UiT The Arctic University of Norway

Department of Language and Culture

Multilingual experience modulates resting-state functional connectivity and executive functioning in cognitive aging

Exploring the relationship between working memory and rs-EEG coherence in healthy bilinguals across the adult lifespan

Anders Gabrielsen

Master's thesis in English Linguistics, ENG-3991, May 2023

Abstract

Bi-/multilingualism has been found to act favourably on the cognitive aging (CA) trajectory due to the increased executive functioning demands that dual-language use exerts on the brain leading to contributions to neurocognitive reserve and resilience. There is a gap in the literature on how individual differences in the degree of multilingualism influence this trajectory. Furthermore, other lifestyle factors such as diet and exercise, have also been shown to influence CA, yet language experiences and lifestyle factors have rarely been examined together. This thesis aims to fill this gap by examining the unique influence of multilingual language engagement on intrinsic brain activity at-rest and working memory performance. A comprehensive language and lifestyle profile was calculated from native Norwegian multilingual speakers with English as one of their additional languages (n=90, mage=49,3, (SD=18.06), range 19-82. Resting-state Electroencephalography (rs-EEG) and working memory were assessed and regressed against a continuous measure of multilingualism (MLD) while controlling for other lifestyle-experiences. Results indicate a near-significant trend hinting that degree of multilingualism offsets the downwards aging trajectory of EEG coherence in alpha and gamma coherence across several electrode regions. A significant positive interaction between age and MLD was found for WM performance. An exploratory post-hoc analysis revealed a null relationship between functional connectivity and working memory. Results suggest that a higher degree of multilingualism leads to increased resilience against CA.

Acknowledgements

I would firstly like to thank my supervisors Dr. Vincent DeLuca, Dr. Jason Rothman and Dr. Toms Voits for the invaluable guidance and help through every stage of this thesis. Thank you for granting me the opportunity to be a part of the EEG-CAP project from its infancy through the end of data-collection. I would also like to thank all members of the AcqVa Aurora and PoLaR lab for creating an encouraging and supportive environment.

A special thanks goes out to my peer and excellent friend Gaute Berglund and the many hours we spent testing and processing in the lab. Your support throughout the EEG-CAP project, this thesis and the five years spent studying together have been invaluable to me. Best of luck going forwards!

Table of contents

List of Figures & Tables

List of Abbreviations

2L1	Simultaneous Bilingual
AoA	Age of Acquisition
BAPSS	Bilingual Anterior to Posterior and Subcortical Shift
BR	Brain Reserves
CA	Cognitive Aging
CE-WM	Central Executive Working Memory
CR	Cognitive Reserves
CRS	Cognitive Reserve Scale
EEG	Electroencephalogram
EF(s)	Executive Functions
ERP	Event Related Potential

FC	Functional Connectivity
GMV	Grey Matter Volume
ERP	Event related potential
MRI	Magnetic Resonance Imaging
MF	Medial Frontal
LFT	Left Frontal Temporal
LP	Left Posterior
L1	Native Language
L2	Second Language
RFT	Right Frontal Temporal
ROI	Region of Interest
RP	Right Posterior
RT	Reaction Time
rs-EEG	Resting State Electroencephalogram
SES	Socioeconomic Status
SEM	Structural Equation Modelling
WM	Working Memory

1 Introduction

Since the turn of the century, human life expectancy has reliably increased as a function of steady developments into medical technology, nutrition and an overall better quality of life (Oeppen & Vaupel, 2002). The consequences of this involve that more people will live into older age and experience the age-related declines in cognition. Fluid abilities such as working memory has been shown to decline rapidly as one ages (Ferguson et al., 2021). Hence, research into altering the trajectory of cognitive aging (CA) has been of great scientific importance. Barring a few experimental drugs that also show some promise in altering this trajectory, experiences over a lifetime are assumed to have the most impact (Chapko et al., 2018; Klimova et al., 2018). The underlying mechanism thought to be responsible for this is referred to as *resilience*, which may be defined as the brain's ability to mitigate age-related degradation through cognitive reserves. The gradual buildup of resilience is generally agreed to come from mentally stimulating activities throughout the lifespan (Stern, 2009). Where these inquiries often fall short, is not accounting for the effect of life-long bilingualism or by omitting it entirely.

Recent evidence points in the direction that bilingualism is a complex experience that lies on a continuum and should not be treated as a categorial variable (DeLuca et al., 2019). For context, bilingualism may be loosely defined as having mental representations of two languages and being able to use both. In the CA literature, bilingualism is often measured through competence or language knowledge (e.g. Proficiency) and less weight is put on the relative use of both languages in various contexts over time (Del Maschio et al., 2018). This means that inquiries into how: (i) bilingualism may affect CA and (ii) how other lifestyle-factors may affect CA, are often conducted separately. This likely obfuscates how these experience-dependent factors may exert influence together or independently of each other (Voits et al., 2022).

This thesis aims to bridge the gap between two disparate lines of research by controlling for lifestyle factors (e.g. diet, exercise, SES) and to independently assess the role of bilingual language engagement. The outcome measures for this investigation will be resting-state EEG coherence, a measure of functional connectivity between various brain regions during wakeful rest. Increased rs-EEG coherence has previously been linked to: (i) greater resilience against the effects of CA (Fleck et al., 2017), (ii) determinants of bilingualism (Bice et al., 2020; Pereira Soares et al., 2021). The second outcome measure is working memory performance, which tends to worsen with age and serves as proxy for age-related decline. Similarly to CR, there are some evidence that this decline in WM performance may be flattened by bilingual language use (Bialystok et al., 2014). Utilizing these two outcome measures, together with a comprehensive lifestyle and language profile for each participant, makes it possible to assess this gap in the literature in a more holistic manner. Namely, does prior experience with these experience-dependent variables affect the outcome measures and does there exist a link between them? To answer this specific inquiry, a theoretical background is needed on the various research topics utilized in this thesis and their relevance for the research questions presented in section 2.5.

2 Theoretical Background

2.1 Aging

The quote “Old minds are like old horses ; you must exercise them if you wish to keep them in working order” (Addams, 1885) summarizes the knowledge of aging as of the mid 17th century and, to some extent, holds true today. The process of aging, both in living creatures and the world around us has been an object of scientific interest for a long time. This process in an integral part of evolution, as it is necessary for the advancement of a species through reproduction and for humans, physiological, neurological and to some extent, psychological changes are inevitable. Harman, (2001) defines the overarching concept of aging as an accumulation of more or less diverse changes over time. This definition is very broad but captures the essence of aging quite nicely. He specifies that some changes that occur are heritable through genes, while others are highly dependent on quality of life. For example, Harman highlights the discrepancy between life expectancy at birth has increased from 30 years in Ancient Rome, to around 80 years in developed countries today. Such dramatic changes over the course of a mere 2000 years speaks to the profound effect that a good quality of life may exert over this process. In today's medical world, aging is measured through chronological age (age from birth) and physiological age. The latter term takes into account other factors that may contribute to the aging process that does not necessarily scale with chronological age and is often measured through various samples and biological markers (Belsky et al., 2015).

Factors that contribute to aging are too many to include in this thesis, but it is worth mentioning that it is not only societal factors, such as quality of life, access to medical care etc. that contribute to the process. Physiological and social factors play an important role as well, as it well documented that for example, social isolation and stress are contributing factors to aging. As the process unfolds, a number of effects on the body and mind may be observed: A decline in muscle mass and strength, impaired hearing and vision are some of the physiological changes common in healthy aging, as well as a myriad of other physiological effects (Amarya et al., 2018). More relevant to this dissertation, aging also impairs general cognition, which in turn may affect behavioral patterns. Through decades of research into what specific cognitive abilities that aging effects, Murman, (2015) postulates that cognitive processes involved in higher-level processing and *on the fly* decision-making is most severely impacted. For example, he highlights the divide of crystallized and fluid abilities: Crystallized abilities are skills and knowledge accumulated in the past, over the course of a lifetime, such as reading comprehension and vocabulary. Fluid abilities, as the name implies, involves any processing where new information must quickly be applied to a task, e.g., executive functioning. In this thesis, fluid ability will be measured using a working memory task and we will likely observe how age will worsen the performance on this task.

2.1.2 The effect of aging on the brain

The aging process is one of progressive neurodegeneration, which in turn affects cognitive abilities and, in some cases, the beginning of age-related pathology such as Mild Cognitive Impairment and dementia (Prince et al., 2013). In humans, aging may be characterized by a large number of changes in the healthy brain, including the deterioration of grey matter volume in several anatomical networks (Hafkemeijer et al., 2014), reduced cortical thickness (Frangou et al., 2022) and reduced white matter integrity (Cox et al., 2016). The loss of white matter integrity is especially problematic, as white matter is an important component of communication within the brain itself. High white matter integrity facilitates the speed of electrical impulses, enabling smoother communication and an action potential that can travel faster and longer, important for functional connectivity (Hartline & Colman, 2007). For reference, functional connectivity may be defined as "a temporal correlation between spatially remote *events"*(Fingelkurts et al., 2005, p. 828). Simplified, it is a measure of communication across different areas of the brain, measured through increased activity between the two areas (see section 2.3.2 for details).

