily basis. They were however fluent and highly proficient in English, following English-speaking curriculum at school, and with native-like English conversation skills comparable to their monolingual peers. The second languages spoken were Afrikaans, Cantonese, French, Hebrew, Korean, Mandarin, Polish, Russian and Spanish. Children were recruited via posters, social media, and word of mouth. Parental education information was collected as an indication of SES. The majority of participants' parents (92%) were educated to degree level or higher, and the groups were not significantly different on this approximation of SES (bilinguals M=2.68, SD=.48; monolinguals M=2.46, SD=.58; Mann-Whitney Z=-1.43, p =.16).

The study was approved by the Cambridge Psychology Research Ethics Committee, and performed in accordance with relevant guidelines and regulations. Prior to the testing session, parents and children were given detailed information on the aims of the project and what to expect from the session. Upon arrival, informed consent was given by parents signing a consent form and the children an assent form. They were told they could withdraw from the study at any time.

Due to the covid pandemic, these data were acquired over a prolonged period from December 2019 to November 2021, with twelve participants tested in December 2019 – March 2020 and the remaining 33 in July 2021-November 2021 after lockdown restrictions were lifted.

4.3.2 Design

The experiment consisted of four conditions (Table 20). In each condition, children were attending to a story in English in one ear. Condition 1 had no interference in the other ear ('Single Talker'). In the other three conditions children were also presented with a non-verbal distractor in the other ear, which they were instructed to ignore. The nature of the distractor varied, from a stream of babble with no intelligible words ('English-Babble'), to a continuous stream of traffic noise ('English-Traffic') and a stream of simple and highly rhythmic melodic interference ('English-Music').

Table 20

Experimental conditions

Condition	***Attended stream***	***Interference***
1. Single Talker	English story 1	No interference
2. English-Babble	English story 2	Multi-talker babble
3. English-Traffic	English story 3	Traffic noise
4. English-Music	English story 4	Music (no words)

4.3.3 Stimuli

The target stories for the attended ear were the same as those used in EEG Experiment 1, i.e., four children's stories in English specifically aimed at this age group, taken from online resource storynory.com. These stories had been transcribed into 120 sentences each, with each sentence lasting approximately 3 seconds in length. Each target story was then split into 2 blocks and children attended to the first half in either the left or right ear (randomly assigned), with interference in the other, and then swapped ears for Block 2. Each block (half of a story) consisted of 60 sentences, with all 60 sentences concatenated with a 300ms gap between them to create a single block lasting 3.3 minutes. Block 1 was always the first half of the target story and Block 2 the second half. Gender of the speaker was kept the same for all target stories to reduce segregation strategies based on talker's gender (Brungart & Simpson, 2007). All stories' volumes were normalised to ensure equivalent average amplitude.

The non-linguistic interference of classroom babble and traffic noise were sourced from the BBC sound effects archive (https://sound-effects.bbcrewind.co.uk) which permits usage for non-commercial projects. The music interference stream was sourced from the online music for video resource Bensound (https://www.bensound.com/free-music-for-videos), which offers royalty-free downloads. As the distractor streams were all continuous, and the target stories concatenated with 300ms gaps of silence, it was necessary to ensure that attention was balanced impartially between the two streams in the "gaps". Accordingly, code in Matlab code was used to create a ramp effect where the distractor stream faded down and then faded back up at 3s intervals, synchronising with the silences in the target narratives. Finally, all distractor streams' volumes were also normalised to ensure equivalent average amplitude.

The same instructions were used as in EEG Experiment 1. These had been recorded by the female speaker who narrated the target stories, and were played before each block in the target ear, telling the child*: "This is your right/left ear. Please listen carefully to the story in this ear, on your right/left side, and ignore the sound in the other ear".*

4.3.4 Procedure

The participants had a practice session of listening to an English story in both the left and the right ear while ignoring a distracting stream in the other ear, in order to familiarise themselves with the dichotic listening paradigm. After practice, they were asked to summarise the target story to check they could hear correctly and had understood the instructions to attend to one ear at a time. The task itself took 45-60 minutes. Children first heard Block 1 of Condition 1 (Single Talker) followed by 10 comprehension questions. They then listened to Block 2 of Condition 1 (Single Talker), again followed by 10 comprehension questions. Each block was preceded by the recorded instructions in the relevant (target) ear. This procedure was repeated for the other three conditions, which were presented in a random order. Children were instructed to stay as still as possible while the stories were playing and were allowed to stretch, yawn etc. during the comprehension breaks. An example sequence of a block is illustrated in Figure 1 in the Methods chapter. Comprehension questions consisted of simple sentences to check understanding of each story (for example: *'This story is about a boy named PETER/TOM'*), and children pointed or verbally confirmed which option they thought was correct. The children did not receive feedback on their responses. At the end of the experiment children were presented with a certificate of completion and a £20 Amazon gift voucher as compensation for their time.

4.3.5 Data collection and preprocessing

As described in the Methods chapter, EEG was recorded using a child-sized 64-channel electrode net while stimuli were played through foam-tipped earphones in the pre-allocated part-randomised order. All data were pre-processed in MATLAB:

EEGLAB Toolbox (Delorme & Makeig, 2004) following the 10 step process described in the Methods chapter. After the data had been cleaned following these steps, including filtering, ICA and removal of noisy components and interpolation of bad channels; epochs of 3s length were extracted, to enable a minimum of five minutes of EEG data per participant per condition as an input for the mTRF toolbox (Jessen et al., 2019), allowing for epoch rejection of outlier epochs. These were defined as epochs outside a 3*SD* of the probability and kurtosis thresholds. This resulted in an overall epoch rejection of 16.15% overall (14.37% for monolinguals and 17.94% for bilinguals). By condition, epoch rejection was 15.9% in Single Talker, 19.26% in English-Babble, 14.74% in English-Traffic and 14.56% in the English-Music datasets. Finally, after re-referencing and resampling to 100Hz, the EEG data from all 44 participants were entered into the subsequent mTRF analysis.

4.3.6 Speech envelopes

Speech envelopes for attended speech streams and unattended non-linguistic stimuli were calculated using the Hilbert2 function in EEGLAB, downsampled to 100Hz to match the data and normalised using *nt_normcol* (Noisetools http://audition.ens.fr/adc/NoiseTools/).

4.3.7 Analyses

Neural tracking of the stimulus envelopes was computed in the same way as EEG Experiment 1, using multivariate temporal response functions in the mTRF toolbox (Crosse et al., 2016). As described in the Methods chapter, the backward model (reconstruction) was used to model the encoding of the speech as a function of the sound input, for all neural data simultaneously. The model was created using inputs of stimulus (normalised envelopes), signal (normalised EEG data), time lag limits, sampling rate and 12 regression parameters (12 λ values, $1{\times}10^{-3}{:}1{\times}10^{8}$). The outputs were 12 reconstruction scores per epoch, of which the optimal (highest) r score was used in analysis. The model generated these scores using the “leave one out" computation described in the Methods chapter. See the Methods chapter for figures 2 and 3 which illustrate the procedure of mTRF model computation, and the outcome of reconstruction for a sample sentence.

The reconstruction accuracy scores were then compared across groups, attention status and condition using linear mixed-effect models (Baayen et al., 2008) as implemented in the lme4 R package (Bates et al., 2014). The step function in the lmerTest package (Kuznetsova et al., 2017) was used to arrive at the best-fitting model. The Satterthwaite approximation (Satterthwaite, 1946) was used for degrees of freedom. Significant p-values are reported at $p<.05$. All post-hoc tests were FDR corrected for multiple comparisons.

4.4 Results

4.4.1 Behavioural comprehension scores

Children from both groups performed the task equally well, with overall comprehension scores of 99.5% (SD= .62) in the monolingual group, and 98.9% (SD=2.6) in the bilingual group. To test for any differences between them, responses were coded as binary correct/incorrect and then analysed in a logistic regression model with binary scores as the dependent variable, and factors of group (two levels: monolingual, bilingual), condition (four levels: Single Talker, English-Babble, English-Traffic and English-Music) and their interaction, in addition to participant age, socio-economic status (SES) plus subjects as a random effect. The results showed that the only significant factor was age [X^2 (1, N = 44) = 9.3, p = .0023] and there was no difference in comprehension either by group or by condition.

In addition, Bayesian analysis showed anecdotal evidence (BF_{10}=.532) for the null hypothesis, defined as group effect of 0, in an independent sample t test for overall comprehension scores. A Bayesian repeated measures ANOVA in JASP (version 0.13), with default priors, including the factors of group and condition, and age as a covariate, identified moderate evidence for an effect of age (BF_{10}=7.8). In a subsequent best model assuming the effect of age, there was strong evidence for the null hypothesis for group (BF_{10}=.051). This offers strong support to the conclusion that the groups performed equivalently in the comprehension task.

A summary of comprehension scores and standard deviations are shown in Table 21 and Figure 20.

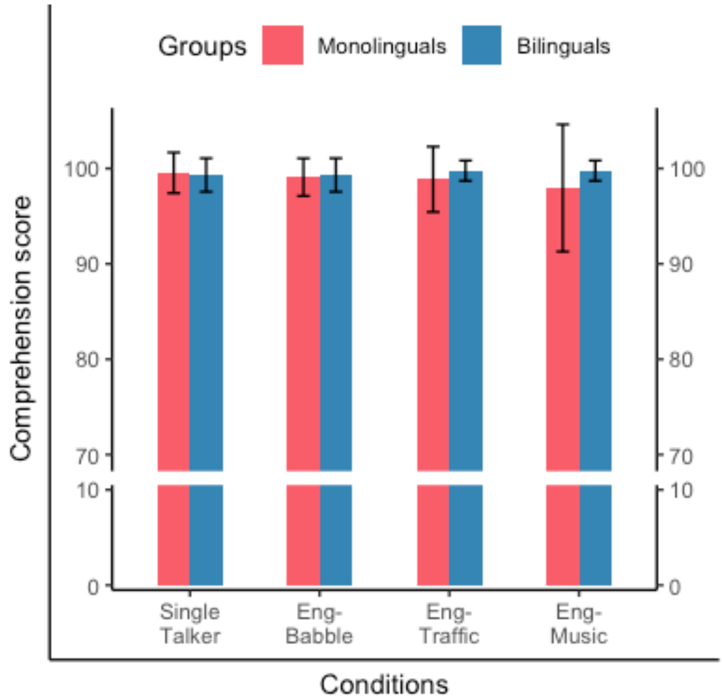
Table 21

Comprehension scores and standard deviation by condition and group

Condition	**Monolinguals**	**Bilinguals**
Single Talker	99.3 (1.76)	99.5 (2.13)
English-Babble	99.3 (1.76)	99.1 (1.97)
English-Traffic	99.8 (1.07)	98.9 (3.43)
English-Music	99.8 (1.07)	98 (6.67)
Overall across conditions	99.5% (.62)	98.9% (2.6)

Figure 20

Comprehension scores and standard deviation by condition and group



4.4.2 EEG Data

4.4.3 The effects of attention on speech reconstruction accuracy

In the analysis of the neural data, datapoints more than 1.5 interquartile ranges above the upper quartile or below the lower quartile were removed as outliers, excluding 157 datapoints (0.5% of the total). Visual inspection of residual plots did not reveal any obvious deviations from normality.

The first analysis of the neural data aimed to establish whether attention modulated speech reconstruction accuracy in children when presented with non-linguistic interference. It included the three conditions where both attended and unattended narratives were presented to the participants (English-Babble, English-Traffic and English-Music); thus excluding the condition where there was no interference (Single Talker). The dependent variable was reconstruction accuracy score, and the fixed factors were group (two levels, monolingual, bilingual), attention (two levels, attended and unattended) and condition (three levels), and the interactions between them. Also included in the model were participant age and parental SES as predictors, and subjects and items as crossed random effects. Contrary to the findings in EEG Experiment 1, results from the model showed no overall effect of attention; however there was a significant effect of condition [F(2, 724.3)=37.1, p<.001, η^2=.73], and significant interactions between condition and attention [F(2, 712.5)=9.3, p<.001, η_p^2=.03] as well as between condition and group [F(2, 25610.1)=3.2, p<.05, η^2=.063].

Post hoc tests investigating the significant effect of condition in the model above found that, for the groups combined, there were significant differences between multiple conditions in the attended and unattended conditions. In the attended conditions, the mean reconstruction accuracy scores for Single Talker and Eng-Traffic were significantly higher than the other conditions; in the unattended streams reconstruction accuracy for English-Traffic was on average higher than either English-Music or English-Babble.

4.4.4 Effect of condition in monolingual and bilingual scores separately

Following the approach taken in analysing EEG1 experiment, to investigate the condition by group interaction, and test how responses might differ between the groups, I next analysed the distribution of reconstruction scores in monolingual and bilingual groups separately. In *monolinguals*, a model including attention (two levels, attended and unattended), condition (three levels) and their interaction, participant age, parental SES, plus subjects and items as crossed random effects showed significant effects of condition [F(2, 721.94)=22.9, p<.001; η^2=.78] and a condition:attention interaction [F(2, 710.94)=6.39, p<.01; η_p^2=.02]. In *bilinguals*, the equivalent model showed a significant effect of condition only [F(2, 727.88)=24.52, p<.001, η_p^2=.06]. Table 22 summarises the scores in language group by condition.

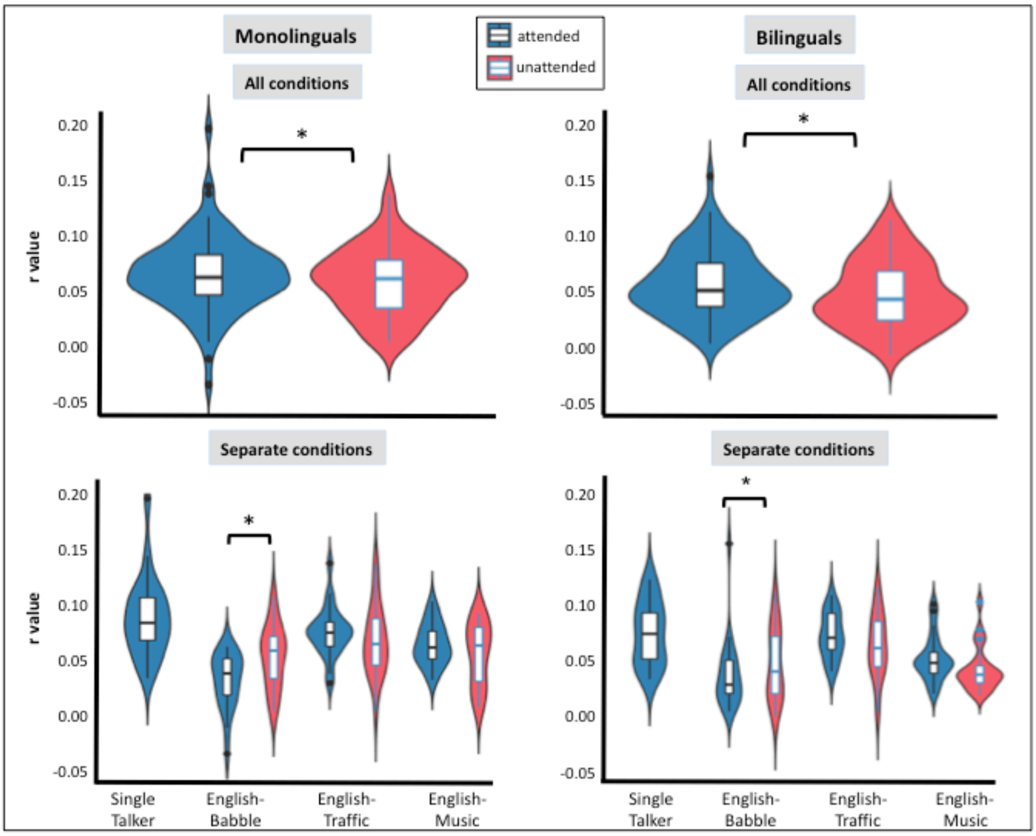
Table 22

Reconstruction accuracy scores for monolinguals and bilinguals by condition

	Monolinguals		Bilinguals	
Condition	Attended	Unattended	Attended	Unattended
Single Talker	.085 (.17)		.073 (.16)	
Eng - Babble	.034 (.16)	.051 (.2)	.032 (.16)	.047 (.19)
Eng - Traffic	.074 (.17)	.067 (.19)	.07 (.17)	.064 (.18)
Eng - Music	.065 (.15)	.054 (.2)	.05 (.16)	.039 (.2)
Overall	.064 (.17)	.057 (.2)	.057 (.16)	.05 (.19)

Figure 21

Attended and unattended reconstruction accuracy scores (r) by condition and group



4.4.5 Reconstruction accuracy of attended streams in monolinguals and bilinguals

A key result emerging from EEG Experiment 1 was the difference in patterns of monolinguals and bilingual groups' reconstruction accuracy scores of attended streams across conditions. This indicated that bilingualism does indeed modulate the neural encoding of attended speech envelopes in children, when ignoring linguistic distractors. To see if this is also true of conditions using non-linguistic stimuli as the distracting stream, I investigated the patterns of reconstruction across attended conditions in each group separately. In *monolinguals*, a model with four levels of attended condition, participant age, parental SES, and subjects and items as random effects, showed a significant effect of condition [$F(3,485.45)=31.1$, $p<.001$, $\eta_p^2=.16$] only, with the post-hoc t tests showing differences in encoding between all attended conditions (the Single Talker condition showing significantly higher encoding than those of English-Traffic [$t=2.04$, $p<.05$, $d=.062$], English-Music [$t=4.18$, $p<.001$, $d=.13$] and English-Babble [$t=10.1$, $p<.001$, $d=.31$]; the English-Traffic condition showing significantly stronger encoding relative to the conditions of English-Music [$t=2.07$, $p<.05$, $d=.06$] and English-Babble [$t=8.19$, $p<.001$, $d=.24$]; and the English-Music condition having significantly higher reconstruction accuracy scores than the English-Babble condition [$t=6.56$, $p<.001$, $d=.19$]).

The equivalent analysis in *bilinguals* showed a comparable, but slightly reduced pattern of differences between conditions, with a significant effect of condition [$F(3,486.24)=21.44$, $p<.001$, $\eta_p^2=.12$], reflecting differences between all attended conditions with the exception of Single Talker and English-Traffic. Hence the Single Talker condition showed significantly higher encoding than those of English-Music [$t=4.83$, $p<.001$, $d=.15$] and English-Babble [$t=8.35$, $p<.001$, $d=.26$]; the English-Traffic condition showed significantly stronger encoding relative to the conditions of English-Music [$t=4.08$, $p<.001$, $d=.13$] and English-Babble [$t=7.52$, $p<.001$, $d=.23$]; and the English-Music condition showed significantly higher reconstruction accuracy scores than the English-Babble condition [$t=3.66$, $p<.001$, $d=.11$]).

4.4.6 Reconstruction accuracy of unattended streams in monolinguals and bilinguals

In both groups, the English-Traffic condition differed from English-Babble and English-Music; with no other differences between conditions emerging. Hence for monolinguals, the English-Traffic condition was significantly higher than both English-Babble ([t=2.78, p<.05, d=.084] and English-Music ([t=2.26, p<.05, d=.067]; and the same pattern emerged for bilinguals with English-Traffic showing significantly higher scores than the conditions of English-Babble ([t=3.03, p<.01, d=.092] and English-Music ([t=4.35, p<.001, d=.13].

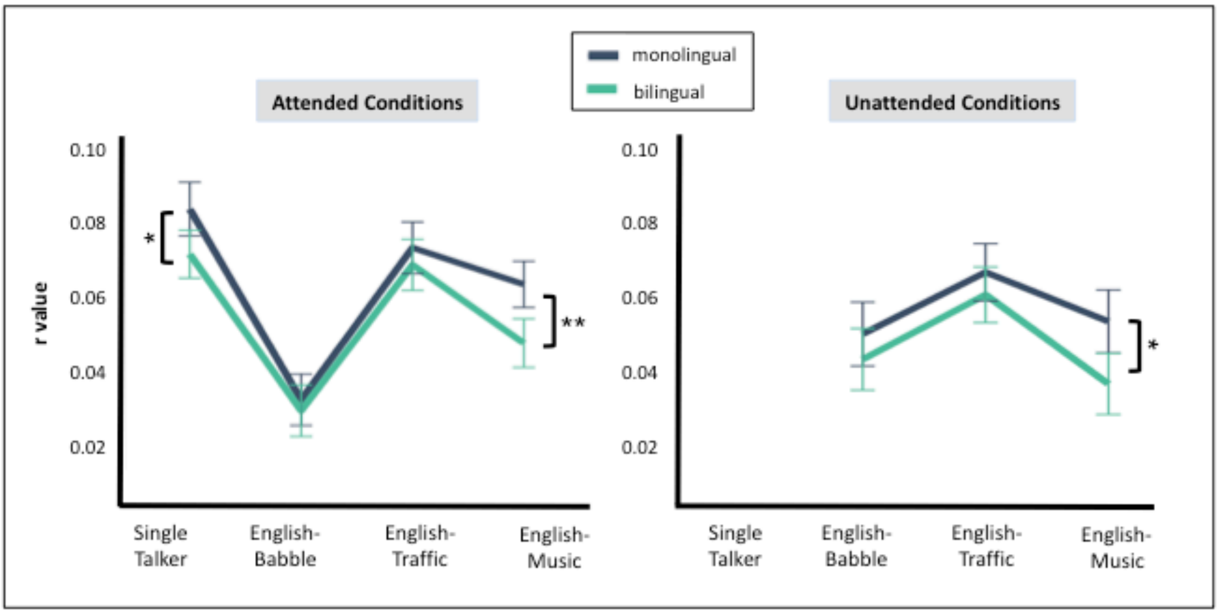
4.4.7 Comparison of scores by condition between groups

One of the key findings from EEG Experiment 1 was significantly higher indices of encoding in conditions of low or no interference in monolinguals relative to bilinguals. To confirm whether comparable effects may be seen in conditions of nonverbal interference, the next analysis directly compared the reconstruction accuracy between the groups in each attended condition separately. These pairwise comparisons for individual conditions showed significantly higher attentional encoding in monolinguals than in bilinguals in the Single Talker and English-Music conditions [t(4359)=2.37, p<.05, d=.072; and t(4426)=3.17, p<.01, d=.095; respectively], but no difference between the groups in the other two non-linguistic interference conditions [English-Babble t(4201)=.4, p=.69; English-Latin t(4413)=.87, p=.51].

This directly replicates the results of EEG Experiment 1, indicating that, despite the similar patterns within groups, monolinguals show higher levels of attentional encoding in Single Talker and English-Music conditions relative to bilinguals. A similar exercise for the unattended streams revealed significantly higher encoding of unattended envelopes in the English-Music condition for monolinguals compared to bilinguals [t(4441)=2.5, *p* <.05, *d*=.075]. The results of differences between the groups for attended and unattended conditions are summarised in Figure 22.

Figure 22

Differences between the groups for attended and unattended conditions



In sum, the results from this study showed that behavioural comprehension scores were equivalent between groups and conditions, replicating the findings in EEG Experiment 1. Regarding the neural data, patterns in the attended reconstruction scores differed slightly between the groups; with monolinguals showing significant variation between all four conditions. Critically however, a direct comparison between attended conditions in the two groups showed significantly lower indices of neural encoding in bilinguals in two of the attended conditions (Single Talker and English-Music) replicating the pattern found in EEG Experiment 1.

4.5 Discussion

Building on the evidence in EEG Experiment 1 that bilingualism modifies the neural mechanisms of selective attention in school-age children performing a dichotic listening task, the current experiment investigated the extent to which this might generalise to conditions of nonverbal interference. Using a variation of the auditory task, I assessed the patterns of responses to different types of non-linguistic interference in monolingual and bilingual children aged 7-12; comparing their behavioural comprehension scores and their cortical tracking of attended and unattended speech envelopes via reconstruction accuracy scores computed by the mTRF toolbox. The participants in both groups displayed equivalent behavioural performance, replicating the results seen in EEG Experiment 1. While the overall effects of attention on neural encoding, evident in Experiment 1, were not confirmed in this study; results nevertheless showed differences in the way monolinguals and bilinguals encoded attended speech, supporting the hypothesis from EEG Experiment 1 that the processing demands of bilingualism shape the supporting neurocognitive architecture (Green & Abutalebi, 2013), and extending the scope of findings from linguistic interference to include non-linguistic interference. More specifically, results again revealed significantly lower indices of selective attention for bilinguals in conditions similar to those observed in EEG Experiment 1 (Single Talker and English-Music). These results present further evidence that instead of enhanced attentional capacity, these neuroadaptive modifications appear to reflect its redistribution, arguably aimed at economising the available resources to support optimal behavioural performance. I discuss these results in more detail below.

In terms of behavioural comprehension scores, the results clearly showed that all children performed the task equally well, with equivalent ceiling scores across groups and stories. None of the distractors interfered with comprehension in the target story, in contrast to the English-English linguistic condition in Experiment 1, which resulted in both the lowest attended reconstruction scores and the lowest comprehension scores. In this study, the lowest attended reconstruction scores were in the English-Babble condition, but this did not impact comprehension, which was comparable to all the other conditions, for both groups.

This is again consistent with the consensus from the literature that the information presented to the attended ear is typically processed accurately (Cherry, 1953;Treisman, 1969). It also aligns with studies that have found equivalent behavioural performance between bilingual and monolingual children performing a non-linguistic selective attention task (Morton & Harper, 2007; Gathercole et al., 2014; Antón et al., 2014). Furthermore, equivalent ceiling performance adds further weight to the view that any observed neural adaptation – caused as a result of the habitual processing demands of an additional language - serves the purpose of facilitating optimal performance. Hence this is consistent with the proposal that any observed bilingual adaptation is in service of a degenerate system, in which structurally diverse components perform the same function or achieve equivalent outcomes.

The analysis of the neural data focused on reconstruction accuracy of speech envelopes in different attended and unattended conditions from the EEG signal, an established index of neural tracking. As reviewed in the Methods chapter, both children and adults typically encode speech through synchronisation of cortical activity to the temporal oscillations of the speech envelope (Obleser & Kayser, 2019; Lalor & Foxe, 2010). This relationship between signal and speech envelope has been calculated previously using linear cross-correlation (Olguin et al., 2018); however, consistent with EEG Experiment 1, I used the stimulus reconstruction approach implemented in the mTRF toolbox (Crosse et al., 2016). This method has been established in the literature (Power et al., 2016; Kalashnikova et al., 2018; ; Attaheri et al., 2020, Phelps et al. 2022), as a reliable index of neural tracking which offers enhanced sensitivity to all neural input simultaneously.