Apart from a few clinical trials with pharmaceuticals thought to aid against age-related pathology (Klimova et al., 2018), the effects of aging are universal and barring the efficacy of certain drugs, irreversible. The most promising protection against age-related neurodegeneration and impaired cognitive functions is believed to experience with certain lifestyle choices over the course of a lifetime (Abud et al., 2022; Dhana et al., 2020). These lifestyle factors generally include socio-economic status, diet, physical exercise, social well-being, to name a few. The unifying factor here is that lifestyle choices are thought to matter in the long term; eating healthy for a week would most likely not offset a lifetime of unhealthy foods, for example. In order to try and explain these effects, the concepts of cognitive and brain reserves have been proposed by Stern, (2002) through the Reserve model, consisting of Cognitive and Brain reserves. As these concepts are quite similar and have a tendency to be used interchangeably, the combined mechanisms are often called *resilience* (Stern et al., 2023). This more general term refers to any concept or theoretical construct that may maintain normal cognitive functioning in the face of age-related disease and healthy aging. The most prominent of these constructs are as follows:

2.1.2 Resilience

Brain reserves (BR) are thought to represent a *neurobiological* capital that is available at any given time. Neurobiological capital can be defined as the number of neurons, synapses etc. (Stern et al., 2023). This implies that everyone has accumulated this neurobiological capital, that will only resist against age-effects up to a cut-off point, i.e., when the neurobiological threshold has been reached, which could vary from person to person. Therefore, as Stern et al (2020) points out: cognitive or functional deficits would not be apparent before this cut-off point and the concept might be interpreted as the more passive resilience construct. Cognitive reserves (CR) on the other hand, represents the more active component. The latest framework proposed defines the concept as "a property of the brain that allows for cognitive performance that is better than expected given the degree of life-course related brain changes and brain injury or disease" (Stern et al., 2023, p. 101). In other words, CR refers to the normal functioning of the cognitive system in the face of age-related degradation or disease. The correlation between CR and healthy cognitive function has been found quite consistently since the idea emerged. For example, a meta-analysis with almost 130 thousand older participants found a modest positive correlation with three proxies of CR and cognition (Opdebeeck et al., 2016). The most prominent of these were occupational status and mentally-stimulating activities, which are variables included in this thesis.

Since the concept and underlying mechanisms are purely theoretical in nature and measured indirectly through proxies, such as lifestyle factors, the concept has been put under scrutiny. For example, heritability studies have shown that genetics may strongly influence the degree of cognitive decline and healthy cognitive ability coming into old age (Harris & Deary, 2011). Studies attempting to explain lifestyle factors and CR often do not include genetics as a variable, which may lead to a less precise analysis. Other traits that are harder to quantify such as creativity has also been shown to have a positive relationship with CR, but seldom included in meta-analyses (Colombo et al., 2018). As mentioned before, using neuroimaging to investigate grey matter volume and white matter integrity clarifies the functional effects that BR/CR might have, but differentiating and identifying variables that might contribute to these reserves is very hard. Thus, using CR as an explanatory variable must be done with great caution and results interpreted accordingly. In the context of this thesis, CR will be represented by a composite life-style score, which includes a comprehensive battery of both cognitive tests (MMSE) and questionnaires (see section 3.2).

2.2 Bilingualism, Mind and Brain

2.2.1 Experience dependent changes to the brain

The fundamental assumption behind this thesis is that certain stimulating experiences and activities, given enough time, will result in some adaptation in the brain. This can either be structural in the form of grey matter volume or functional through for example rs-EEG coherence. Therefore, it is important to consider that experience-based change also occurs outside the scope of this thesis, as the brain is a very malleable organ. A classic example of brain-change induced by a lifestyle of a specific experience is a study conducted by Maguire et al., (2000). They used structural magnetic resonance imaging on London taxi drivers and found that those who had spent their careers navigating through London had significantly larger posterior hippocampal volume, an area of the brain associated with storing spatial data on the environment. A control group compromising of similar participants that did not drive a taxi showed a more normal hippocampal volume. This correlation increased as a factor of time spent as a taxi driver, exemplifying that certain stimulating experiences over time, may be correlated to some neurostructural changes. Whether these changes in the brain translates to observable differences in neurocognition and behavior is still under debate and especially when considering the unique influence of bilingualism.

2.2.3 Adaptations through bilingualism

Increased volume as a result of engagement over time for a specific part of the brain is only piece of the puzzle on whether prior experience has a long-lasting effect on the brain and cognition. Bilingualism sets itself apart in this respect, as it is argued that the representations on a bilingual's two languages is constantly competing for access in two ways: indirectly in the form of dual language activation and more directly, when the bilingual speakers are forced to actively inhibit one of the languages for example when code-switching (Kroll et al., 2014) The constant inhibition that is thought to drive dual language activation may have implications for structural and functional outcomes in the brain. For example, a longitudinal study spanning over two years, where the authors recorded and compared GMV in the inferior parietal lobule (IPL), an area associated with bilingual and cognitive control. After a period of 1 year between the first and the second recording, they found that GMV increased as a function of gradual bilingual experience in 15 bilingual children (Della Rosa et al., 2013). Short-term language training has also been shown to correlate with changes over time, such as one study that examined structural changes in Japanese native speakers that received intensive vocabulary training. After a 16-week session of training, the participants who received this training saw an increase in both GMV and white matter integrity compared to a control group that did not receive training (Hosoda et al., 2013). That being said, this thesis rather focuses on how prior experience may be correlated to adaptations during wakeful rest. Thus, the most promising mechanism of bilingualism is its ability to contain two active and competing representations of language (Kroll et al., 2014).

Dual language activation is the idea that a bilingual or multilingual speaker has all their languages activated at all times, with each language competing for selection dependent on context (Spivey & Marian, 1999). There does exist considerable evidence of dual language activation in various domains of language, but no general scientific consensus has yet been reached. An area of linguistics well suited for this type of investigation is visual word recognition, i.e., the bottom-up processing of orthographic representation to conceptual semantics. In theory, if a bilingual had selective language access, which means that only one language is activated, there would not exist any interference from the competing language when encountering a word. This idea is possible to investigate using a masked translation priming paradigm (see Lupker & Kinoshita, 2003 for review). Translation priming in the masked condition is an experimental paradigm that usually precedes a lexical decision task. It involves being unconsciously primed by a non-cognate word in another language that the participant knows, which only shares a conceptual meaning (non-cognate) with the target word.

As the prime is perceived unconsciously, the language of the prime must be activated in order for the prime to exert it's influence on the lexical decision. Therefore, if only one language were active at any given time, this effect would not be visible. This has been reported across the literature, making the priming effect a scientifically robust finding, which is magnified when the bilinguals are highly proficient in the second language (Wen & van Heuven, 2017). The existence of adaptions to the brains structural and functional organization over a relatively short and intense period such as the study from Della Rosa et al (2013) and the constant suppression of either language is likely to have an effect on the brain, especially for fluid abilities such as executive functions.

Recall the distinction from section 2.1.1 on crystallized abilities such a vocabulary knowledge and fluid abilities such as WM. The literature reviewed here seems to support the notion that the mechanisms of dual-language use benefits fluid abilities the most, often visible through performance on tasks designed to assess these abilities and a tendency to perform worse on tasks that involves crystallized abilities. For example, one finding that was established quite early involves bilingual versus monolingual children's vocabulary. Several studies found that monolingual children outperformed bilingual children on the relative size and application of their vocabulary, leading to the notion that bilingualism impairs language knowledge (Genesee, 2015). The problem with this comes from comparing the bilingual children using the native language of the monolingual group, because when the relative vocabulary of both languages were considered for the bilingual children, the discrepancy disappeared (Bialystok et al., 2010). The same logic can be inferred to bilingualism research in general, as proposed by Rothman et al., (2022) and is the reason why only bilingual participants were used in this thesis.

2.2.4 Executive Functions

Since dual language activation in bilinguals relies on selective attentional control when actively inhibiting a language, as well as the net effect, a significant portion of research with this in mind, postulate that the neurocognitive demands of bilingualism may benefit executive functions (EF) when compared to monolinguals.

EF may be considered an umbrella term for higher-cognitive processes that manage, regulate, and otherwise coordinate other cognitive processes such as visual perception and attention. Inhibition of impulsive behavior and the conscious ability to focus on something regardless of distractions are important aspects of normal cognitive functioning. Previous research has revealed that increased EF performance positively correlates with several other areas such as general quality of life, academic performance, public safety and interpersonal relationships (Diamond, 2013). When considering general cognitive functioning, EFs are associated with effortful behavior and is considered domain general. These processes are not specific to any task or domain, as opposed to something like reading comprehension, usually correlated to Wernicke’s area (Ardila et al., 2016). Recall that another term for the cognitive skills that tend to deteriorate at a faster rate during a normal aging process are *fluid* abilities and EFs fall under this category. Recent research into the developmental trajectory of EFs suggest that the decline of inhibitory control and working memory occurs quite early at around 40 years of age (Ferguson et al., 2021). Thus, the possibility that bilingualism might offset or otherwise delay this degenerative process is of great interest to policy-makers concerned with an increasingly aging population (WHO, 2023).

EFs are generally comprised of three core parts (Diamond, 2013; Miyake et al., 2000):

1. Inhibition, which includes inhibition of unwanted behavior, often driven by impulses and interference control i.e., the ability to selectively inhibit unwanted stimuli. Interference control is the mechanism mostly associated with bilingualism, as the mechanism is argued to mostly apply in a bilingual language control situation. This also seems to be the aspect of inhibition that is mostly affected by dual-language use, as bilinguals show a slight advantage in tasks that tap into interference control, such as the Flanker task (Donnelly et al., 2019). Worth mentioning is that this small effect size disappeared when correcting for publication bias, making the results inconclusive.
2. Working memory, which refers to the ability to temporarily store and manipulate information in a limited window of time, most often directly after the information was presented. Diamond (2013, p.8) accentuates the difference between short term memory and working memory, with the key difference being that short-term memory may be characterized as the storage of novel information, while working memory allows this information to be manipulated.
3. Cognitive flexibility, specifically the ability to change perspectives dependent on the situation or the adaptability of focused attention (Diamond, 2013). It is a rather broad concept and incorporates other parts of EFs, such as inhibition and WM.