4.5.1 The role of attention

The synchronisation between cortical activity and speech envelopes is widely assumed to be influenced by selective attention, with numerous studies (including EEG Experiment 1) showing preferential tracking of the attended stream over the ignored one (Rimmele et al., 2015; Horton et al., 2014). In contrast to the literature and EEG Experiment 1, the results for this study showed a weak effect of attention, and even one condition (English-Babble) in which the unattended reconstruction accuracy scores were significantly higher than the ones shown for the target narrative in English. One possible explanation of these anomalous results is that preferential encoding, linked to intelligibility (Millman et al., 2014; Peelle et al., 2013), is necessary in conditions of linguistic interference, such as a classic cocktail party design, but may not be a prerequisite of processing the attended stream when the stream to be ignored is non-linguistic. Indeed, there was no reduction in comprehension scores in the Babble condition despite the apparent preferential tracking of the unattended stream. What is more, the Babble stimulus, although selected as an example of nonverbal noise, could be reasonably characterised as an exception as it contained the (unintelligible) speech of multiple talkers, which is not only derived from linguistic sources, but also widely recognised as "one of the most challenging noise interference for all speech systems" (Krishnamurthy & Hansen, 2009), a challenge which increases with the number of speakers featured (McAuley et al., 2020; Pollack & Pickett, 1958) and is arguably extremely difficult for school-age children to ignore irrespective of cognitive ability (Nagaraj et al., 2020). This makes it in some respects analogous to the English-English condition in EEG Experiment 1, which also generated the lowest reconstruction accuracy scores in the attended stream for both groups. However, comprehension suffered in EEG Experiment 1 in the English-English condition relative to the other conditions, whereas in this study comprehension in all conditions was equivalent, including the English-Babble condition.

However, another possible explanation for these inconsistent results, which do not conform to the usual effect of attention, might be to do with the issues with the acquisition of data for this second EEG experiment. Due to the restrictions enforced during the Covid-19 pandemic, data acquisition was severely disrupted with a substantial gap in the recruitment and testing of participants between March 2020 and July 2021. Furthermore, once testing resumed in 2021, it was conducted in a different EEG suite, with alternative equipment (albeit of similar specification). These disruptions may have impacted the uniformity of the EEG data collected, making it inherently noisy.

4.5.2 Encoding across conditions

In further comparisons with EEG Experiment 1, analysis of the patterns across conditions again showed that attentional encoding across conditions differed between the monolingual and the bilingual children. In the monolingual group in Experiment 1, a prominent contrast between all four attended conditions was observed; yet this effect was somewhat attenuated in the bilingual group (Chapter 4, Figure 8). The differential patterns of encoding in monolingual and bilingual listeners observed in the current study replicates not only the results from EEG Experiment 1 (Phelps et al., 2022), but also the results found in adults (Olguin et al., 2019), adding further support to the hypothesis that bilingualism modifies the neural mechanisms of selective attention across the lifespan (Comishen et al., 2019; Krizman et al., 2014; Garbin et al., 2010). In the Introduction, I presented two accounts that might explain the possible mechanisms of this modification. The first was that the need for constant management and inhibition of competing languages in bilinguals enhances their capacity for selective attention, resulting in better performance and increased attentional control (Bialystok, 2015). The second was that these demands of selection and inhibition will themselves utilise some of the existing attentional resources, which might impact on the available attentional capacity and require that the remaining resources are optimised in order to achieve full task performance. The results of the current study again showed no evidence for the enhanced attentional capacity, behaviourally or neurally, in the bilingual group. In contrast, results showed weaker neural encoding in bilinguals overall for both attended and unattended streams in Experiment 2 (r_{attd}=.057 for bilinguals vs r_{attd}=.064 for monolinguals; and r_{unattd}=.0499 for bilinguals vs r_{unattd}=.057 for monolinguals), differences which were statistically significant [overall attended scores between groups: $t(17577)=3.07$, $p<.01$, $d=.046$; overall unattended scores between groups: $t(13226) = 2.23$, $p<.05$, $d=.039$]. This is consistent with the findings in EEG Experiment 1 for significantly weaker bilingual scores, relative to monolinguals, in both attended and unattended conditions (see Chapter 4 for detailed analysis). As noted before, the observed indication of reduced cortical encoding overall in bilinguals is not without a precedent, with examples of reduced neural activity during nonverbal selective attention tasks most commonly seen in the cortical areas associated with conflict processing. Lower patterns of activation have been observed in bilinguals performing a Flanker task (Abutalebi et al., 2012), Stroop-like switching task (Garbin et al., 2010), Simon task, and both of the tasks above with the addition of the Simon task (Kousaie & Phillips, 2012). These observations led the authors to conclude explicitly that the bilinguals were resolving the demands of the tasks with less neural resource (Abutalebi et al., 2012).

Of additional note, in EEG Experiment 1 comparison of the groups' pattern of response showed that significant differences between their reconstruction accuracy scores of attended streams occurred in the conditions of no interference (Single Talker) or low interference (English-Musical Rain). In this study, a similar trend was observed for significantly different reconstruction accuracy scores between the groups in the conditions of Single Talker (no interference) and English-Music. In Experiment 1, the significant differences between the groups in the Single Talker and English-Musical Rain conditions were interpreted as an adaptation in the conditions of lowest interference, and hence easiest comprehension; in which the bilingual's more limited capacity processor could economise attention without compromising comprehension; whereas the monolingual attentional system, with greater bandwidth, would have no such need for economisation.

Clearly the Single Talker condition in EEG Experiment 2 can also be defined as a low interference condition, being exactly the same as the condition presented in EEG Experiment 1. However, it is also plausible that Music represented a low-interference stream, making it analogous to the Musical Rain condition in EEG Experiment 1. First, the melody selected for the Music condition was highly predictable and rhythmic. Not only is there evidence that neural oscillations synchronise with the pulse-rate of music in addition to the rhythms and stress-rate of speech (Haegens & Zion Golumbic, 2018), even when these rhythms are below the perceptual threshold (Oever et al., 2017); but that altered background rhythm in an interference stream has been found to facilitate entrainment and improve comprehension of a target speaker stream (McAuley et al., 2020). Second, the melody was in a major key and a 'feel-good' tune. There is evidence from fMRI (Fernandez et al., 2019) that background music which is happy and high-arousing enhances attention through greater activation of fronto-parietal regions and improved performance in attention tasks, whereas sad and low-valence music elicits slower responses and greater occipital recruitment. Both of these factors support a proposition that the music selected for this task would contribute towards an enhanced attentional capability in the target stream notwithstanding any other constraints. This would explain why monolinguals showed elevated indices of neural attention in both the attended and unattended streams of this condition, relative to bilinguals.

However, EEG Experiment 1 also posited that the linguistic conditions of English-English and English-Latin generate equivalent reconstruction scores between the groups precisely because they cause stronger interference. The two conditions in this study (English-Traffic and English-Babble) with a similar effect on scores cannot be said to be analogous to linguistic interference spoken by a single voice. It could be argued that Babble is derived from linguistic sources and is therefore the most similar interference stream to the linguistic distractor streams in EEG Experiment 1 and thus similarly generates the lowest reconstruction accuracy scores for the attended stream.

Another interpretation, however, is based on the inherent content and structure of the Babble and Traffic streams, which are continuous environmental sounds devoid of rhythm or predictability. As discussed above, rhythm enhances entrainment; it is plausible that a non-rhythmic and unpredictable stream of interference actively diminishes it. This explanation, however, only works in the context of the differences between the groups' scores and does not resolve the finding that reconstruction accuracy scores for the attended stream in the English-Traffic condition are higher in each of the groups than the scores for the target stream in the English-Music condition. One reason for this unexpected finding could be that children are instructed to be on high alert for traffic noise from an early age, but this explanation is as yet lacking in evidence and may not be entirely convincing.

The final set of findings concerned the pattern of reconstruction accuracy scores seen for the unattended streams. These results showed that, in both groups, the unattended Traffic stream was significantly better reconstructed than the unattended Babble and Music streams, similar to the pattern found in the attended streams. In addition, the Music stream encoding was significantly stronger in the monolingual than in the bilingual group. This second result again replicates the finding in EEG Experiment 1 where there was a significant difference in the groups' unattended scores for the English-Musical Rain condition.

In sum, the current study extended the investigation in EEG Experiment 1 - which explored the mechanisms underlying the modification of selective attention in bilingual children – by adding nonverbal interference to the unattended stimuli that participants were asked to ignore. Again, equivalent behavioural performance was observed and there was no evidence for enhanced attentional capacity in the bilingual group. Results in EEG Experiment 1 revealed a modified pattern of neural encoding that showed significant differences between the groups in conditions of weak or no interference. This study also showed significant differences in the condition of no interference, replicating the results from EEG1, and the condition of rhythmic interference, which arguably enhances encoding of the target stream (McAuley et al., 2020), and represents the nonverbal interference most similar to the stimulus of Musical Rain used in EEG Experiment 1. Therefore these data are interpreted as supporting the conclusion of EEG Experiment 1 that the available resources are economised to support optimal behavioural performance; potentially suggesting increased flexibility of their usage in response to the demands of bilingual language processing. This account is consistent with theories of degeneracy (Navarro-Torres et al., 2021), in which different patterns of neural processing still lead to equivalent behavioural outcomes.

Furthermore, this study showed that the effects observed in EEG Experiment 1 – of equivalent comprehension, lower indices of attentional resource in bilinguals, and different patterns of tracking in the attended streams – are not only applicable in dichotic listening tasks using speech and linguistic interference; but that similar, but attenuated, patterns can be observed when the interference streams are entirely non-linguistic. This aligns with other studies, which have found evidence of modification to the bilingual attentional system when performing nonverbal tasks (Luk et al., 2010; Kousaie & Phillips, 2012; Bialystok et al., 2005; Abutalebi et al., 2012). In this study, however, the distractors used were naturalistic environmental sounds that children of this age group encounter in everyday life, making the study ecologically valid and differentiating it from the designs featuring manufactured nonverbal tasks (Simon, Flanker, ANT etc.) which have typically been used. Hence this study confirms, using naturalistic non-linguistic stimuli, that modification to neural processing in bilinguals as a result of linguistic demands, generalises beyond the linguistic domain and can be observed in nonverbal tests of selective attention.

Chapter 7: Summary and Conclusions

The research presented in this thesis aimed to address three distinct but interrelated research questions:

1. Establish whether neural and behavioural modifications triggered by bilingualism are discernible in childhood.
2. Determine if the increased processing demands of bilingualism enhance attentional capacity, or lead to an economisation of limited attentional resource, in order to optimise performance; and examine any influences exerted by maturation and language experience.
3. Investigate the effect of these modifications on behaviour beyond the language domain.

In this concluding chapter I review the results of all the experiments and draw overall conclusions on the effects of bilingualism on selective attention and influence of maturation and language exposure. I also compare the findings to some of the studies presented in Chapter 2 to assess where this research fits with the broader literature. Finally, I suggest theoretical implications and future directions.

7.1 Neural and behavioural modifications to selective attention in bilinguals – summary of findings and conclusions

The aim of the research in this thesis was to investigate the effects of bilingual modifications to selective attention, in a series of behavioural and neural experiments, with children and adults, using linguistic and nonverbal stimuli, in auditory and visual domains. Each of these variations was based on the same core assumptions. The first was that the additional processing demands of bilingualism (due to parallel activation, Green, 1998), lead to neuroplastic change, which has been documented across the lifespan (Bialystok, 2017; Kovács & Mehler, 2009; Poulin-Dubois et al., 2011; Costa et al., 2008). The second was that bilingualism specifically influences the neurocognitive architecture of selective attention, with an effect on attentional processing (Olguin et al., 2019; Garbin et al., 2010) across tasks ranging in complexity, but with conflicting evidence on the behavioural consequences of these neural adaptations. The third is that these attentional modifications take place in the context of finite selective attention capacity, i.e., a limited pool of attentional resources (Kahneman, 1973), which can only process a restricted amount of information at any given point (Broadbent, 1965; Clark & Dukas, 2003).

7.1.1 Experiment 1

The first experiment, addressing research question 1), and described in Chapter 4, investigated neural tracking of natural speech under different conditions of linguistic and non-linguistic interference, for monolingual and bilingual children. The accuracy of neural tracking was computed by correlating the EEG response with the attended and unattended speech envelopes, using the mTRF toolbox (Crosse et al., 2016), resulting in reconstruction accuracy scores per participants, per sentence in each condition. In each condition, the target stream was a narrative in English. Distractors ranged in intelligibility (no stream; competing narrative in English; competing narrative in unknown language (Latin); and acoustic stream (Musical Rain). Behavioural performance was also measured through comprehension scores of each target narrative. Behavioural performance was equivalent between the groups. Neural results substantiated the ‘selective entrainment hypothesis’ (Schroeder & Lakatos, 2009; Zion Golumbic et al., 2013; Giraud & Poeppel, 2012b) with robustly higher scores for attended than unattended streams in all conditions across both groups. Additionally, responses varied according to the type of interference presented, also consistent with the existing literature (Olguin et al., 2018; Har-shai Yahav & Zion Golumbic, 2021).

Most importantly for the questions in this thesis, monolingual and bilingual participants showed different patterns of neural tracking of the attended stream, with monolinguals displaying substantially more variability between attended conditions, and higher scores overall. The bilingual pattern of reconstruction accuracy scores for attended conditions, by comparison, was lower and flatter. These results suggest three conclusions: first, that modifications as a result of bilingualism affect auditory selective processing in the developing brain before continuing into adulthood (Olguin et al., 2019 found similar patterns in adults). Secondly, the lower and flatter scores for bilinguals arguably represent a reduced measure of selective attention, raising the possibility that the management of another language limits overall capacity (Wickens, 2007; Dornic, 1980). Crucially, this did not affect comprehension scores, which were equivalent between the groups. Therefore the third conclusion is that any modifications to neural processing occur in order to mitigate the limitations in attentional capacity that occur as a result of bilingualism, and support optimal performance. This equivalent performance, despite different neural patterns, is an example of degeneracy, in which structurally different components generate comparable outcomes (Navarro-Torres et al., 2021).