As the object of interest for this thesis, working memory may be divided into several slave systems subservient to a higher WM *executive* center as highlighted by Baddeley & Logie, (1999). These include the phonological loop, mostly concerned with storing and recalling auditory information, the visuo-spatial sketchpad concerned with storing and manipulating spatial and visual information. The overarching aspect of working memory in this respect is called central executive working memory (CE-WM), which is thought to be responsible for managing the stimuli in the auditory, spatial and visual domains of WM (Baddeley, 2011).

One may also argue that CE-WM plays a role in tasks that primarily tap into visuo-spatial WM as the CE system oversees and possibly delegates resources to the slave systems. Previous research shows that CE-WM is more closely associated to the visuo-spatial domain, results which stem from studies on individual differences in WM capacity. Several studies have shown a stronger correlation between the visuo-spatial WM and CE-WM, compared to the phonological loop and CE-WM in typically developing children and for adults with bipolar mood disorder (Alloway et al., 2006; Thompson et al., 2006). To the authors knowledge there are no studies that examine the specific relationship between visuo-spatial WM and the central executive. There does however exist neuro-imaging evidence on different associations of these two systems in the architecture of the brain (Gathercole, 1999). There was a clear divide between the phonological loop and the visuo-spatial domain, with the latter being more associated with the right hemisphere, namely the inferior prefrontal, anterior occipital, posterior parietal and premotor cortex. The phonological loop and the central executive was more closely associated with the left hemisphere, with specifically CE-WM associated with bilateral activation (Gathercole, 1999). As is the case with many other brain-task relationships, there is debate on the domain-specificity of the Central Executive and visuo-spatial domains and whether it is possible to differentiate between the various slave systems and the executive.

2.2.5 The Bilingual Advantage Debate

Now that we have established that WM and its executive and slave systems may be considered a central part of the EF battery, I will now focus on previous research highlighting the relationship between the two. The focus will be on various meta-analyses and a select few case studies relevant to the research question(s) at hand. In the bilingualism literature, there is a debate on whether bilinguals outperform monolinguals on EF tasks due to the increased inhibitory demands of bilingualism. This debate is still ongoing as the results are not conclusive enough to support either side.

These meta-analyses often look at the whole spectrum of EFs or focus on a specific aspect such as working memory. For example, a meta-analysis from Lehtonen et al., (2018) found a very small positive effect for bilinguals, both overall and specifically for WM. The effect of WM was moderated by age, with younger participants exhibiting an advantage over older participants, a finding that aligns with the developmental trajectory of EFs (Ferguson et al., 2021). This slight advantage that Lehtonen et al (2018) found was mitigated when adjusted for publication bias. On these grounds they concluded that bilingualism does not confer any advantage. Although thorough, the meta-analysis has been criticized for including too many studies with a sample size of 50< per group (Brysbaert, 2021) and for not basing the meta-analysis on a common criteria for measuring language proficiency. The field would greatly benefit from a standardization process for each of the variables, such as degree of bi-multilingualism, standardized proficiency measures and less monolingual comparative studies (see Rothman et al., 2022). Due to the broad nature of a meta-analysis on the overall effect of EFs, it is hard to properly capture the nuances that each component of executive functioning may exert.

2.3.2 WM Meta-analyses

Fortunately, there is also a sizable meta-analytic literature on the specific effects of working memory: Grundy & Timmer, (2017) conducted a review of the available literature and found a small to moderate effect size of greater WM capacity for bilinguals, as opposed to monolinguals. They explained this result as a consequence of dual-language experience over time. Interestingly, they also found a difference within-groups, namely between low-proficient and high-proficient participants using a Pearson *r* correlation. This lines up with previous findings from Linck et al. (2014), who did a meta-analysis on the relationship between L2 proficiency and WM capacity, a finding that was replicated by Grundy & Timmer's meta-analysis. As the authors argue, this is most likely due to increased experience with the L2 and more effort spent inhibiting influence from the L1, as outlined in 2.2.3.

A more recent metanalysis from 2022 included a detailed analysis of variables known to influence experimental outcomes, such as more restrictive age groups, task type (verbal WM or non-verbal WM), AoE, matching SES and in which language the test was administered (Monnier et al., 2022). Overall, they found a tangential advantage for bilinguals over monolinguals with a p-value of .054, but only one of the explanatory variables was statistically significant, namely the language of instruction during the task. When the participants were instructed on the respective WM tasks in their L2, a significant p-value of

.001 revealed itself. As the authors point out, this goes against previous findings from Grundy & Timmer (2017) which showed the opposite: when the WM task was presented in the L1, performance increased. This is an interesting finding that exemplifies two aspects of the bilingual experience. Firstly, it highlights the huge variability and often unstable moderator effects that are present in experimental settings with bilinguals, and it may shed light on the importance of language mode. First introduced by Grosjean, (1988) it attempts to quantify the interactional context of a bilingual. They may be either in monolingual mode, where there are no *L2 distractions* i.e., there is less interference from the L2 and in bilingual mode, where they may need to use both languages, presumably leading to an increased readiness to utilize both languages. When participants performed the WM task in the L2, they may already have been be in this mode or otherwise primed by how the experiment was designed, i.e., if they used the L1/L2 in previous segments of the experimental procedure.

Dunn & Fox Tree, (2012) conducted an experiment where they attempted to establish whether there exists a language mode, as there is no consensus on the phenomena. They designed the study in a way that made the participants wholly unaware that both their languages were important and completed a lexical decision task ("is this a word or not") using English monolinguals and English-Spanish bilinguals. They found an effect of language mode for non-words between the two groups. Bilinguals were slower in correctly identifying the non-word, presumably because of increased interference in bilingual mode, meaning they had to inhibit words from both their languages as opposed to just one. Furthermore, they revealed an effect of language dominance, as bilinguals dominant in English were faster at identifying non-words.

Extrapolating these results to the WM literature, more weight on language mode during experimental sessions and an assessment of language dominance may uncover modulating factors which has previously gone unseen. It is also worth mentioning that in Monnier et al (2022), the relevant studies were extracted in 2017 which highlights a need for an updated meta-analysis, taking into account the bountiful literature on WM and bilingualism past 2017.

2.3 Neuroimaging and resting state

2.3.1 MRI Studies

The rise of neuroimaging techniques has advanced the field to new heights, as it makes it possible to observe neurological processes inside the brain as they happen. With techniques such as functional MRI, it is possible to localize hot spots of activity in the brain using localized changes in blood flow in specific locations, both on-task and during wakeful rest. As opposed to EEG, MRI scans provide researchers with excellent spatial resolution and a temporal resolution of a few seconds (Frahm et al., 1993). Using MRI to investigate the brains functional connectivity at rest has a longer history than it's complementary EEG counterpart and much of the insight into using EEG to investigate resting state activity has been inferred from this fMRI literature (Rossi et al., 2023).

One study that is very relevant for this thesis originally sought to investigate how life-long bilingualism maintains white matter integrity for older participants (Olsen et al., 2015). They found that bilingualism correlated with increased white matter integrity and to confirm this, they also conducted a FC analysis using rs-FMRI. They hypothesized that increased white matter integrity would also result in a more widely distributed resting state network. In other words, since white matter integrity facilitates the speed of electrical impulses within the brain, this would presumably be reflected by a more widespread brain activation at-rest. Results from 7 monolingual and 14 bilingual speakers revealed that the bilinguals exhibited greater functional connectivity between anterior and posterior regions, relative to comparable monolingual peers.

A point worth noting is that the functional connectivity analysis was limited to an area heavily implicated in bilingual language control, namely the bilateral inferior frontal gyri, located in the pre-frontal cortex (Luk et al., 2011). This means that only functional connectivity between the frontal and posterior regions were assessed, as it was not possible to assess FC between the left and right hemispheres (between the ears, for example). Nevertheless, it showed that the bilingual brain has increased connectivity across the brain, while monolinguals exhibited increased connectivity between the left and right frontal areas. Although not expressly stated in Olsen et al., (2015), these results are in line with the BAPSS model, which is explained in section 2.4.5.

2.3.2. Mechanisms of EEG

The specific non-invasive-neuroimaging tool utilized in this thesis is called an electroencephalogram (EEG) and measures electrical signals coming from the brain and other electrophysiological signals, for example the action potentials from muscle contractions (Amzica & Lopes da Silva, 2017). Electrical activity that does not originate from cortical activity is referred to artifacts. As a single neuron is infinitesimally small, the brain waves that EEG captures is thought to reflect aggregates of millions of neurons activating. Essentially, EEG is a measure of the frequency in which these millions of neurons fire periodically, categorized into frequency bands (Brazier, 1961; Shackman et al., 2010). These frequency bands are biologically significant and has been sectioned with this in mind. EEG captures electrical activity from similarly oriented pyramidal neurons that lies in the outer cerebral cortex, meaning that it cannot capture brainwaves originating deeper in the brain (Rossi et al., 2023). As the electrical signal must travel from the cerebral cortex through the skull and underlying tissue, the spatial resolution is quite poor. It does make up for this with its excellent temporal resolution, making it possible to record changes in brainwaves down the millisecond. When compared to fMRI, this makes EEG a more suitable tool to investigate processing as it unfolds with great accuracy as to when a specific process takes place, but not necessarily where.

2.3.4 Frequency band associations

Raw EEG data is usually separated into the frequencies at which the EEG signal oscillates. These rhythmical oscillations are also called brain waves. The alpha frequency for example, was first described by the EEG pioneer Hans Berger, where he noted that alpha frequency was very prominent during wakeful rest with the eyes closed (Berger, 1929, as cited in Stone & Hughes, 2013). Much of the terminology and frequency bands are still in use today and can be roughly sectioned into the following frequencies: alpha (8-12 Hz), beta (13-30 Hz), delta (1-2 Hz), gamma (30-200 Hz) and theta (4-8 Hz). The specific hertz range vary to some degree, depending on the study and there also exist subcategorizes within each band, such as low gamma (30-70 Hz) and high gamma (70-150 Hz). Certain bands can also vary based on individual differences, which has prompted a methodological framework that calculates each participant's own alpha range, often determined by individual traits such as peak alpha frequency, age etc. (Corcoran et al., 2018). To account for individual differences in the alpha band, this thesis utilizes individual alpha frequency (IAF) to account for this variability (see section 3.5.2 for details).