7.1.2 Experiment 2

The second experiment, addressing research question 2), and described in Chapter 5, built on the conclusions of Experiment 1, by testing how the bilingual processing system adapts when the demands of a task increase, and seeing if performance across tasks reveals any more about the economisation and prioritisation of attentional resource.

The study used a modified version of the listening task from Experiment 1 (with the same conditions of interference), coupled with a simple visual task (T.O.V.A.), in a dual-task paradigm, designed to stretch attentional load beyond the boundaries of a typical primary task. The intention was that, by increasing the processing demands in a controlled way, results would reveal if there are any indicators of additional interference in the bilingual group, as well as the expected PRP (psychological refractory period, a well-documented delay as a result of simultaneous task processing) for all participants as a result of the "central bottleneck" (Pashler, 1994). The prediction was that performance in the primary (auditory) and secondary (visual) task would reveal any prioritization of attention to competing task demands. Such additional demands might disproportionately affect bilinguals, with reduced attentional capacity due to managing their additional language processing demands. This reduction in attentional capacity might cause bilinguals to prioritise and economise their responses to competing task demands, to maintain task performance.

In order to assess effects across age groups and language experience, I recruited three groups spanning age ranges and L2 exposure, with one group of school-age children (Study 1, age range 7-12), and two groups of adults (Studies 2 and 3, age range 18-45), who were differentiated by exposure to L2 (English). Study 2 recruited a high-exposure bilingual group and Study 3 a low-exposure bilingual group, as well as monolingual adults matched by age in both studies.

Consistent with Experiment 1 (Chapter 4), the results showed equivalent performance in the auditory (primary) task between monolingual and bilingual participants, across all three studies. In addition, accuracy in the visual task, measured by error rates, was extremely high and equivalent between monolingual and bilingual participants, in all studies.

Reaction times from the visual task, however, revealed significant differences in speed (but not accuracy) between conditions, age groups and language groups. As expected, all groups showed a psychological refractory period (PRP), the delay produced as a result of processing competing task demands, when the auditory task was added to the visual task. Thus the Control condition (visual only) was significantly faster for all groups of participants across all three studies, confirming a robust psychological refractory period (PRP), consistent with the literature (Pashler, 1994).

In addition, bilingual children's reaction times were significantly slower relative to monolingual children's in all the dual-interference conditions (reaction times for children were equivalent in the Control condition, which was the visual task alone). This result, however, was not replicated in either of the adult groups, with both the high-exposure and low-exposure bilinguals showing statistically equivalent performance to their monolingual counterparts in both the primary (auditory) and secondary (visual) tasks, with one exception (Musical Rain interference), in which low-exposure bilinguals were faster than their monolingual peers in the visual task. When the high and low exposure bilingual adults were compared directly, however, differences emerged between them, revealing that across every single dual interference condition, low-exposure bilinguals were significantly faster than high-exposure bilinguals.

These results suggest the following conclusions: In children, the constraints on attention as a result of bilingualism appear to cause an economisation and prioritisation of attentional resource to meet a hierarchy of demands - in this case comprehension in the auditory task, and accuracy in the visual task - at the expense of speed in the visual task. In adults, however, any such limitations are overcome with maturation, resulting in equivalent performance between monolingual and bilinguals adults across all tasks, even ones that exceed 'typical' processing demands (Moray, 1967; Gopher, 1986). Nevertheless, comparisons of the two groups of adult bilinguals with differing language experience suggest that the effect of maturation on selective attention proposed above is enough to close any gap between monolingual and bilingual speakers; but that there is still some residual processing cost for high-exposure bilinguals that, although not apparent relative to monolinguals, is exposed in a statistically significant reduction in speed of response when compared to low-exposure bilinguals who do not face the same daily processing demands.

These findings add more nuance to the conclusions from Experiment 1 by suggesting a developmental trajectory for bilinguals in a dual-task paradigm. Results suggest that apparent limitations of attentional resource, while still not impacting on the primary task, are shown in scores of the secondary task, in conditions of dual interference in children. Importantly, however, these effects on response times withdraw as the attentional system fully matures. In addition, this also adds more nuance to the conclusion in Experiment 1 that bilingualism creates a degenerate attentional system. Results from Experiment 2 indicate that there is a difference between performance in a primary task and dual task in childhood. Thus, findings indicate behavioural performance on a *primary* task is indeed equivalent from childhood (as concluded from Experiment 1 and the sample of children in the dual task experiment). However, the results from Experiment 2 also suggest that attentional systems impacted by bilingualism may not reach equivalence under the increased demands of *dual tasks*, which extend beyond a normal processing load, until adulthood. Importantly, this occurs when the prefrontal cortex associated with selective attention processing is fully mature (Giedd et al., 1999; Gogtay et al., 2004; Sowell et al., 2001; Tsujimoto, 2008).

Additionally, however, comparison between bilinguals with different language exposure reveals some residual processing constraints (shown in reaction times in the secondary task), which although not large enough to differentiate bilinguals significantly from monolingual peers, are large enough to differentiate high and low exposure groups of bilinguals. In fact, low-exposure bilinguals showed the overall fastest reaction times of all the language groups across all the cohorts in Experiment 2. This result of low-exposure L2 speakers outperforming high-exposure bilinguals has precedent in the literature, for example in a study comparing monolinguals, fully immersed language learners and classroom learners, the classroom learners outperformed both the monolinguals and immersed language learners in tasks of inhibitory control, such as the Simon task (Linck et al., 2008). Additionally, greater L2 proficiency was associated with worse inhibitory control, confounding the anticipated outcome that greater proficiency and immersion would lead to better inhibitory control. In Experiment 2 of my thesis, the high-exposure bilinguals could also be categorised as immersed bilinguals, as they were all recruited as UK residents but with L1 in a language other than English. Hence they had daily exposure (full immersion) to their L2 (English). In the conclusions for Experiment 2 at the end of Chapter 5, I suggested that the fact that low-proficiency bilinguals outperformed their monolingual and high-proficiency peers might be used as an incentive in educational settings to promote learning a second language to a reasonable degree of proficiency, which will yield benefits in selective attention tasks with multiple demands even when the L2 will not subsequently be used on a frequent basis. Similarly, in the study of immersion and proficiency of L2 described above (Linck et al., 2008), the authors conclude that “even L2 learners with a late age of acquisition may benefit cognitively from learning the L2”.

7.1.3 Experiment 3

The third experiment, addressing research question 3), and described in Chapter 6, replicated the design and target sample of Experiment 1, but changed the interference conditions to exclusively non-linguistic streams, in order to assess whether the same patterns of attentional processing emerge for monolingual and bilingual children in a non-verbal context. Only one of the conditions was the same as in the first study (Single Talker) and the others were changed to naturalistic environmental sounds that would be encountered by a typical school-aged child (traffic, classroom babble and music). Once again there was no difference in comprehension by language group. However, there was no confirmation of the ‘selective entrainment hypothesis’, with scores for attended and unattended streams equivalent except in the English-Babble condition in which children showed significantly higher scores for the *unattended* stream (classroom babble) than for the attended narrative in English. Critically, this did not affect comprehension, which was as accurate for both groups in the English-Babble condition as for the narratives in all other conditions. One interpretation of this finding is that children find classroom chatter extremely distracting (as teachers can attest, but also confirmed by Krishnamurthy & Hansen, 2009 and Nagaraj et al., 2020), but have developed cognitive strategies to overcome this specific interference and maintain optimal comprehension.

In similar patterns to Experiment 1, bilinguals showed less variation across the conditions relative to monolinguals, and significantly lower scores for both attended and unattended conditions overall. When examining attended conditions specifically, bilinguals had significantly lower scores than monolinguals in two conditions (Single Talker and English-Music) which were either the same or similar to the attended conditions with largest differences between the groups in Experiment 1 (Single Talker and English-Musical Rain). This significant disparity between the groups is interpreted in both EEG Experiment 1 and behavioural Experiment 2 as bilinguals' economising attentional resource in the conditions of lowest interference (and hence easiest comprehension); with such redistribution unnecessary for monolinguals whose attentional system is not constrained by the demands of an additional language. In this context, music was explained as a lower interference than traffic or babble due to its inherent rhythmic and predictable qualities.

Notwithstanding the above, in the conditions of interference, the highest attended and unattended scores for both groups were in the English-Traffic condition. This was a puzzling result, with a tentative explanation that children might be primed to pay extra attention to all stimuli when encountering traffic in real life.

The results from Experiment 3 suggest the following conclusions: Bilingual children display consistently lower indices of attentional encoding in non-verbal as well as linguistic conditions of interference, adding further evidence to the hypothesis that attention is constrained and economised in bilinguals, but redistribution enables optimal (equivalent) behavioural performance. Furthermore, equivalent performance despite disparities in neural indices further corroborates the account that bilingualism creates a degenerate system capable of supporting optimal behaviour from its neural modifications. Finally, the similar patterns of results in EEG Experiments 1 and 3 indicate that neural modifications are not only apparent for cases of linguistic processing but are also applicable in (this design, naturalistic) non-verbal contexts. There was also the anomalous finding of a lack of preferential tracking of the attended stream (and even preferential tracking of the unattended stream in the English-Babble condition). One possible interpretation of this finding is that the 'selective entrainment hypothesis' may only be applicable to competing speech streams as it was not corroborated when the streams were non-linguistic. However, it must also be noted that a key limitation of this study was the extensive interruption when collecting data, due the national lockdown during the Covid-19 pandemic, which not only affected the timeline of this study but the location and equipment used. These disruptions may have contributed to some of the inconsistent results.

Overall, however, Experiment 3 corroborated the key conclusions from Experiment 1 and Experiment 2. Therefore, the overall conclusions across all three experiments can be summarised as: bilingual children and adults display equivalent behavioural performance in a primary task across both linguistic and non-verbal contexts. Bilingual children, meanwhile, show lower and flatter patterns of neural activation, indicating attentional constraints as a result of managing an additional language. These neural disparities do not affect optimal performance, indicating a degenerate system. However, when the processing load is increased, bilingual children show performance disparities, relative to monolinguals, in the elements of the task with the lowest priority. These disparities disappear by adulthood, although some differences remain between bilinguals with different language exposure, indicating differential adaptation of attention in bilinguals, according to maturation and language experience.

7.2 Conclusions in the context of the literature

The conclusions above are relevant to the current discourse in the field of bilingualism and selective attention, with many aspects either being consistent with, or building on, findings from some of the studies in the literature reviewed in Chapter 2. I will take each of the conclusions and in turn, and compare or contrast to relevant findings in the literature:

1. *Bilingual children and adults display equivalent behavioural performance in a primary selective attention task across both linguistic and non-verbal contexts*

Despite the assertion that bilingualism creates a 'bilingual advantage' in both linguistic (Kaushanskaya & Marian, 2009; Antoniou et al., 2015; Canbay, 2011; Filippi et al., 2015) and non-linguistic tasks (Kovács & Mehler, 2009; Poulin-Dubois et al., 2011; Costa et al., 2008; Bialystok et al., 2012), there is also ample evidence of equivalent behavioural performance across the lifespan (Filippi et al., 2020; von Bastian et al., 2016; Samuel et al., 2018; Jones et al., 2021; Nichols et al., 2020).

The equivalent comprehension scores in the dichotic listening task used as the primary task in this thesis were replicated across five studies (two EEG experiments and three behavioural dual task studies), four of which used linguistic interference, and one non-verbal. The results contrast with studies featured in the Literature Review such as the sentence comprehension test (Filippi et al., 2015) and tones in noise study (Krizman et al., 2017), which both found behavioural differences between monolinguals and bilinguals under different conditions of interference in a listening task (albeit different designs). However, other dichotic listening tasks have also revealed no behavioural differences between monolinguals and bilinguals

(Oliveira et al., 1997) in different age groups (Desjardins et al., 2020). A related design combining auditory comprehension and visual interference, accuracy in a listening and picture naming task (Blumenfeld & Marian, 2011), revealed no difference between the language groups when listening to words and ignoring the interference of visual cues. These inconsistencies may reflect that, as presented in the Literature Review in Chapter 2, factors such as language exposure, age of acquisition, proficiency and language similarity have influenced studies' results. All of the children recruited across all three experiments for this thesis had a similar language profile: all were highly proficient early bilinguals who spoke English at school and a different language at home. The adults, however, differed by language profile and still maintained the same comprehension. One additional consideration is that the dichotic listening task was designed to be engaging and comprehensible, using children's stories, as opposed to designs using tones in noise (Krizman et al., 2017) or syntactically challenging sentences (Filippi et al., 2015). Thus the participants in these studies equated on behaviour in a design more akin to natural speech.

One consequence of using a highly naturalistic and engaging story with simple comprehension questions, was that behavioural performance was consistently extremely high and averaged 98.42% for monolinguals and 98.44% for bilinguals across the five studies. The auditory behavioural scores therefore are not normally distributed and represent behavioural performance at ceiling. My method of analysis of comprehension scores took this into account, by using a glmer model analysis in R, with binary scores as the dependent variable and factors of group, condition, age SES and subjects as a random effect, in order to provide detailed insight of any variance within this upper range.

One finding that emerged from these analyses was significantly lower comprehension scores in the English-English condition in Experiment 1, demonstrating the relative difficulty of ignoring the distractor in this condition. What is more, this mean decline in comprehension scores was experienced equally across both language groups, indicating that the processing of competing known languages was equivalently effortful for both monolingual and bilingual speakers. Importantly, the variability of scores in this condition did not correlate with age ($r=.15$; $t=1.06$; $p=.29$).

There is clearly a possibility that a more difficult comprehension task would have revealed more variance in scores across conditions. However, a more difficult comprehension test would have arguably also made more demands on working memory or lexical retrieval than on comprehension. The development of working memory is highly correlated with age for children until adolescence (S. E. Gathercole et al., 2004). Given that in all studies the task was administered to children as young as 7, it is plausible that any increase in task difficulty would reveal a performance variable with age, rather than provide insights into processing differences due to language background. Similarly, a potentially poorer performance by bilinguals that might have arisen in a more difficult task could have emerged due to problems with lexical retrieval and limitations in bilingual vocabulary, or the "distributed characteristic" (Oller et al., 2007; Pearson et al., 1993) rather than differences in processing per se. As it would have been difficult to isolate comprehension from working memory and lexical retrieval on a more difficult task, especially in the 7-12 age range, the originally designed task has arguably proved to be valid and informative for the questions I aimed to assess.

2. *Bilingual children show lower and flatter patterns of neural encoding, indicating attentional constraints as a result of managing an additional language.*

The results in Experiment 1 and Experiment 3 of different patterns of response in attended conditions for bilinguals and monolinguals are consistent with an associated study with an adult sample (Olguin et al., 2019). This study, based on a dichotic listening task with different levels of interference, also found greater variability in monolinguals' correlation to the attended stream, while bilinguals showed a much flatter pattern with comparable levels of neural tracking in all attended conditions. In other study designs, lower measures of attentional encoding overall in bilinguals have also been observed, with examples of reduced neural activity during various selective attention tasks, observed predominantly in the cortical areas associated with conflict processing. Functional imaging during a Flanker task performed by bilinguals and monolinguals (Abutalebi et al., 2012) revealed significantly lower patterns of activation in the anterior cingulate cortex (ACC) for bilinguals, leading the authors to conclude that 'bilinguals…resolve cognitive conflicts with less neural resource'. A similar fMRI study of a Stroop-like switching task (Garbin et al., 2010) also found that monolinguals activated the ACC during the task, whereas bilinguals did not. An ERP study tracking bilingual and monolinguals' neural responses during a variety of selective attention tasks (Kousaie & Phillips, 2012), predicted superior performance (greater accuracy and faster reaction times) and larger N2 amplitudes for bilinguals relative to monolinguals. On the contrary, behaviour was equivalent between the two groups; and the monolingual group exhibited larger N2 amplitudes than the bilingual group during the Stroop task. In the Simon task, expectations were reversed when monolinguals demonstrated larger P3 amplitudes than bilinguals. In the Flanker task, higher ERN (error-related negativity) amplitudes for bilinguals than monolinguals, instead of corroborating enhanced cognitive control, were due to a longer tail for incongruent trials, indicating a prolonged post-response conflict and slower recovery for bilinguals in these trials.

Another study used fMRI to measure brain activity in passive listening and picture-naming tasks with two groups: monolinguals and early highly-proficient bilinguals (Palomar-García et al., 2015). The fMRI results revealed that monolinguals and bilinguals displayed different patterns of activity, leading to the conclusion that monolinguals were displaying more efficient use of language networks because bilinguals 'utilised a more distributed network, which may imply subtle processing disadvantages' (Palomar-García et al., 2015). Such a conclusion is analogous to the lower indices of attentional encoding in the EEG studies of Experiments 1 and 3 being interpreted as evidence of attentional constraints due to greater demands on bilingual attentional resource. In sum, the interpretation of lower attentional resource is consistent with accounts of lower activation, flatter amplitudes and more distributed processing, from other neural studies.

3. *These neural disparities occur alongside optimal behavioural performance, indicating a degenerate system*

There are several examples in the literature of equivalent performance despite neural differences between monolinguals and bilinguals. Once again, the dichotic listening study coupled with EEG (Olguin et al., 2019) showed the same result with adults. Other examples include the MEG study to investigate neural differences for a group of monolinguals and two groups of bilinguals performing a Simon task (Bialystok, Craik, et al., 2005). The behavioural results of the Simon test showed no difference between the groups, and analyses of the MEG data showed activity in the left and medial prefrontal areas for all three groups. However, the two bilingual groups showed activity in selected left hemisphere regions, whereas the monolingual group showed activity in the middle frontal regions. This finding was replicated in other tasks such as the flanker (Luk et al., 2010) which used fMRI data to compare activation. Although there was no significant difference between the language groups' response times, a difference was found in the pattern of neural activity between the groups. Similar studies using ERP (Kousaie & Phillips, 2012) (Kousaie & Phillips, 2017) found no behavioural bilingual advantage in groups of young adults in the Stroop, flanker and Simon tasks; and no difference in groups of young and older adults in the Stroop task, but ERP data (2017) revealed different patterns of activation for monolinguals and bilinguals in the tasks.

As per the parallel drawn in the Literature Review chapter, these neural differences in spite of equivalent behavioural performance are also demonstrated in the influence of environmental variables other than bilingualism. SES is a prime example, with a study showing equivalent behavioural performance (comprehension) in a listening task but different magnitudes of response to attended and unattended probes according to groups of higher or lower SES, when age was matched (Hampton Wray et al., 2017).

The above examples – of comparable performance despite neural differences – are examples of how environmental variables create degenerate systems. As discussed in the Introduction, degeneracy in the scientific definition comprises structurally diverse components leading to the same output or performing the same function, arguably a desirable characteristic, making systems robust and enabling natural evolution (Whitacre & Bender, 2010; Edelman & Gally, 2001). Degenerate systems are functionally plastic (Mason et al., 2015), therefore the neuroplastic changes effected by bilingualism can be seen as the formation of a degenerate system (Green et al., 2006; Mason et al., 2015; Navarro-Torres et al., 2021). One interpretation discussed in the preceding chapters is that the neural modifications generated by bilingualism may exist precisely in order to overcome the attentional constraints imposed by the management of the additional language and hence create a system that, while showing structural or processing differences, achieves full behavioural performance.

4. *However, when the processing load is increased, bilingual children show performance disparities, relative to monolinguals, in the elements of the task with the lowest priority.*

There does not appear to be a precedent in the literature comparing monolingual and bilingual children in a dual task paradigm. All the examples cited in Chapter 5 feature adult samples and show inconsistent results, some attributed to poorer lexical access in bilinguals. Therefore this represents a wholly new finding and interpretation.

5. *These disparities disappear by adulthood, although some differences remain between bilinguals with different language exposure, indicating differential adaptation of attention in bilinguals, according to maturation and language experience.*

There are many studies in the literature indicating differences in bilingual performance as a result of variables such as age of acquisition, proficiency or language exposure, usually revealing that early, highly-proficient bilinguals or those fully immersed, show higher performance across age groups (Durand López, 2021; Bonfieni et al., 2019; Struys et al., 2015; Kaushanskaya & Marian, 2007). In this study, however, low-exposure bilinguals outperformed high-exposure bilinguals in response times to the visual task. This does have some precedent in the literature, namely the study described above comparing monolinguals, fully immersed language learners and classroom learners (Linck et al., 2008), in which the classroom learners outperformed both the monolinguals and immersed language learners in tasks of inhibitory control, such as the Simon task. Additionally, greater L2 proficiency was associated with worse inhibitory control, in contradiction to the studies above showing that greater proficiency and immersion lead to better inhibitory control. In another study, an ANT (attentional network) test performed by early and late bilinguals revealed better conflict resolution by the late bilinguals, indicating age of acquisition is not necessarily linked to better performance in all aspects of selective attention tasks (Tao et al., 2011). Therefore, enhanced performance in some tasks by bilinguals with either lower exposure/immersion (as in Experiment 2), or later age of acquisition, has been found before, and is usually attributed to reduced processing difficulty in code-switching or lexical access (Linck et al., 2008).

In terms of bilingual vs monolingual performance across age groups, Experiment 2 found a bilingual disadvantage in children for speed in the secondary task (despite equivalent comprehension in the primary auditory task and accuracy in the visual task), which disappeared by adulthood. Many of the studies indicating a trajectory in bilingual performance report the opposite effect – i.e., a bilingual advantage in childhood, which tends to disappear in young adulthood (and then reappears in late adulthood, albeit a finding not relevant to the studies in this thesis). This is often attributed to a "cognitive ceiling" in which young adults have developed peak cognitive ability (Valian, 2015b). In a study comparing four age groups of bilingual and monolinguals participants (Bialystok, Craik, et al., 2005), the interpretation of equivalent behavioural results between monolinguals and bilinguals in the young adult group is that the undergraduate group is already operating at peak cognitive efficiency, (unlike children still in development, or adults in cognitive decline as the result of ageing), which explains the lack of demonstrable bilingual advantage. Other studies have found no difference at all between language groups at different ages (Filippi et al., 2020). The bilingual difference in a secondary task in childhood, which disappears by adulthood, is unprecedented in the literature but, as stated above, there does not appear to be an existing study of monolingual and bilingual children performing a dual-task paradigm against which to compare and contrast results.

7.3 Implications and future directions

7.3.1 Theoretical implications

In the main, the findings from my research corroborate various findings from similar studies in the literature. There are, however, novel findings that add nuance to existing theoretical positions.

One key finding is that equivalence in behavioural performance for both monolinguals and bilinguals, in a primary task, applies to both children and adults; however, this changes when the task is modified beyond what normal attentional capacity can process. In this case, bilingual children reveal deficits in performance of the lowest priority task (speed in the secondary task, in this case), which are overcome by adulthood. This has implications for considerations about the limits of flexible adaptation to the environmental processing demands (i.e., the concept of degeneracy), which can be further broken down into a) a degenerate system for processing within typical boundaries or b) a degenerate system for *all* processing, even demands beyond the typical load. It also implies that degeneracy itself may have a developmental trajectory, i.e., the system in children is degenerate to the point of equivalence in a primary task, but complete degeneracy is not reached until full maturation of the cognitive system.

This is a plausible account from the perspective of both theories of educational psychology (Winne & Nesbit, 2010) and a neuroscientific account of learning (Goswami, 2008) in which the cognitive architecture adapts based either on experience-dependent or maturational factors to form a learning trajectory (Westermann et al., 2006). In the case of bilingualism and selective attention, as a child matures, the interrelation between developmental changes in the brain and cognitive abilities follows a trajectory in which attentional processing reaches its peak in adulthood, and fully accommodates the existing demands of bilingualism.

The second interpretation that contrasts with some existing theoretical positions, is that bilingualism does not lead to an enhanced attentional capacity and therefore a bilingual advantage on selective processing tasks; rather, the lower and flatter neural indices indicate a constrained attentional capacity that needs to 'do more with less' to reach behavioural parity with monolinguals. This interpretation adds a competing account to the dominant view in the literature of 'enhanced' attention (Costa & Sebastián-Gallés, 2014; Bialystok, 2017; Timmer et al., 2021; Comishen et al., 2019; Bialystok, 2015; Kapa & Colombo, 2013) which leads to superior behavioural performance on tasks requiring attentional control. Importantly, however, the interpretation of doing 'more with less' still allows an account of increased flexibility. Thus recruiting fewer neural resources to achieve tasks in no way precludes bilingual optimal performance, but goes some way to explaining the inconsistent behavioural results in the literature, and may mark out a middle way in the heated and polarised debate of a bilingual advantage in certain tasks.

7.3.2 Future lines of enquiry

There are clearly limitations of the studies described in this thesis, which should be addressed by future experiments. The first was that the distractor stream of Musical Rain in EEG Experiment 1 was derived from the same narrative as the target story, resulting in extremely similar speech envelopes, which had the potential to artificially inflate the unattended reconstruction scores in the English-Musical Rain condition. Future studies using a similar design and conditions can avoid this by creating the Musical Rain from a completely unrelated narrative.

A further challenge was the recruitment of a high quality bilingual adult sample on the online dual task study. The adult sample was recruited via Prolific, an online recruitment platform, which sources participants globally and invites a selection to participate according to pre-screening criteria. One advantage of using online recruitment platforms such as Prolific is that they have large, globally-distributed databases of potential participants, allowing researchers to access a larger and more diverse pool of potential participants in a short time, which increases speed of recruitment and may strengthen the ecological validity of the resulting sample. However, critics of online recruitment have raised issues of self-selection biases and lack of context (Dewaele, 2018). In addition, such platforms are known to suffer from potential problems with recruiting genuine participants who will perform the study or task in good faith (Downs et al., 2010), and controlling for participant characteristics when eligibility criteria are self-reported (Chandler & Paolacci, 2017). Issues with fraudulent self-selection, such as participants claiming incorrectly to be eligible for studies, are more pronounced in more specific populations (such as high-exposure bilinguals) and are exacerbated by the relative anonymity of online recruitment (Franzen, 2023). Controlling for this risk is extremely important in future studies using similar designs, and can be counteracted through the use of stringent recruitment criteria and careful monitoring of participants throughout the study. A rapid response rate to the study can be slowed down by releasing participant places in batches. This allows time to monitor responses, filter out unsuitable candidates and calibrate the criteria for ongoing recruitment as the study progresses.

Lastly, due to the COVID-19 pandemic, my testing period for EEG Experiment 2 suffered from a protracted interruption in data collection. This possibly led to inconsistent results, due to data being collected in different locations and with different equipment after a 15-month hiatus. A future study could replicate the non-linguistic experimental design and see if it garners more uniform results with consistent testing in one window of time and using the same equipment throughout.