Keep in mind that EEG has a rich history and each frequency band have been associated with several cognitive and neural processes not directly relevant to this thesis. I will go through a few of these that may have the potential to obscure the interpretation of the results. For example, gamma band activity has been associated with sensorimotor processes related to the planning and execution of movements, as well as other motor-processes not yet fully understood (Ulloa, 2021). One would presuppose that this would not be present with a rs-EEG investigation, but activity in the same band has also been associated with the imagination of motor actions, visible through the use of EEG (Amo Usanos et al., 2020). Combine this with relatively few results on the gamma band for the case studies that will be presented in section 2.4, significant results in the gamma band should be approached with this in mind. Combinations of different frequencies has also been accounted for in the literature when it comes to long range (between ROIs) and local processing (within ROIs). Since gamma oscillations fluctuates in short waves, gamma frequency in EEG is thought to somewhat reflect local processing. When compared to slow-wave frequencies such as alpha and theta, they rather indicate long-range processing between regions of the brain (von Stein

& Sarnthein, 2000). Associations to exponents of bilingualism and aging will be described in section 2.4.

2.3.3 Different types of EEG analysis

Combining the temporal resolution with a clever experimental design with triggers, makes it possible to phase-lock EEG data to certain events to investigate fine-grain processing as it unfolds. The electrophysiological response associated with an event is referred to as Event Related Potentials, a technique extensively used when attempting to describe linguistic processing. ERPs are only one way to analyze the brains signals and the focus here will be on the severely understudied area of neural oscillations. Compared to ERPs, where the desired event related potential is averaged across multiple trials and participants, the extraneous *noise* or other signals deemed irrelevant for the study of the relevant ERPs are often overlooked. As an ERP is tied to a change in the EEG signal based of that event, the brain data around this specific event is often lost. There is nothing inherently wrong with this when conducting an ERP study, but there exists comparatively little data on spontaneous neural oscillations thought to reflect the inherent spontaneous activity within the brain (Rossi et al., 2023).

In order to get a better understanding of activity over time that is not evoked by a stimulus, an analysis of the spectral signal is a better solution. As Rossi et al., (2023) highlights, there are two analyses at play here. Firstly, a spectral power analysis records relative changes in power over time, over each electrode or electrode sites (ROIs). Recall that changes in power in these circumstances reflect large-scale neuronal activity over the electrodes. Therefore, changes in power over an electrode site likely reflects increased activity over that specific ROI. One could also measure the synchronization of power over different electrode sites through a mean coherence analysis. For example, if electrode 1 and electrode 2 oscillated in the same frequency at the same time, this would indicate communication within the brain between these two electrode sites, giving rise to the description of functional connectivity.

To further complicate this, EEG is thought to only capture pyramidal neurons near the scalp, therefore it is not possible to capture activity that originate from areas closer to the cerebellum. This has led to doubts as to whether a spectral power and mean coherence analysis is sufficient to extrapolate functional connectivity with EEG (Marinazzo et al., 2019; Van de Steen et al., 2019). Thus, any kind of analysis pertaining to functional connectivity with EEG should be interpreted carefully. Nonetheless, spectral analysis both on task and at rest have been used extensively in various fields, including language processing, neurocognition and more recently at the intersection between the two (Rossi et al., 2023).

2.3.3 Resting State EEG and WM

If rs-EEG is a measure of the brains synchronized activity at rest, what exactly can be inferred from it? A review from 2018 highlights some areas that rs-EEG have been successfully utilized for this purpose (Anderson & Perone, 2018). Adopting a developmental viewpoint, this article shows that several EEG frequency bands change in power as a function of age, with every band except for alpha decreasing in power as the brain ages. This decrease in EEG measures has also been observed in rs-EEG coherence. For example, one study with seventeen thousand healthy polish drivers with a mean age of 43.2 years (SD = 11.2), conducted rs-EEG coherence analysis and found a steady coherence decrease in all frequency bands, except for beta (Vysata et al., 2014). These results were confirmed by a similar review on EEG functional connectivity which found that coherence over the frontal, temporal, parietal and occipital ROIs decreased with age (Moezzi et al., 2019). These articles only investigated how age impacts functional connectivity, so their usefulness in connection with this thesis is limited, as the crux of my RQs is how prior experience may impact rs-EEG coherence, but nevertheless provides a solid foundation for understanding how the brain's connectivity decreases over time.

For working memory, there has been disparate results when relating rs-EEG power to WM performance in various domains across age groups and most studies assessed on-task EEG. Jabès et al., (2021) investigated rs-EEG power in relation to an allocentric visuospatial WM task. Allocentric WM refers to a property of visuo-spatial WM that concerns itself with manipulating visuo-spatial information from different points of view. For example, navigating through a maze and remembering the path may be considered allocentric WM, while memorizing the layout of a maze without traversing is considered as visuospatial WM. Jabès et al (2021) found that alpha, beta and theta power was correlated with allocentric WM performance in older, but not younger adults. They also concluded that rs-EEG power was not sufficient to predict WM performance, as the EEG results varied based on condition (eyes-open vs eyes-closed) and the parameters of the task, yet there were noticable differences by age. The last study that is somewhat relevant, looked at whether rs-EEG *power* could predict cognitive performance in healthy older adults (Finnigan & Robertson, 2011). In the cognitive test battery, they included the digit span test, which is a robust measure of verbal WM capacity, but did not find any statistically significant relationship for working memory.

When it comes to functional connectivity, I could find no studies has directly related rs-EEG mean coherence to WM performance. There does however exist a study that examines EEG coherence on-task: Sauseng et al., (2005) recorded EEG from 29 participants during a central executive WM task. They found increased connectivity between the pre-frontal areas and anterior areas in the alpha frequency simoultaneously, which implicate that these two areas work in tandem when dealing with WM load. Whether these results can be extrapolated to rs-EEG coherence is hard to answer as the field lacks a specific framework that connects experience-dependent functional changes over the course of a lifetime to task performance (Anderson & Perone, 2018, p. 49). The gamma band has also been implicated in WM maintenance, but again this correlation has not been investigated using resting state EEG (Miller et al., 2018).

2.4 Case Studies & Models

2.4.1 Fleck and colleagues

The only study that examines the effect of reserves on resting state brain coherence in healthy adults was conducted by Fleck et al. (2017). They recorded rs-EEG in the eyes open and eyes closed condition for 90 participants in the 45-64 age range. They utilized a cross-sectional design where they divided the participants into a low-CR group and a high-CR group to examine group differences by CR. Age groups were also created by placing participants aged below or above the mean age of 58.51 years of age. They measured cognitive reserve through a composite score which consisted of an estimated verbal IQ from the National Adult Reading Test and years of education. They also included several other measures, to validate differences between the two CR groups and found that the high CR group performed better on the MMSE, digit span (WM) and verbal fluency. This finding is in line with the reserve hypothesis (Stern, 2002). As the authors only utilized verbal IQ scores and years of education to assess CR for the participants, an argument can be made that these two measures are not sufficient to gauge cognitive reserve levels. Since they validated the CR groups by correlating each group’s behavioral performance with the CR score, this somewhat strengthens their methodology. Future studies would benefit from a more comprehensive measure of CR.

Instead of employing a ROI design with electrode pairings based of the location of electrodes on the scalp, Fleck et al (2017) used a right-hemisphere and left-hemisphere design to examine coherence within hemispheres. Younger participants had greater coherence in the left hemisphere, while older participants exhibited greater coherence in the right hemisphere. As for the CR group differences, young participants with low CR had a greater coherence in both hemispheres than their young participants with high CR. For older participants, the authors reported the opposite findings in the theta and alpha bands, which suggests that higher levels of CR in older participants is a contributing factor for greater rs-EEG coherence. A limitation that the authors acknowledge is that they did not investigate coherence between hemispheres, rendering the full-picture of how age and CR affect rs-EEG incomplete.

2.4.2 Bice and colleagues

Bice et al., (2020) investigated 106 bilinguals vs 91 monolinguals with resting state EEG (eyes closed) and using Individualized Alpha Frequency (IAF). They found that bilinguals had greater alpha power compared to monolinguals. A slight power increase in the gamma-band was also found between Frontal regions and right posterior, which has been associated with bottom-up integration with WM (Miller et al., 2018). For coherence specifically, bilinguals exhibited significantly greater and broader coherence in the alpha and beta bands. They attributed the increased power and coherence of the alpha band as an indication of increased experience with managing two languages. Further analysis of the alpha band revealed that this increase was associated with several exponents of bilingualism, namely L2 use, higher L1 proficiency and earlier age of acquisition (AoA), which is in line with the notion that the alpha band is heavily involved in language control (Klimesch et al., 2007). To verify these at-rest oscillatory dynamics, they also included a Simon task, designed to measure inhibitory control. Again, they found a small advantage in behavioral performance for the bilinguals, but this increased performance did not correlate with increased power or coherence.

The opposite was found for the monolinguals, where a spike in alpha power over frontal electrodes correlated with increased behavioral performance. As the monolinguals do not have as much experience with the high inhibitory demands that accompanies dual language use, this renders their sensitivity to changes in alpha power band higher than the bilinguals. For the greater beta coherence in bilinguals, this was attributed to enhanced bilingual language processing, presumably because beta oscillations has previously been linked to language processing in dual-language contexts (Stocco & Prat, 2014) and working memory (Miller et al., 2018). Most studies investigating the beta band uses on-task EEG, so the modulation of the beta frequency during wakeful rest is relatively unknown, save for a few studies that found the beta-frequency associated with a willingness to use the L2 and L2 learning rate (Prat et al., 2016, 2019). The last frequency band that Bice and colleagues investigated was the theta-band, where they found significantly greater power and marginally greater coherence over the left frontotemporal and medial electrodes for monolinguals. This increase in theta power was localized over the frontotemporal electrodes and was correlated to L1 proficiency. Overall, the EEG results lines up with the BAPSS model, which postulates that bilinguals rely more on posterior networks, while monolinguals exhibit more frontal activation (J. G. Grundy et al., 2017).

2.4.3 Pereira Soares and colleagues

Adopting a purely bilingual approach, Pereira Soares et al., (2021) investigated a diverse pool of bilinguals, 55 German and 48 L1 Norwegian/L2 English participants. 25 Germans were considered early bilinguals with Italian as their heritage language and the rest were late L1 German/L2 English bilinguals (Mean AoA: 6.25 yrs). This diversified participant pool reflects an important step into using bilingual speakers with different language backgrounds, rather than comparing results to monolingual speakers. Building off the previous study discussed, the authors investigated if differential language use can affect rs-EEG power and coherence. Overall, their findings did not match with the results from Bice et al: No correlations between language background variables were found in alpha power and theta power. AoA for L2/2L1 correlated significantly with high beta and gamma, revealing a relationship with these two bands and the earlier a participant acquired their L2, the stronger the correlation. Further analysis of this result showed that this effect was broadly distributed across brain regions ; the effect was not modulated by any specific brain areas, which again is the opposite findings to from Bice et al (2020).

As for the coherence results (Fig 1.), Pereira Soares et al (2021) found increased coherence in the alpha and theta bands which correlated with the non-predicted variable of *Social Use,* a measure of how often a bilingual mix their languages in social settings. A correlation between high beta and AoA was found, and again the effect scaled with how early a participant acquired the L2/2L1. This same correlation was also nearly significant in the gamma band between posterior regions. Socio-economic status negatively predicted low beta coherence and the negative effect was widely distributed.

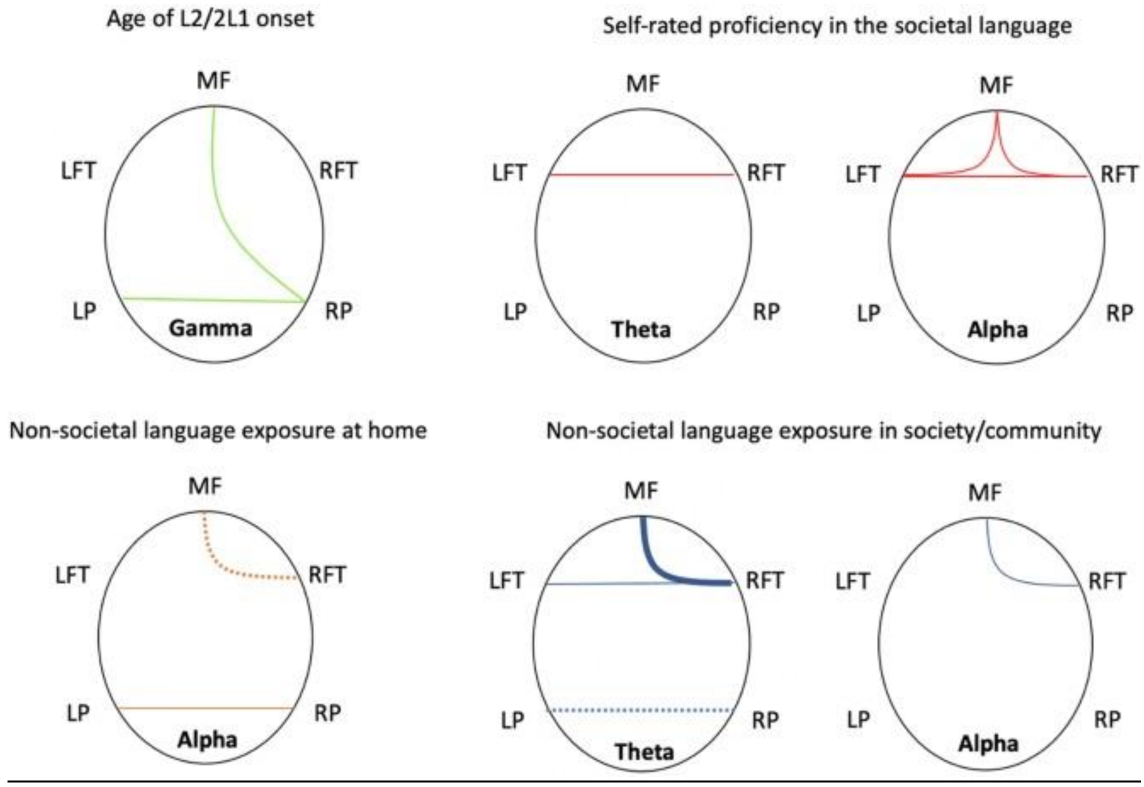


Figure 1: *Results of mean coherence in Pereira Soares et al (2021). The lines represent functional connectivity in brain region pairings mean coherence in each denoted frequency band. The dotted lines represent significant correlations that were unexpected. Thin lines represent correlations between expected predictor variables. Bold lines represent significant correlations related to language background.*

Results from the coherence analysis reveal a few interesting findings highly relevant to this thesis. There was a difference in the modulatory effects for self-rated proficiency in the societal language and different uses of the societal language. Proficiency in the societal language predicted coherence between frontal regions, but not for the posterior regions (LP-RP), while *usage* of the non-societal language in different contexts predicted greater coherence between both the frontal region and the posterior regions

Firstly, alpha coherence was not only shown to be modulated by language experience on a larger scale, but it revealed that alpha coherence was related to three different determinants of dual-language use, as seen in Figure 1. Proficiency in the societal language predicted coherence between frontal regions, but not for the posterior regions, indicative of a more complex relationship between self-perceived proficiency and language use. The really interesting finding is that different uses of the non-societal language at home and in social settings independently affects coherence, as posterior Alpha coherence was modulated by usage at home, but not in social settings. Theta was also not found to modulate usage at home, even though it was implicated in both proficiency and social use. This sets the precedent for a new wave of research that treats bilingualism not only as a spectrum of experiences, but also considers that different language contexts also plays into neurocognitive outcomes.

2.4.4 Calvo and colleagues

The last study related to functional connectivity at rest and bilingualism investigated differences in power, reactivity and coherence in 25 monolinguals and bilinguals (Calvo et al., 2023). They conducted rs-EEG recordings in both the eyes open and eyes closed conditions. Interestingly, they found that monolinguals had greater coherence in the alpha band for the eyes closed condition and found increased alpha power and coherence for the bilinguals in the eyes open condition. In the beta band, they found that monolinguals exhibited greater coherence in both conditions, except for the posterior electrodes in the eyes open condition.

These results are the opposite of what Bice et al (2020) found, as they reported increased alpha power and coherence for eyes closed. These reversed findings may be due to the interplay between the two conditions, as Calvo et al (2023) hypothesize that increased coherence in the eyes open condition may be interpreted as increased neural efficiency. They state: “bilinguals recruited fewer attentional resources when they opened their eyes and the difference between both conditions indicated a pattern of efficiency” (p.5). Including both conditions in a given experiment may give insight as to specific processing differences that otherwise would not have been captured with single-condition experiments. Furthermore, the general localization of changes in power and coherence in the two groups shows that monolinguals rely more on frontal regions than bilinguals. Calvo et al (2023) and Bice (2020) both found less neural recruitment for the frontal regions and increased recruitment for the posterior regions during wakeful rest, indicating a trend in the reviewed studies.

2.4.5 PASA to BAPSS

This last finding is supported by the Bilingual Anterior to Posterior and Subcortical Shift (J. G. Grundy et al., 2017). This model was originally devised to account for differential neuroimaging findings for monolinguals versus bilinguals. The model postulates that given enough engagement with dual-language use, bilinguals will shift their executive control processing and language processing from the anterior regions to the posterior and subcortical areas. Thus, the BAPSS model is a model of efficiency, with the result being that monolinguals and bilinguals recruit neural resources from different areas when confronted with stimuli that requires a degree of executive and language control. Interestingly, this hemispherical shift also occurs in the literature of neural recruitment in conjunction with aging, only in the opposite direction.

The posterior-anterior shift in aging (PASA) is a phenomenon in older adults where it is consistently found that neural recruitment shifts from less occipital activity and increased frontal activity (Davis et al., 2008). Keep in mind that this shift in efficiency has not only been found in executive and language control, but also for long-term retrieval and encoding of memories (Daselaar et al., 2003; Dennis et al., 2007). This shift has been attributed to the degenerative effects of aging on the brain and results in an increased reliance on the pre-frontal cortex. As the authors put it: “results suggest that this PASA pattern acts in a compensatory manner to offset posterior-related neuroanatomical declines associated with aging” (Davis et al., 2008, p. 10). When examining this shift in activation specifically for bilinguals, the opposite pattern emerges, which suggest that life-long bilingualism makes the bilingual brain more efficient and able to recruit neural networks more efficiently and especially so during older age. One could argue that the BAPSS was created to account for findings in bilinguals where the classic PASA was reversed or otherwise delayed.

Juxtaposed next to the reserve model (section 2.1.2), the BAPSS rather seeks to understand differential recruitment as a function of bilingual experience, rather than focus on how CR is accrued and how if the accrued CR contribute to more successful aging. Thus, the reserve model attempts to *cast a wider net* by also postulating that other cognitively challenging activities and life-style choices may also contribute to CR, while the BAPSS seeks to specifically clarify divergent neuro-imaging evidence that the PASA model cannot properly account for. As mentioned, the results of Bice et al (2020) and Calvo et al (2023) was largely in line with the BAPSS model. On the other hand, the BAPSS model was not satisfactory in explaining the results from Pereira-Soares et al (2021), as the results were relatively broadly distributed across the brain. The basis of these results will influence my predictions as to the link between WM and rs-EEG coherence and for which exponents of bilingualism and age that best accounts for coherence and WM performance in healthy bilinguals.