In addition, there are alternative future directions related to these studies. A first potential future direction would be to investigate the composition of the measures of attention generated in Experiment 1 and Experiment 3. The reconstruction accuracy scores used as an index of neural tracking in the EEG experiments were an overall measure, averaged across channels and frequencies (delta, theta, beta, gamma). However, studies have also revealed details of neural oscillations in different frequency bands, which can detail the encoding of different types of lower-level features of the signal (e.g. Di Liberto et al., 2015 analysed the processing of phonemes in specific frequency bands). Hence the scores broken down by frequency band for bilinguals and monolinguals would reveal information contained in different frequencies that might have been obscured to date by an averaged measure.

The second future direction could extend results from measuring the processing of lower-level, perceptual information; to the processing of higher-level semantic and syntactic information contained in the speech streams. This can be achieved using similar methods to the EEG experiments in this thesis (using the mTRF toolbox); but changing input to assess how semantic and syntactic vectors computed from the stimulus content are encoded in the neural activation. In addition, this could also be further analysed in different frequency bands (see Direction 1) as previous research suggests that different functions in the processing of speech, such as higher-level semantic and syntactic cues, engage distinct neural components (Keitel et al., 2018; Ding & Simon, 2014), giving an overall score and more detailed breakdown.

In a bilingual context, the above would drill down into the modifications in bilingual processing of the speech signal and test whether they are applicable to all aspects of language processing. It would also reveal more specific differences between monolinguals and bilinguals by frequency band, revealing the composition underlying the overall scores that have been computed so far.

Finally, these studies have focused on children and young adults. Previous studies on age groups across the lifespan have revealed age-related differences in both performance (Bialystok, Martin, et al., 2005) and in neural activation and architecture (Tao et al., 2021). Therefore, in the third future direction, I suggest further investigating the impact of bilingualism on cognitive processing and maturation, by expanding the participant age range to older adults. The concept of "cognitive reserve", and the potential delay to cognitive deterioration as a result of bilingualism, is an area to which the detailed EEG and behavioural studies presented in this thesis could be applied next. This would not only reveal how bilingualism interacts with aging and cognitive decline; but also, when combined with the studies in this thesis, build a fuller picture of the impact of bilingualism on selective attention at different stages across the lifespan.

Thus future directions could build on the research presented in this thesis by investigating how bilingual adaptation affects neural response across different frequency bands, in different linguistic processing contexts (both lower-level and higher-level features), and across the lifespan.

In summary, the results of the experiments presented in this thesis indicate that, in the developing brain, bilingualism modifies the neural mechanisms that support selective auditory attention to natural speech, in conditions of both linguistic and non-linguistic interference. This does not affect behaviour, suggesting bilingualism creates a degenerate system, in which neural modifications lead to equivalent performance on a primary task in childhood. Lower neural indices, however, indicate that bilinguals have constraints on the extent of attentional capacity to meet task demands, due to the inhibition of the omnipresent second language. This manifests as a limitation on the performance of ‘extreme’ tasks, with attention economised to meet the demands of highest priority, at the expense of aspects of a secondary task. Any such differences in behaviour on a dual task, relative to monolinguals, dissipates with maturation; although residual processing costs are revealed when adult bilinguals with different L2 exposure are compared. This combination of experiments, bridging research on cognitive development, selective attention, bilingualism and degeneracy, provides new insights into how the developing mind adapts to the demands of bilingualism on finite selective attention capacity and processing of linguistic and non-verbal attention tasks.

Appendix A

Transcripts of linguistic stimuli

<u>Attended Narratives</u>

A. THE BOY AND BIRDS

<u>Block 1</u>

1. Once in Russia, there lived a merchant and his wife.
2. Their only son was called Peter.
3. Peter was a kind-hearted boy who loved animals.
4. He owned a little pet bird in a cage.
5. The bird sang beautifully every day.
6. Peter wished he knew the meaning of its song.
7. One winter, it snowed very heavily.
8. Peter was out for a walk in the snow
9. When he spotted some baby birds in a tree.
10. They were desperately tweeting with cold.
11. He took pity on them and fetched a blanket from his room.
12. He climbed the tree and put the blanket over the birds.
13. They snuggled under it and tweeted happily.
14. The next day he received a visit from the birds' mother.
15. "Young man" she said "you are so kind
16. I would like to reward you with my magical powers.
17. Tell me what is your dearest wish?"
18. Peter thought hard and then said:
19. "I would like to be able to understand birdsong".
20. "Very well," said the mother bird with magical powers
21. I will teach you the language of the birds".
22. So for the next month she gave Peter lessons
23. On the tunes, the words and the grammar of the birds.
24. He was a quick learner and soon could understand everything.
25. Including what his own pet bird was singing.
26. To his astonishment, it sang of his future
27. It said that Peter would one day be rich
28. What is more, he would be a prince
29. And his father would be his servant.
30. Peter found this very puzzling.
31. He would be rich and his father a servant!
32. Peter's parents wondered what was bothering him.
33. So they asked him what on earth was wrong.
34. Peter made the mistake of telling his parents
35. The future his pet bird had predicted.
36. And they were not pleased at all – oh no!

37. In fact, they decided he had gone quite mad
38. And the best thing to do was get rid of him
39. While he was sleeping, they took him down to the seashore
40. Then they pushed him out in a little wooden boat
41. He quickly drifted out across the wide sea
42. And his parents supposed they would never see him again.
43. But Peter's little boat was spotted by a ship
44. And they rescued him and brought him on board.
45. The next morning, he heard some birds flying past.
46. "Quick! Quick!" they were squawking to each other
47. "A terrible storm in on its way!"
48. Peter warned the sailors about the storm
49. But they laughed and did not believe him
50. Then the storm did come, and it was as fierce as he'd said.
51. The next week he heard some geese flying past
52. They were also squawking excitedly
53. "Those pirates over there are waiting!
54. They will attack the next ship that goes past."
55. Peter went to warn the ship's captain.
56. And this time everyone believed Peter.
57. They sailed in the opposite direction as fast as they could.
58. And warned every ship that they passed.
59. That some pirates were lying in wait
60. And so Peter became very useful.

<u>Block 2</u>

1 He stayed on the ship for some years
2 And warned the crew about dangers ahead
3 Always from listening to the birds
4 Some years later, he heard about a king
5 Who was being bothered by three pesky crows.
6 These noisy birds sat on his window sill
7 And cawed at him all hours of night and day.
8 His servants had tried to shoo them away
9 But the birds refused to leave the king's window
10 The king was so annoyed by these birds
11 That he promised that the person who got rid of them
12 Would have half his kingdom as reward!
13 Since that proclamation, many people had tried
14 But nobody had succeeded in making the crows go away
15 The king was beginning to despair
16 "Aha" thought Peter. "This is my chance!"
17 He made his way to the castle and said
18 "Give me a chance, your majesty, to rid you of these crows"
19 He was shown to the window where the birds were sitting.
20 He listened for a few minutes and then spoke:
21 "There are three crows – a father, mother and son.
22 The mother and father are getting divorced.
23 They cannot agree who the son should live with
24 So they want to ask the king to decide

25 And will not leave until they have heard his ruling".
26 The king thought carefully for a moment
27 Finally he proclaimed: "Crow family
28 I think it is best for the son to stay with the…
29 Mother!" and with a great CAW!
30 All three birds flew away and left him in peace.
31 So Peter then received the reward
32 Of half the king's riches and kingdom
33 He stayed on to live at the castle
34 And advise the king on all matters.
35 The king's daughter was full of admiration
36 And before long she and Peter fell in love
37 They were married, and so now Peter
38 Was rich and a prince as his bird had sung.
39 Meanwhile, Peter's mother had fallen ill and died.
40 His father was old and had lost all his money
41 After pirates had attacked his merchant ships
42 And stolen all his goods and profits.
43 Peter's father decided to go to the king.
44 He came to the castle to beg for a job.
45 He said, "Your majesty, I will do anything
46 Let me be your humble servant
47 And work in the castle for your family.
48 Now Peter's father had grown very old
49 And his eyesight was a bit blurry
50 Besides, many years had now passed
51 And Peter was a fully-grown man, not a boy
52 So he didn't recognise his own son
53 Standing there behind the king as chief advisor
54 But Peter recognised him and said:
55 "Father! It is I, Peter, your son.
56 Come stay with me and my family.
57 And let us look after you in your old age."
58 For Peter was still kind-hearted.
59 He looked after his father from that day on.
60 And so it was, the bird's song came true.

B. THE TORTOISE AND THE KING

<u>Block 1</u>

1. Many centuries ago, there was a King in India.
2. He had been king for many many years
3. He was a good, kind king, but had one fault
4. His fault was this: he talked too much!
5. He loved nothing better than the sound of his own voice.
6. He had lived a long time, seen many things,
7. read many books, and met many fascinating people.
8. But his thoughts rambled, and he talked on and on.
9. Everyone knew that if you asked him a question

10. You would never get a clear and short reply.
11. If one of his generals were to ask him what to do
12. About difficult soldiers in the army
13. he would begin, “What would my grandfather do?
14. When I met the old commander 35 years ago,
15. he told me that an army marches on its stomach,
16. And that reminds me of another thing…”
17. and then would launch into an unrelated story.
18. By the time he had finished telling the story,
19. he had quite forgotten what the question was!
20. The king had a beautiful palace
21. With wonderful neatly kept gardens all around
22. One day, the weather was fine and sunny
23. And the king decided to go for a nice walk
24. He went for a stroll around his beautiful garden
25. But in the garden of his palace, he found a tortoise.
26. It was lying on the path and when the king looked closer
27. He saw that the poor creature was well and truly dead.
28. It had obviously come to a very violent end
29. As its shell was smashed into several pieces.
30. The king was puzzled by this strange discovery,
31. for he was sure that the dead tortoise had a hidden meaning,
32. but he struggled to think what it might be.
33. “It must be a sign from the gods!” he said
34. “But I have no idea what it means!
35. I will ask if anyone knows in the palace.”
36. So one by one, everyone came out
37. And looked upon the poor dead tortoise
38. But nobody could say what it meant.
39. At last, the king sent a messenger
40. To the oldest and wisest man in the land,
41. and asked him to take a look at the tortoise
42. and explain the meaning of this very strange sign.
43. On seeing the tortoise, the wise man nodded
44. He said, “Master, let me tell you a story.
45. This story will explain everything to you
46. Once upon a time there lived an old tortoise
47. He lived by the side of a beautiful lake.
48. He spent his days resting in the shade of the grass,
49. and nibbling on the juicy weeds that grew around the lake.
50. Lots of animals lived there together.
51. And there was enough food and drink for everyone.
52. But one year there was no rain all summer
53. There was a drought up and down the land.
54. The hot sun baked the land drier and drier.
55. The weeds and grasses shrivelled away.
56. The water in the lake dried first into puddles
57. And then started to disappear altogether.
58. The animals started to starve.
59. There was nothing to eat or drink.
60. They were getting weaker and weaker every day.

Block 2

The tortoise was friends with some geese nearby.
One day, two of the geese came to say goodbye,
for their flock was planning to fly to the mountains
far, far away to the north of the country
in search of water and fresh juicy grass.
“And what will become of me?” asked the tortoise.
“I am 100 years old, my shell is heavy,
and my legs are short and stumpy.
If I plodded all day I would reach no further
than that boulder that you see over there.
“I must stay here until I am all dried up.
Oh, woe is me! What can I do?
Please take me with you, I beg of you.”
The two geese took pity on the old tortoise
And they thought hard about how to help him
They made a plan so he could get away from the lake:
They would hold a stick between them as they flew.
The tortoise must hold on to the stick with his mouth
and they would transport him to a cooler place.
Off they set the very next morning.
The tortoise found himself flying through the skies.
He felt quite sick but was determined to hold on.
The other geese in the flock thought it was hilarious.
“Hey look,” said one, “I’ve seen everything now.
A tortoise has grown wings. Ha ha ha!”.
“That’s not what’s happened,” said another,
“He’s chewing on a stick because he’s hungry.”
Then a third goose joined in the teasing.
“I’m sure he would whizz along a lot faster
If he didn’t have that heavy shell”, he said.
The comments continued, as the geese flew.
Because they had nothing else to talk about
Except the tortoise and his unusual travel mode.
The tortoise could hear every word they said
He was getting more and more annoyed.
Eventually the tortoise could stand it no more.
“See here,” he said, “Do you think I’m enjoying this?”
And that, of course, was when he opened his mouth,
let go of the stick, and started to fall.
He fell, and he fell, until he hit the ground,
Splat! in the garden of your palace, my lord.
And that is why you have this dead tortoise before you."
That was the end of the wise man’s tale.
In reply, the king began to talk at length
about the hibernation patterns of tortoises.
The wise man listened patiently without interrupting.
He knew the king had not yet understood his story.
When the opportunity arose to speak politely

49 the wise man walked once again carefully
50 around the body of the poor dead tortoise
51 and said these following lines very clearly:
52 “Oh gracious king, remember well
53 To speak wisely and to speak in season
54 For to his death the tortoise fell
55 He talked too much: that was the reason.”
56 Suddenly, the king understood what he meant.
57 The gods had sent him a sign to not talk so much.
58 And from then on, he was careful to think
59 Before he opened his mouth to speak.
60 And that is how a tortoise stopped a chatterbox king!