2.5 The Present Study

This thesis seeks to investigate whether there is a relationship between visuo-spatial WM performance and the brains intrinsic activity at rest, measured through eyes-closed resting-state EEG. Crucially, how do experience-based factors such as varying bilingual engagement mediate this possible connection, when other lifestyle factors are controlled for? Since bilingualism occupies a unique role within the brain and has been shown to induce some neurocognitive adaptations, examining how dual-language use may induce these adaptations independently from other experience-dependent factors (diet, exercise, education etc.) is an important step for further research. This inquiry is made possible through an extensive questionnaire battery on prior language engagement and lifestyle experiences. Furthermore, exploring how these factors affect functional connectivity is inherent to such a design, which may provide some insight into how multilingualism independently affects coherence throughout the adult lifespan. The thesis builds on previous research in the field, with the added novelty of including various age groups and utilizing a bilingual-centric approach that contrasts the monolingual comparative approaches that much of the previous literature builds on (Rothman et al., 2022). The use of EEG to assess functional connectivity is central to this investigation and provides a novel approach to how prior bilingual experience may be decisive in predicting WM performance and rs-EEG coherence.

Research Question 1: Does bilingual language engagement modulate rs-EEG coherence patterns throughout the lifespan, when other lifestyle factors are controlled for?

Research Question 2: Does bilingual language engagement modulate visuo-spatial WM performance throughout the lifespan, when other lifestyle factors are controlled for?

Research Question 3: Does WM performance correlate with rs-EEG coherence patterns and if so, what are the modulating factors between this connection?

2.5.1 Predictions

RQ1

Predictions for RQ1 will be presented in order of likelihood, with bilingual engagement predicted to affect rs-EEG mean coherence independently, that is above and beyond contributions from other lifestyle factors.

1.

Participants with a high degree of multilingual engagement will exhibit higher alpha, beta and theta coherence in Posterior regions (LP-RP) and between Anterior and Posterior regions (RFT-RP, RFT-LP, LFT-LP, LFT-RP). This prediction is based on the findings from Bice et al (2020), where participants with more dual-language experience showed greater coherence in these frequencies and ROIs. The BAPSS model also postulates that seasoned bilinguals rely more on posterior regions as opposed to bilinguals with less engagement and experience with two languages. The reasoning for enhanced theta coherence stems from a finding from Pereira-Soares et al (2021) where they found a correlation between theta coherence and social dual-language use.

2.

Concerning lifestyle factors related to the accrual of CR (See Section 2.1), there will be a positive correlation for age and lifestyle-score in RFT-RP coherence and MF-RP coherence in alpha and theta frequency. There will also be a negative correlation for age between LFT-LP & MF-LP coherence in alpha frequency. This prediction builds on findings from Fleck et al (2017), who found that older participants high in CR exhibited increased coherence in the right hemisphere, while younger participants exhibited increased coherence in the left hemisphere. Keep in mind that Fleck's participant sample only included participants above the age of 45, so previous findings on the relationship between rs-EEG coherence and CR in younger participants have thus far gone unexplored in the literature.

3.

Participants with a higher lifestyle score will have lower coherence in low beta across various ROIs. This prediction builds upon a finding from Pereira-Soares (2021) where SES negatively predicted low beta coherence, but not in any specific ROIs. Furthermore, older participants with a high lifestyle score will exhibit more coherence in frontal regions (RFT-MF, LFT-MF) in line with the PASA model (Davis et al., 2008).

RQ2

1.

WM performance will positively correlate with MLD. This prediction builds off previous literature on the bilingual advantage (see Section 3.2.4) where there are some evidence that bilingual engagement provides a net benefit to EFs, which will be visible through MLD.

2.

WM performance will negatively correlate with age and have a positive interaction with MLD. This prediction expands on the notion that the possible bilingual advantage will positively affect the negative relationship between age and deteriorating EFs coming into older age, possibly flattening this negative correlation (see figure 5.) For older participants with a high lifestyle score, the negative relationship will also be flattened by the accrual of CR over time, as measured by lifestyle score, supported by the reserve hypothesis as discussed in section 2.1.2.

RQ3

1.

Whether WM performance will correlate with rs-EEG coherence is hard to predict, as the research surrounding this is not very developed, as discussed in section 2.3.2. Nevertheless, Sauseng et al (2005) found increased connectivity between pre-frontal and posterior areas in the alpha and theta frequency when performing a central-executive WM task. Seeing as the central executive WM system is directly related to the other slave-systems of WM, it is possible that this increase in alpha may be reflected in rs-EEG patterns as well, but this is highly speculatory. To that end, there will be a positive correlation for alpha and theta coherence between the following ROIs: (RFT-LP, RFT-RP, LFT-LP, LFT-LP) and WM performance.

3 Methodology

3.1. Participant demographics

Data was initially collected from 93 participants with 3 participants excluded due to noisy data, 29 of the participants were male and 61 were female. The ages ranged from 19-82 (mean=49,3, SD=18.06). All participants were native speakers of Norwegian and most were early sequential English bilinguals. All participants had normal or corrected-to-normal vision and hearing. As the overarching goal of the study is to investigate healthy bilinguals, participants were excluded based off on these possibly confounding variables: colorblindness, diagnoses related to learning difficulties, traumatic brain injury, psychiatric or neurological disorders, depression, and psychotropic medicine. Participants were recruited from various platforms where the study was advertised, such as social media, newspapers, notice boards etc. Upon completion of the experiment, participants were compensated with a 500 NOK gift card.

3.2 Materials and procedure

3.2.1 Materials

<u>Corsi Block-tapping test</u>

A computerized version of the Corsi Block-tapping test (Corsi, 1972) was used in the experiment. The stimuli were presented on a 27" monitor running at 60 hertz. The task was administered using E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA). The trial consisted of two slides with instructions for the controls and the procedure. Following instructions, a trial run of with 4 trials with corrective feedback is shown. A green checkmark is displayed for the correct replication of the sequence or a red X for the incorrect replication. Following the completion of the trial, final instructions are displayed indicating the start of the experimental stimuli and corrective feedback is turned off. The experimental part consists of 20 trials with increasing difficulty. The stimuli consist of nine 7x7 cm rectangular blocks that are numbered 1-9. The blocks light up in a certain sequence which is randomized for each participant. When the sequence is completed, participants immediately use a computer mouse to repeat the sequence shown.

3.3 Procedure

3.3.1 Data collection

The experiment itself consisted of two parts, both approved by the Norwegian Centre for Research Data (NSD). Part one took place online as in a virtual meeting room after participants signed a consent form which detailed what the experiment entailed, the anonymization of data post-collection and their rights as voluntary participants. The rest of part one is carried out interview style where the interviewer, together with the participant completes the following questionnaires: Language History Questionnaire (LHQ3) which maps bi-multilingualism (Li et al., 2020). The short form Dietary Questionnaire, mapping the participants diet (Cleghorn et al., 2016). The International Physical Activity questionnaire which maps physical activity (Craig et al., 2003) The Social Network index which assess social activity (Cohen et al., 1997). Taken together, these questionnaires form a comprehensive picture of each participants language and lifestyle profile, as well as ensuring relative proficiency of the L2 through self-reported measures and by the fact that each participant had to complete the interview in English. Aside from fatigue, splitting the experiment into two sessions allowed us to keep the language of the interview separate from the language of use during the EEG experimental session. All materials and the spoken language by the researcher during part two were in Norwegian to ensure that the participant did not activate their second language and switch language modes (Grosjean, 1988, 1998).

Upon arrival to the second part, participants completed the Cognitive Reserve Scale (Leoń et al., 2014), which quantifies the degree of CR in a given participant based on mentally stimulating activities performed throughout the lifetime and the Mini-Mental Status Evaluation in Norwegian (Strobel & Engedal, 2009). The participants also completed the MacArthur Scale of Subjective Social status, a single-item measure of subjective social status relative to others in Norway and in the local community (Adler et al., 2000). After completing these two tests, the participant was capped with a 32 Channel Wet-Sponge R-Net cap, then the cap is connected to a LiveAmp 32 channel amplifier (Brain Products). After capping, the participant is seated in a dimly-lit room with acoustic attenuation, approximately 60cm in front of a 27-inch PC monitor. The 10-20 system was used for electrode placement where the FpZ (Ground) and FCz (Ref) were used as reference. The impedance threshold was set at 100 kΩs with no electrodes exceeding this threshold. Data was collected using a LiveAmp amplifier (Brain Products) at a 2000Hz sampling interval with a sampling rate of 500Hz. After capping, the participant is shown a fixation cross and asked to close their eyes for 5 minutes during which Resting-State EEG is recorded. Following the EEG experimental block, the participants completed the Corsi Block Tapping test without the EEG-cap, using the same PC setup.

3.4 Behavioral data analysis

3.4.1 Corsi analysis

Raw experimental data was merged using E-merge and exported to an r-friendly environment. The raw data was then put through a script which removed excess data and calculates two measures of performance, adapted from Monaco et al., (2013). The first proxy for performance is the Corsi-Span which is the longest correctly reproduced sequence, where the mean for all participants were 6.91. As this measure alone is not sufficient to determine overall performance, as there may be cases with anomalies, where a participant for example fails to reproduce the majority of sequences, save for one. To account for this and get a more comprehensive measure, the percentage of correctly reproduced sequences was calculated for each participant. The Corsi-span and total percentage of correct scores were normalized and added up together with equal weight, following Broadway & Engle, (2011). This outcome variable was named Corsi Performance.