C. THE DUMPLING

<u>Block 1</u>

1. LONG, LONG ago there lived a woman
2. She was an old woman and funny,
3. who liked to laugh and to make dumplings to eat.
4. One day, while she was preparing some dumplings,
5. One fell off the table, then it rolled away.
6. It rolled across the floor, through the door and..
7. Plop! fell down a hole, and disappeared.
8. The old woman looked down the hole
9. Then she tried to reach the dumpling by putting her hand down.
10. But suddenly the earth started to shake
11. With a roar the ground gave way beneath her
12. And the old woman fell down the hole.
13. She fell down and down and slid all the way to the bottom.
14. She wasn’t hurt and still wanted to find her dumpling.
15. When she got up on her feet again, she was standing on a road.
16. It was in a strange land with rolling hills all around.
17. Now I can’t even tell you how this had happened.
18. But the funny old woman had fallen into another country!
19. The road she was on went winding down a steep hill
20. So she thought that the dumpling must have rolled down.
21. She ran down the road to look, saying:
22. "My dumpling, my dumpling! Where is my dumpling?"
23. After a little while she saw a stone statue.
24. The woman stared at the statue and said:
25. "Excuse me, did you see my dumpling roll past?"
26. The statue answered: "Yes, indeed I did!
27. But don’t go down the hill to look for it,
28. for there is a wicked giant living down there.
29. And he will capture you if you go any further."
30. But the old woman took no notice of the statue.
31. She carried on running down the road saying
32. "My dumpling, my dumpling! Where is my dumpling?"
33. Soon, she spotted another stone statue.
34. The woman asked this statue the same question:

35. “Excuse me, have you seen a dumpling roll past?”
36. “Yes”, replied the statue, “I saw your dumpling.
37. But please don’t go down any further
38. Because a terrible giant lives down there
39. Who will take you prisoner if you go near his house.”
40. But the woman just laughed at the statue.
41. Then the statue whispered: “Here comes the giant.
42. Sit behind me, and don't make any noise."
43. Presently the giant came very close,
44. and stopped and bowed to the statue.
45. “Good day Mr Statue!” the giant said.
46. Then the giant sniffed the air suspiciously,
47. And said, “Do you smell what I smell?
48. I smell the smell of a nice juicy woman!"
49. “Oh no, you are mistaken” said the statue.
50. “There’s no woman around here.”
51. But the giant carried on sniffing. Sniff! Sniff!
52. “I can definitely smell the smell of a woman!” he said.
53. The old woman thought all this was very funny
54. And she couldn't help laughing. “Te he-he!"
55. The giant immediately reached down his big hand
56. and pulled her out, still laughing, "Te-he-he!"
57. "Aha!" cried the giant, excitedly.
58. “I’ve got you! I knew I could smell a woman.
59. You smell of dumplings and lovely food.
60. I will take you home with me to be my cook."

<u>Block 2</u>

1 Then the giant took the old woman down the hill.
2 At the end of the winding road was his house.
3 It was a big house with lots of huge rooms.
4 He led her through to the kitchen, and said
5 “This is the kitchen, and you are now our chef
6 “Cook some dinner for me and the other giants who live here!“
7 The old woman started to get a bit worried
8 How was she going to cook enough food for the giants?
9 She only knew how to cook for herself.
10 However, the giant had not finished.
11 He gave her a small wooden spoon, and said:
12 "Only put one grain of rice into the pot,
13 Then add a little bit of water to the pot
14 when you stir that one grain of rice with this spoon,
15 the grain will multiply until the pot is full."
16 So the woman put just one rice-grain into the pot,
17 She then added a little splash of water
18 and began to stir it with the wooden spoon; .
19 one grain turned to two, then two to four
20 And so on and so on and so on.
21 Every time she moved the spoon the rice doubled;
22 and in a few minutes the great pot was full.

23 The old woman was delighted with the magic spoon.
24 It made cooking for the giants quick and easy.
25 The funny old woman stayed a long time in the house
26 and every day cooked food for the giant and his friends.
27 The giant never hurt or frightened her,
28 and her work was made quite easy by the magic spoon,
29 although she did have to cook a LOT of rice,
30 because a giant eats much more than any human being eats.
31 But she felt lonely, and always wished to go home,
32 and make her own tasty dumplings again.
33 She missed her own little kitchen
34 And wanted to see all her friends again.
35 One day, when the giants were all out somewhere,
36 She noticed they had left the huge gates unlocked.
37 So she thought she would try to run away.
38 She first picked up the useful magic spoon,
39 and slipped it quickly under her belt;
40 then she tiptoed through the unlocked gates
41 and ran away up the road as fast as she could.
42 Back up the hill she went, huffing and puffing.
43 Past the two stone statues who were still standing there.
44 But this time she didn’t stop to chat.
45 She never stopped running until she was home again.
46 After that she was very happy to be home.
47 She was back in her own little kitchen
48 She could make dumplings whenever she pleased.
49 Plus, she had the magic spoon to make rice for her.
50 She started to sell her dumplings and rice.
51 And all her neighbours and friends bought them from her.
52 She sold so many of her tasty dumplings
53 That in the end the old woman
54 Was funny.. and old…and very rich.
55 She still laughed all day: “Tee hee hee!”
56 But from then on if she accidentally dropped a dumpling
57 She left it to roll away and didn’t chase it.
58 And she was always careful around holes
59 She never put her hand down one again.
60 For the one adventure down a hole was enough!

D. THE SHEPHERD AND THE TIGER

<u>Block 1</u>

1. Once upon a time there was a good-hearted shepherd
2. He was out walking alone one fine morning
3. When he heard a strange howling noise.
4. It sounded like an animal roaring in distress.
5. As he got closer, he saw it was a huge tiger.
6. The tiger had been caught in a very strong trap.
7. And was rattling the cage door furiously.

8. He had been in the trap for hours and hours.
9. And despite all his pushing couldn’t open the door.
10. All at once the tiger saw the shepherd.
11. He cried: “Please, I beg you, kind sir!
12. You look like an honest and kindly gentleman.
13. Would you please let me out of this terrible cage?
14. I have been trapped all night and cannot get out!
15. All you have to do is open this little door here.”
16. But the shepherd did not trust the tiger.
17. He was worried the tiger would gobble him up
18. The tiger was big and ferocious
19. And the man was unarmed and all on his own.
20. The shepherd replied, “Do I look like an idiot to you?
21. If I set you free you will eat me in a flash!”
22. “No, no, I promise!” said the tiger
23. shaking his head, and smiling at the shepherd.
24. “If you let me out, I will be eternally grateful
25. I will serve you as a slave for ever!”
26. Well, the shepherd thought about his proposal.
27. It would be pretty cool to have a tiger as a slave.
28. Besides, he was now feeling quite sorry for the tiger.
29. Who was looking more and more dejected.
30. So he went and opened the door of the cage.
31. Creeeeak! The door of the cage swung open.
32. Out sprang the tiger and grabbed the shepherd.
33. “Aha!” he growled, “You foolish man!
34. I am extremely hungry after a night in that cage
35. So I think I might just gobble you up right now.
36. You look nice and tasty as a snack”.
37. The shepherd pleaded with the tiger for his life.
38. “Please please spare me! Let me go free!
39. You cannot break the promise you made!”
40. Suddenly the shepherd thought of a plan.
41. He suggested this to the tiger:
42. The shepherd could ask for the opinion
43. of the next three objects he came across
44. To decide if the shepherd deserved to live.
45. If any of them thought that the shepherd was right,
46. The tiger would let him go unharmed.
47. But if they all agreed with the tiger’s view
48. That the man deserved to be eaten
49. He would gobble the shepherd up straight away.
50. “Hmm” said the tiger “all right
51. I agree to this little plan of yours
52. But make it quick! My stomach’s rumbling
53. And I’m sure nobody will side with you.”
54. Now the shepherd had to find something
55. That would save him from the tiger
56. He started to look around desperately
57. For three things that he could ask
58. And hopefully one would agree

59. That he, the shepherd, should go free
60. And not be eaten by the hungry tiger

<u>Block 2</u>

1 So the shepherd looked around for someone to ask.
2 He decided to ask first a nearby tree.
3 “Trees are old and wise,” he thought to himself.
4 “Surely the tree will be on my side”
5 and he told the tree his sorry story:
6 “Oh, Mr Tree, I have been trapped by a tiger
7 Who at first promised to set me free
8 And now he wants to gobble me up!
9 Do you think this is a fair way to treat me?”
10 But the tree looked at him coldly and said:
11 “What have you got to complain about?
12 I give shade and shelter to everyone.
13 And they repay me by cutting my branches off!
14 Don’t be a wimp – be a man!”
15 This was not the reply the shepherd wanted.
16 He next decided to ask the road the same question.
17 “Oh, Mr Road, I have been trapped by a tiger
18 Who at first promised to set me free
19 And now he wants to gobble me up!
20 Do you think this is a fair way to treat me?”
21 But the road answered unsympathetically:
22 “Well, what do you expect, you silly man?
23 Here am I, useful to everyone.
24 I take everyone where they want to go.
25 But they all trample on me as they go past.”
26 This wasn’t what the shepherd wanted to hear either.
27 He was now very worried about being eaten.
28 He was walking back towards the tiger and the cage
29 Trembling and muttering, when up came a monkey.
30 “Hey, Mr Shepherd, what’s wrong with you?”
31 said the monkey. “You look terrible”
32 So the shepherd explained what had happened.
33 However, the monkey only scratched his head.
34 “I am very confused,” he said.
35 “I cannot understand what has happened.
36 What a strange situation this all seems to be
37 I would like to ask the tiger some questions
38 And then I can make up my mind whether it’s fair.”
39 So they went back to the tiger and the shepherd said,
40 “I asked this monkey but he has some questions.”
41 “Yes”, said the monkey “I’m extremely confused.
42 Please explain to me exactly how this all started.
43 Was the shepherd in the cage when the tiger….”
44 “No, no, no” said the tiger “that’s wrong!
45 You have got it the wrong way around”
46 “Aha!” said the monkey, “I’ve got it!

47 You were both in the cage and then….what happened?”
48 “Wrong again!” said the tiger. “It was me!”
49 “I was the one who was trapped in the cage!
50 “Let me show you, you stupid little creature
51 I can see that you don’t have any brains.”
52 The tiger hopped into the cage, where he shouted:
53 “Look here! I was the one trapped in the cage!
54 “NOW do you understand how it all started?”
55 “Perfectly!” said the monkey as he shut and locked the door.
56 “And now that is also how it ends! Ha ha!”
57 And he smiled a big smile at the shepherd.
58 Who realised the monkey was not stupid at all.
59 And that is the story of how the monkey
60 Helped the shepherd escape from the tiger.

Unattended Narratives

E. THE MAGIC RING

Block 1

1. There was once a house that I used to visit.
2. I knew the way in very well indeed –
3. there was a tiny little door at the back,
4. so small that you would probably never notice it,
5. but I’m a mouse, and I can squeeze through anything.
6. Every time I visited, there were fewer and fewer crumbs.
7. It was hardly worth going there anymore.
8. There was also the problem of a cat in the house.
9. This cat was getting skinnier and skinnier,
10. and desperate to catch a mouse to eat.
11. One night, I couldn’t help overhearing an argument.
12. The owners of the house were shouting loudly.
13. “It’s all your fault we’re starving,” said the woman.
14. “You shouldn’t have gone and sold my mother’s ring.
15. All you got for it was an old horse that died.
16. Now we’ve got nothing, nothing.”
17. “What’s your mother’s ring got to do with it?” asked the man.
18. “Because I told you a thousand times,
19. the person who wears that ring will never go hungry.”
20. “Well I don’t believe in that magic and nonsense,”
21. replied the man in a huff.
22. “You don’t believe in anything I say.
23. That’s why you’re so thin your trousers keep falling down.”
24. Ooh, that was quite an argument.
25. But now I understood why the house was getting so poor.
26. The man had sold the woman’s magic ring
27. A ring that kept the cupboards full of food.
28. I wish I had a ring like that, I thought.
29. Next thing - Bam! Everything went black.

30. “Am I dead or alive?” I thought.
31. But I soon knew that I was alive because I heard a voice.
32. The dog, a scratchy smelly creature, was saying:
33. “Hey cat, hang on, don’t eat that mouse just yet.”
34. “Why shouldn’t I?” whined the cat. “
35. I haven’t had a decent meal in days.”
36. “Neither have I,” said the dog,
37. “But the mouse will only fill you up for a few hours.
38. Let’s be smart about this, my friend.
39. He can help us fill our stomachs for the rest of our days.”
40. “You’ve gone mad from hunger,” said the cat.
41. “This is a mouse, not a hen. He can’t lay eggs.”
42. “No,” woofed the dog, “That’s not what I mean.
43. The thing about a mouse is that he’s small…”
44. “And he can slip through the tiniest of holes…”
45. “So what?” said the cat.
46. “And if we take him to the house where the magic ring is now,
47. he can slip inside and get it for us.
48. He’ll do this for you, because otherwise you’ll eat him.
49. But if he gets the ring, you will set him free.
50. The magpie told me where that house is.
51. Come on, let’s head off straight away.”
52. The cat saw that the dog was not quite as stupid as he looked.
53. She put me in her mouth and jumped through the window.
54. The dog followed and they ran down the alleyway.
55. It was hot and smelly in the cat’s mouth
56. I was bouncing around all over the place,
57. It was the worst journey of my life
58. but I was alive, thank goodness.
59. I just had to find the magic ring
60. If I wanted to keep it that way.

Block 2

1. We left the town and reached a river.
2. The dog said, “Right-oh, in we go!”
3. But the cat put me down and held me with a paw.
4. “Not so fast,” she said, “I can’t swim.”
5. “Never mind that, “ woofed the dog,
6. “Jump on my back and I’ll carry you over.”
7. So “Splash!” In we all went.
8. The dog paddled quickly to the other side
9. And over to the house where the ring was to be found.
10. Inside we could see a man and woman,
11. both plump, with happy expressions on their faces.
12. The dog said: “We’ve come to the right place.
13. Let’s hope she takes the ring off when she goes to bed.”
14. The cat prowled round the house looking for a way in.
15. There’s usually one, if you search hard enough.
16. We found a tiny little hole that only I could squeeze through.
17. “In you go,” she said, “And bring back that ring!”

18. “If you bring us the ring you can live!”
19. In I went, still glad to be alive, but quite nervous.
20. I can sniff out crumbs, but not gold and silver.
21. Fortunately, I saw the ring glinting in the moonlight.
22. The lady had left it on the table with her other jewellery.
23. I put the ring in my mouth, and slipped back out again.
24. “Here it is,” I said, “I hope you are happy.”
25. “Say goodbye to this world, little mouse,” replied the cat.
26. I trembled for my life, but the dog woofed:
27. “Stop right there, cat. A promise is a promise. “
28. We returned to the river, and swam back like before.
29. Soon we were back near where they lived.
30. This time, the cat went over the rooftops –
31. while the dog ran down the alleyways.
32. I went home to my nest for a good sleep.
33. Now there is a follow up to this story.
34. A few weeks later, I was going past the cat and dog’s house.
35. The light was on, and I looked through the window.
36. The human couple were having a feast,
37. and the cat was looking fat and happy.
38. “So,” I thought, “What they said was true.
39. The owners of the magic ring will never go hungry.”
40. I too deserved a reward for my part in the rescue of the ring,
41. and I decided to slip inside and take some crumbs.
42. But round the back, I found the dog tied up.
43. He was still thin and more miserable than ever.
44. “What on earth has happened?” I asked,
45. “The house is full of food. Why aren’t you tucking in?”
46. The dog whined. “Aroooo!
47. That filthy lying cat played a trick on me!
48. She ran to the house before me, taking a shortcut over the rooftops.
49. As soon as she got back, she sprang onto our owners’ bed
50. and woke them up with the great gift of the ring.
51. Oh how delighted they were!
52. She is rewarded every day.
53. But as for me, they punished me.
54. They think I’m just a smelly, useless animal,
55. and they tie me up outside.
56. I’m lucky if they remember to throw me a scrap.
57. GRRRRRRR! I shall hate that cat till the day I die,
58. and so shall all my puppies hate all cats for ever!”
59. That’s the story of why cats and dogs are enemies
60. They have hated each other ever since!

F. THE ADVENTURES OF PERSEUS

LATIN TRANSCRIPT

Block 1

1. Haec narrantur a poetis de Perseo.
2. Perseus filius erat Iovis, maximi deorum;
3. avus eius Acrisius appellabatur.
4. Acrisius volebat Perseum nepotem suum necare;
5. nam propter oraculum puerum timebat.
6. Comprehendit igitur Perseum adhuc infantem,
7. et cum matre in arca lignea inclusit.
8. Tum arcam ipsam in mare coniecit.
9. Danae, Persei mater, magnopere territa est;
10. tempestas enim magna mare turbabat.
11. Perseus autem in sinu matris dormiebat.
12. Iuppiter tamen haec omnia vidit,
13. et filium suum servare constituit.
14. Tranquillum igitur fecit mare,
15. et arcam ad insulam Seriphum perduxit.
16. Huius insulae Polydectes tum rex erat.
17. Postquam arca ad litus appulsa est,
18. Danae in harena quietem capiebat.
19. Post breve tempus a piscatore quodam reperta est,
20. et ad domum regis Polydectis adducta est.
21. Ille matrem et puerum benigne excepit,
22. et iis sedem tutam in finibus suis dedit.
23. Danae hoc donum libenter accepit,
24. et pro tanto beneficio regi gratias egit.
25. Perseus igitur multos annos ibi habitabat,
26. et cum matre sua vitam beatam agebat.
27. At Polydectes Danaen magnopere amabat,
28. atque eam in matrimonium ducere volebat.
29. Hoc tamen consilium Perseo minime gratum erat.
30. Polydectes igitur Perseum dimittere constituit.
31. Tum iuvenem ad se vocavit et haec dixit:
32. "Turpe est hanc ignavam vitam agere;
33. iam dudum tu adulescens es.
34. Quo usque hic manebis?
35. Tempus est arma capere et virtutem praestare.
36. Hinc abi, et caput Medusae mihi refer."
37. Perseus ubi haec audivit, ex insula discessit,
38. et postquam ad continentem venit, Medusam quaesivit.
39. Diu frustra quaerebat; namque naturam loci ignorabat.
40. Tandem Apollo et Minerva viam demonstraverunt.
41. Primum ad Graeas, sorores Medusae, pervenit.
42. Ab his talaria et galeam magicam accepit.
43. Apollo autem et Minerva falcem et speculum dederunt.

44. Tum postquam talaria pedibus induit,
45. in aera ascendit. Diu per aera volabat;
46. tandem tamen ad eum locum venit
47. ubi Medusa cum ceteris Gorgonibus habitabat.
48. Gorgones autem monstra erant specie horribili;
49. capita enim earum anguibus omnino contecta erant.
50. Manus etiam ex aere factae erant.
51. Res difficillima erat caput Gorgonis abscidere;
52. <u>eius enim conspectu homines in saxum vertebantur.</u>
53. Propter hanc causam Minerva speculum Perseo dederat.
54. Ille igitur tergum vertit, et in speculum inspiciebat;
55. hoc modo ad locum venit ubi Medusa dormiebat.
56. Tum falce sua caput eius uno ictu abscidit.
57. Ceterae Gorgones statim e somno excitatae sunt,
58. et ubi rem viderunt, ira commotae sunt.
59. Arma rapuerunt, et Perseum occidere volebant.
60. Ille autem dum fugit, galeam magicam induit.

<u>Block 2</u>

1. et ubi hoc fecit, statim e conspectu earum evasit.
2. Post haec Perseus in finis Aethiopum venit.
3. Ibi Cepheus quidam illo tempore regnabat.
4. Hic Neptunum, maris deum, olim offenderat;
5. Neptunus autem monstrum saevissimum miserat.
6. Hoc cottidie e mari veniebat et homines devorabat.
7. Ob hanc causam pavor animos omnium occupaverat.
8. Cepheus igitur oraculum dei Hammonis consuluit,
9. atque a deo iussus est filiam monstro tradere.
10. Eius autem filia, nomine Andromeda,
11. virgo formosissima erat.
12. Cepheus ubi haec audivit, magnum dolorem percepit.
13. Volebat tamen civis suos e tanto periculo extrahere,
14. atque ob eam causam imperata Hammonis facere constituit.
15. Tum rex diem certam dixit et omnia paravit.
16. Ubi ea dies venit, Andromeda ad litus deducta est,
17. et in conspectu omnium ad rupem adligata est.
18. Omnes fatum eius deplorabant,
19. nec lacrimas tenebant. At subito,
20. dum monstrum exspectant, Perseus accurrit;
21. et ubi lacrimas vidit, causam doloris quaerit.
22. Illi rem totam exponunt et puellam demonstrant.
23. Dum haec geruntur, fremitus terribilis auditur;
24. simul monstrum horribili specie procul conspicitur.
25. Eius conspectus timorem maximum omnibus iniecit.
26. Monstrum magna celeritate ad litus contendit,
27. iamque ad locum appropinquabat ubi puella stabat.
28. At Perseus ubi haec vidit, gladium suum eduxit,
29. et postquam talaria induit, in aera sublatus est.
30. Tum desuper in monstrum impetum subito fecit,

31. et gladio suo collum eius graviter vulneravit.
32. Monstrum ubi sensit vulnus, fremitum horribilem edidit,
33. et sine mora totum corpus in aquam mersit.
34. Perseus dum circum litus volat,
35. reditum eius exspectabat.
36. Mare autem interea undique sanguine inficitur.
37. Post breve tempus belua rursus caput sustulit;
38. mox tamen a Perseo ictu graviore vulnerata est.
39. Tum iterum se in undas mersit,
40. neque postea visa est.
41. Perseus postquam ad litus descendit,
42. primum talaria exuit;
43. tum ad rupem venit ubi Andromeda vincta erat.
44. Ea autem omnem spem salutis deposuerat,
45. et ubi Perseus adiit, terrore paene exanimata erat.
46. Ille vincula statim solvit, et puellam patri reddidit.
47. Cepheus ob hanc rem maximo gaudio adfectus est.
48. Meritam gratiam pro tanto beneficio Perseo rettulit;
49. praeterea Andromedam ipsam ei in matrimonium dedit.
50. Ille libenter hoc donum accepit et puellam duxit.
51. Paucos annos cum uxore sua in ea regione habitabat,
52. et in magno honore erat apud omnis Aethiopes.
53. Magnopere tamen matrem suam rursus videre cupiebat.
54. Tandem igitur cum uxore sua e regno Cephei discessit.
55. Postquam Perseus ad insulam navem appulit,
56. se ad locum contulit ubi mater olim habitaverat,
57. sed domum invenit vacuam et omnino desertam.
58. Tris dies per totam insulam matrem quaerebat;
59. tandem quarto die ad templum Dianae pervenit.
60. Huc Danae refugerat, quod Polydectem timebat.

Appendix B

Comprehension questions

A. THE BOY AND BIRDS

Block 1

1. This is a story about a boy called PETER/TOM
2. Who was very NASTY / KIND
3. And looked after some baby BIRDS / FROGS
4. He learnt BIRD LANGUAGE / MATHEMATICS
5. His own bird said he was going to be POOR / RICH
6. His parents were pleased with the news. YES / NO
7. His parents put him in a TRAIN / BOAT
8. But he was rescued by a SHIP / PLANE
9. Peter heard birds saying some SUBMARINES / PIRATES were ahead
10. And this time the sailors thought he was RIGHT / WRONG

Block 2

1. Peter then STAYED SOME YEARS / LEFT STRAIGHT AWAY
2. He then heard about a QUEEN / KING
3. Who was having a problem with some CROWS / DOGS
4. Who were too QUIET / NOISY
5. The king had promised that if anyone solved the problem he would MAKE THEM RICH / THROW THEM IN PRISON
6. So Peter then lived at the CHURCH / CASTLE
7. His FATHER / MOTHER came to beg for a job

8. Peter IGNORED / RECOGNISED him
9. And told him to GO AWAY / STAY WITH HIM
10. For Peter was still EVIL / KIND-HEARTED

B. THE TORTOISE AND THE KING

Block 1

1. This story is about a KING / QUEEN
2. Who DANCES / TALKS too much
3. And finds a RABBIT / TORTOISE
4. Who is DEAD / ALIVE
5. In his SWIMMING POOL / GARDEN.
6. He asks a MAN / WOMAN
7. Who is FORGETFUL / WISE
8. To EXPLAIN / COOK the tortoise
9. He tells a story of a tortoise who lives by a SHED / LAKE
10. But one year there is no RAIN / LIGHT

Block 2

1. The tortoise is friendly with some MONKEYS / GEESE
2. They are going to FLY AWAY / HAVE A PARTY
3. The tortoise wants to STAY WHERE HE IS / GO WITH THEM
4. The geese AGREE / REFUSE to help him.
5. The tortoise has to hold onto a WING / STICK
6. With his TAIL / MOUTH while they fly
7. The other geese start to SING / TALK
8. The tortoise gets very ANNOYED / PLEASED

9. Opens his mouth to talk and FALLS DOWN / STAYS IN THE AIR
10. Finally the king DIES / UNDERSTANDS

C. THE DUMPLING

Block 1

1. This story is about a funny old MAN / WOMAN
2. Who liked to make DUMPLINGS / FAIRY CAKES
3. One day, one STARTED SPEAKING / ROLLED AWAY
4. The woman went TO BED / DOWN A HOLE
5. She found herself on a ROAD / BUS
6. That went DOWN / UP a hill
7. She saw a WIZARD / STATUE
8. Who told her not to go down the hill as a DRAGON / GIANT lived there
9. The giant came and SMELLED / KICKED the woman
10. He heard the woman SCREAMING / LAUGHING

Block 2

1. The giant took the woman to his SHIP / HOUSE
2. He showed her the KITCHEN / BATHROOM
3. And gave her a magic wooden FORK / SPOON
4. To help her cook POTATOES / RICE
5. And make the pot FULL / EMPTY
6. After that she stayed to CLEAN / COOK for the giant and his friends
7. But after a while she wanted to go HOME / TO THE SHOPS
8. She LEFT / TOOK WITH HER the magic spoon
9. And RAN / SWAM all the way home

10. After that, she SOLD / THREW AWAY her dumplings

D. THE SHEPHERD AND THE TIGER

Block 1

1. This is a story about a BEGGAR / SHEPHERD
2. Who finds a TIGER / FISH
3. In a LAKE / CAGE
4. The tiger wants to DANCE / GET OUT
5. At first the shepherd AGREES STRAIGHT AWAY / DOESN'T WANT TO
6. But the tiger makes him a PROMISE / SANDWICH
7. So eventually he SETS HIM FREE / POKES HIM IN THE EYE
8. The tiger then wants to KISS HIM / EAT HIM
9. But then AGREES / DISAGREES with the shepherd's plan
10. That the shepherd can ASK / KICK three objects for their judgement

Block 2

1. First of all the shepherd asks a CLOUD / TREE
2. Then the shepherd asks the ROAD / SKY
3. Both of these call the shepherd a wimp and silly TRUE / FALSE
4. Then the shepherd spots a PARROT / MONKEY
5. The monkey says he is CONFUSED / ANGRY
6. And wants to see THE SHEPHERD'S HOUSE / THE TIGER AND THE CAGE
7. The tiger wants to SHOW WHAT HAPPENED / THROW A BALL TO the monkey
8. So the tiger RUNS AWAY / GETS BACK IN THE CAGE
9. Then the monkey SHUTS THE DOOR / LETS HIM OUT AGAIN
10. And that is how the monkey HELPS / SHOUTS AT the shepherd

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