3.4.2 MLD

Using data gathered from the LHQ3 a composite score of bilingual engagement named MLD was calculated for each participant using the method derived from Gullifer & Titone, (2020). The composite score is designed to measure individual differences in bi-multilingual language use in various interactional contexts using each participants proficiency, dominance in both languages and how often they use their languages in different contexts, which was gathered from the LHQ3's supplemental materials (Li et al., 2020). The calculation provides a score ranging from 0-2, where 0 represents the most extreme cases where a bilingual may be considered functionally monolingual and a score of 2 represents a scenario where a speaker uses all (4) languages equally. The mean MLD score for the participants was 1.007 (SD = 0.036) with a max value of 1.05 and a minimum value of 0.85. This means that all participants are fairly balanced in their language use.

3.4.3 Lifestyle score

In order to control for each participants lifestyle experiences, separate from the bilingual engagement, a lifestyle composite score was calculated from the various questionnaires and supplemental data. The lifestyle score includes data from activities through the lifespan from the CRS, data on each participant's social network, their diet, physical exercise, MMSE and their socioeconomic status derived from the questionnaires described in section 3.3.1. SES was calculated as the mean education level for the participant and their parents. The score produces values on a scale from 0-1, where 0 represent the lowest possible score from the questionnaires and 1 represents the highest achievable score. The mean lifestyle score from the participant sample was 0.65 (SD = 0.07) with a max value of 0.79 and a minimum value of 0.47. Including data on several activities related to lifestyle and the possible accrual of CR, enabled the model to account for the influence of these variables during the analysis

3.5 EEG Analysis & Models

3.5.1 EEG preprocessing

The recorded rs-EEG signal for each participant was pre-processed using BrainVision Analyzer, Version 2.2.2, (Brain Products) to ensure clean data for analysis. The data is first sampled down to 128hz, then a visual inspection is done to determine the best point for segmentation. The data is trimmed down to a 4.5 minute long recording and sampled down again to 128hz. Next, the data is re-referenced down to the average of all electrodes, then filtered with a band-pass filter (1-45 Hz) and 50 Hz notch filter. Then an Independent Component Analysis (ICA) for detecting blinks or other artifacts were applied using an infomax restricted algorithm. The processed data was then exported to an r-friendly environment for further processing.

3.5.2 rs-EEG coherence processing

The preprocessed data was loaded into a script adapted from Prat et al (2016) by Pereira-Soares et al (2021) and Rook (2022) to make it compatible with a 32-channel wet-sponge system. As highlighted above, recent research shows that alpha frequency can vary considerably from participant to participant, so IAF will be used in lieu of a fixed bandwidth (normally 8-12 Hz). The script calculates IAF using the alpha peaks each participant exhibits within the 7-14,5 Hz range and calculates this in respect to the alpha frequency over all electrodes (Whole-Head IAF) with a fixed bandwidth[1]. Theta is defined as all frequencies below IAF-6 Hz to IAF-2 Hz, alpha from IAF-2 Hz to IAF+2.5 Hz, low beta from IAF+2.5 Hz to IAF+8 Hz, high beta from IAF+8 Hz to IAF+20 Hz, and gamma as anything between IAF+20 Hz and 40 Hz.

Then long-term signal drift not detected during pre-processing is removed, then the time-series EEG signal is divided into 2-second segments with a 25% overlap (default sliding 0.75). This limits the lower bounds of the frequency to 0.5 Hz, rendering the delta frequency imprecise and therefore removed. Then each segment is analyzed for any blinks or artefacts that preprocessing might have missed, and any > 100 microvolt oscillations is removed. Every segment that passes quality control is passed through a Fast Fourier Transformation which is maintained and squared. The FFT spectra for the segmented data is averaged together and a mean spectrogram created, which is then log-transformed to represent power in decibels. Then the data is grouped to reflect electrode regions or Regions of Interests (ROIs) and coherence and power is calculated in the following regions: Right Parietal (RP), Right Frontal Temporal (RFT), Left-Frontal Temporal (LFT), Left Posterior (LP) and Medial Frontal (MF).

---

[1] Adapted from https://github.com/UWCCDL/QEEG: See link for detailed walkthrough of coherence script created by Prat et al (2016).

The script then outputs the coherence between these ROIs using any channels that have not been rejected, as well as the coherence between all electrode pairings.

After the initial analysis, the exclusion criteria of Pereira-Soares et (2021) were followed, which involves excluding any channels with an average log power exceeding ±2.5 standard deviations to the average of all channels, which turned out to be 2.14% of all processed channels. Then any channels that did not have an identifiable alpha peak were omitted from the IAF, resulting in 4.95% of all electrode pairings. These were only omitted from the IAF, but still included in the coherence analysis as the data was still within acceptable levels. Lastly, 3 participants with less than 24-channels of usable data were then discarded to ensure stability and reliability for the remaining participants.

3.5.3 Model 1: Coherence

Model 1 attempts to answer research question 1: Does bilingual language engagement modulate rs-EEG coherence patterns throughout the lifespan, when other lifestyle factors are controlled for?

A robust regression model was run for each ROI pairing on all five frequency bands, resulting in a total of 50 robust regression models (Maechler et al 2023). Robust regression with a MM-type estimator was chosen in favor of a linear regression, as brain oscillations tends to be non-normally distributed. A robust regression has the added benefit of being less sensitive to outliers and sub-optimal residuals (Soares et al., 2022). In order to account for prediction 1, age and MLD was treated as an interaction term. All independent variables were normalized using the scale function from base R to make interpretation easier and to ensure that the independent variables were on the same scale. Variance Inflation Factor tests were done to ensure that the data was not multicollinear, as well as the Durbin Watson test for autocorrelation (Fox & Weisberg, 2018).

Every model was structured in the following way, with differences in frequency and ROIs:

lmRob (Coherence ~ Age * MLD + Lifestyle)

3.5.4 Model 2: WM performance

Model 2 attempts to answer Research Question 2:

Does bilingual language engagement modulate visuo-spatial WM performance throughout the lifespan, when other lifestyle factors are controlled for?

A multiple linear regression model was run with the composite Corsi Performance variable, which includes each participants corsi-span and the total percentage of correct answers, normalized and added together with equal weight. All independent variables were normalized using the scale function. Again, age and MLD was treated as an interaction to account for the effect of bilingual language engagement when other lifestyle factors are controlled for.

lm (Corsi Performance ~ MLD * Age + Lifestyle)

4 Results

4.1 Model 1: rs-EEG Coherence

4.1.1 Alpha Frequency

Between LP-RFT, age negatively correlated with coherence (E = -0.009, SE = .004, p = *.031).* Interestingly, MLD also had a negative relationship with coherence (E = -0.011, SE = .004, p = .027). There was almost a significant interaction between Age and MLD with a p-value of .063, but as it did not exceed the threshold of 0.05 it is not possible to distinguish the result as deviating from a random distribution.

Between MF-RFT, age negatively correlated with coherence (E = -0.02, SE = .007, p = *.006)*

4.1.2 High Beta Frequency

No significant results were found in the high beta frequency band between any ROIs.

4.1.3 Low Beta Frequency

Between LFT – MF, age negatively correlated with coherence (E = -007, SE = 0.003, p = .047).

Between MF-RP, lifestyle positively correlated with coherence (E = .005, SE = .002, p = 0.035)

4.1.4 Gamma Frequency

Between LFT-MF, MLD positively correlated with coherence (E = -0.008, SE = .003, p = .019)

Between MF-RFT, age negatively correlated with coherence (E = -0.011, SE = .002, p = .0001). There was also a negative correlation between MLD and coherence (E = -0.008, SE = .002, p = .003)

Between MF-RP, age negatively correlated with coherence (E = -0.006, SE = 0.02, p = .009)

4.1.5 Theta Frequency

In theta-band, there were significant negative correlations between age and coherence in the following ROIs: LFT-LP, LFT-MF, LP-RFT, MF-RFT and MF-RP. Interestingly, there were also one negative relationship between lifestyle and coherence between LFT-LP and one positive relationship between the same variables in LP-RFT. See table 1 for significant values and figure 2 for illustration of all significant results.

Model 1 Theta

	Theta LFT-LP			Theta LFT-MF			Theta LFT-RP			LP-RFT			MF-RFT			MF-RP		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.527	0.524 – 0.530	**<0.001**	0.546	0.538 – 0.554	**<0.001**	0.573	0.565 – 0.581	**<0.001**	0.569	0.564 – 0.574	**<0.001**	0.549	0.542 – 0.555	**<0.001**	0.568	0.562 – 0.573	**<0.001**
Age c[, 1]	-0.004	-0.007 – -0.001	**0.008**	-0.012	-0.020 – -0.004	**0.002**	-0.009	-0.017 – -0.001	**0.025**	-0.007	-0.013 – -0.002	**0.006**	-0.013	-0.020 – -0.007	**<0.001**	-0.007	-0.013 – -0.001	**0.029**
MLD c[, 1]	0.000	-0.003 – 0.004	0.785	-0.005	-0.013 – 0.003	0.202	-0.005	-0.013 – 0.003	0.198	-0.005	-0.011 – 0.000	0.067	-0.006	-0.013 – 0.001	0.100	-0.001	-0.008 – 0.005	0.643
Lifestyle Score c[, 1]	-0.004	-0.007 – -0.001	**0.004**	-0.001	-0.008 – 0.007	0.834	0.001	-0.007 – 0.008	0.827	-0.007	-0.011 – -0.002	**0.010**	-0.001	-0.007 – 0.005	0.701	0.002	-0.004 – 0.008	0.444
Age c[, 1] Ã — MLD c[, 1]	-0.001	-0.004 – 0.002	0.517	0.000	-0.009 – 0.009	0.942	0.006	-0.002 – 0.015	0.147	0.002	-0.004 – 0.008	0.533	0.000	-0.007 – 0.008	0.929	0.004	-0.003 – 0.011	0.273
Observations	72			86			85			73			85			84		
R^2	0.079			0.126			0.091			0.089			0.217			0.068		

*Table 1**:** Significant results from Model 1 in the theta band.*

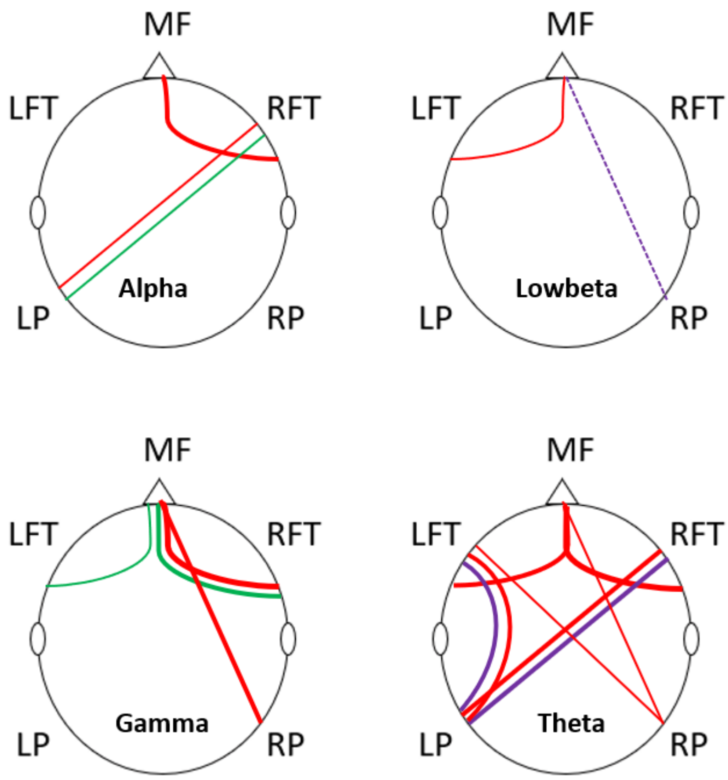


Figure 2: Coherence map of significant results from model 1. Top-down view of the brain with ROIs. Red lines indicate age as the predictor. Green lines indicate MLD as the predictor. Purple lines indicate Lifestyle score as the predictor. Dotted lines represent positive correlations. Boldness of lines indicate p-value significance: Weak lines = <0.05, Medium lines = <0.01, Bold lines = <0.005

4.2 Model 2: WM Performance

The results of a multiple linear regression revealed a very strong negative relationship between age and Corsi performance (E = -0.44, SE = 0.087, p = <*0.001*. An positive interaction between age and MLD was also found on Corsi performance (E = 0.196, SE = 0.09 p = *.039)* The model explained 22% of the variance in Corsi Performance (R^2= 0.25, F=(4,85) = 7.35, p = .039). Assumption testing of the model was done with the following tests: A Q-Q plot revealed that the residuals were normally distributed. A Durbin-Watson statistic of 1.88 revealed no autocorrelation and the model was not multicollinear with a VIF score below 1.3 for all variables.

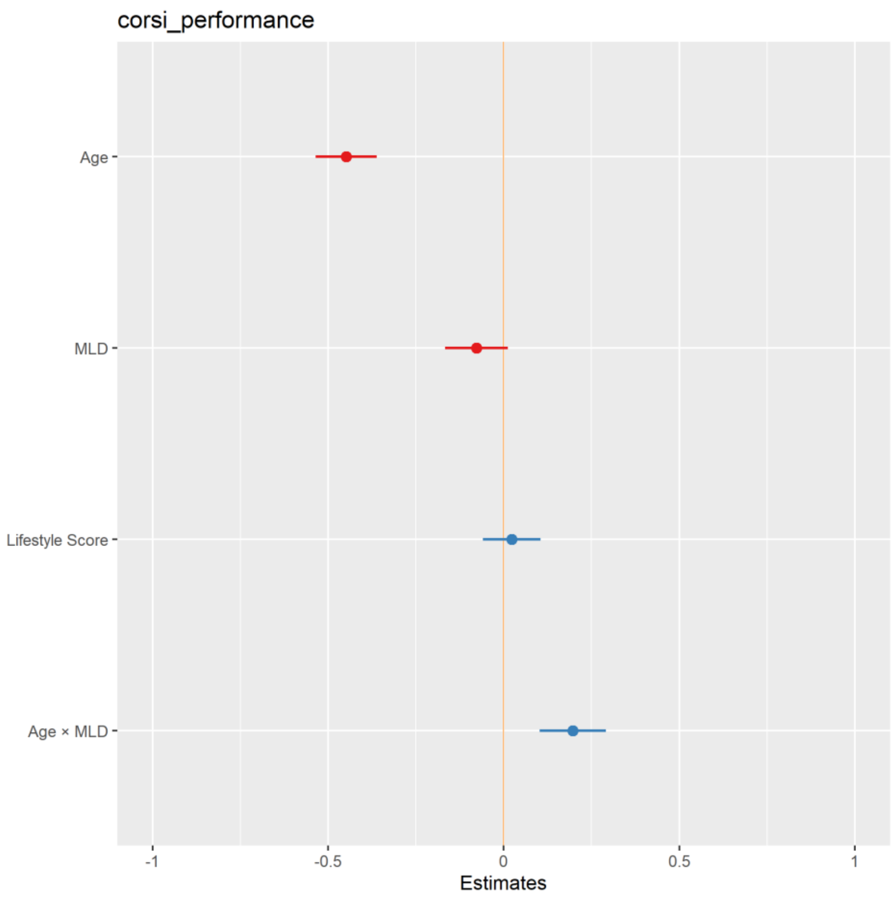


Figure 3: Coefficient plot of predictor variables for model 2.

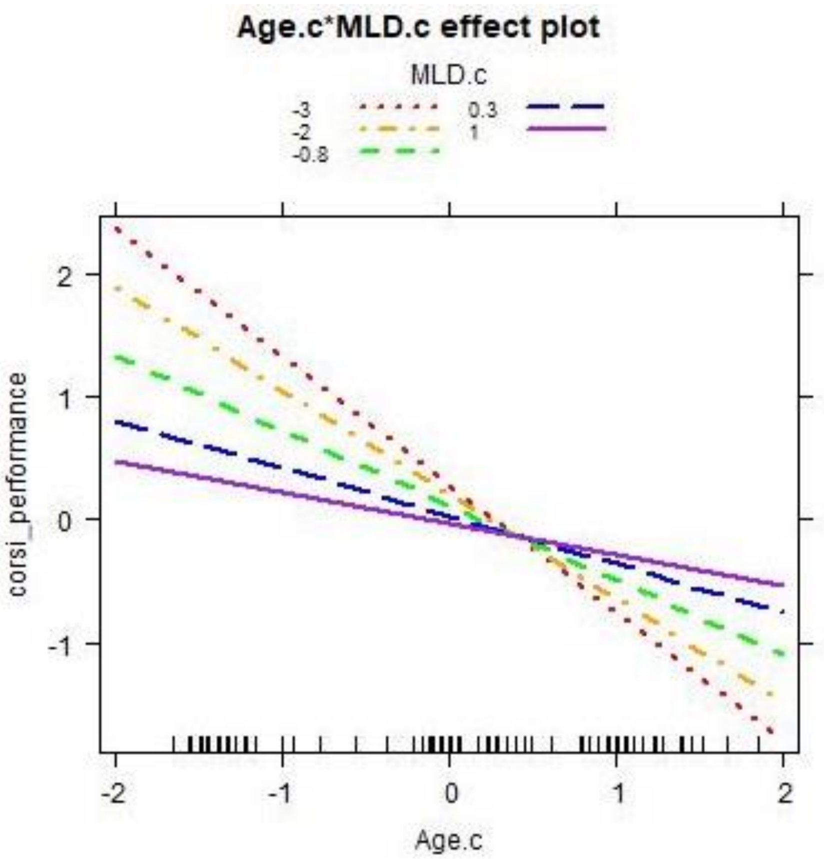


Figure 4: Effect plot of the interaction between age and MLD from model 2. Colored and dotted lines represent normalized MLD scores on scaling levels.

4.3 Model 3: Coherence and WM performance

An exploratory post hoc analysis was run to assess if WM performance could be associated with rs-EEG coherence using a robust linear regression model. A robust regression was used in favor of a mixed regression, as highlighted in section 3.5.3. The exploratory regression was only run with the frequency bands and ROIs that produced significant results in model 1 (see figure 2), following the methodology from Soares et al., (2022). As lifestyle and MLD is already controlled for during model 1, only coherence and WM performance was included in the call:

lmRob (Corsi Performance ~ Coherence)

The follow-up analysis revealed no significant results in any of the significant ROIs from model 1 in any frequency bands.

5 Discussion

The present study sought to investigate how differential bilingual language engagement impact neurocognitive outcomes during the cognitive aging trajectory and whether the same modulatory variables also affect visuo-spatial working memory performance. Functional connectivity using rs-EEG coherence was utilized to investigate this in conjunction with the Corsi Block tapping test. The overarching idea surrounding these two questions, was whether the two outcome variables affected each other: can rs-EEG coherence predict WM performance when language and lifestyle factors are controlled for. To properly investigate and interpret the results from the three-pronged analysis, research questions and models 1-2 involves using age and experience-dependent variables to account for the variance in the outcome measures, while RQ3 and model three attempts to bridge the gap between the first two research questions.

Results from model 1 revealed significant age-related negative correlations in all frequency bands, except for high beta. This entails that as participants age, their coherence also decreases. This general effect of age was to be expected, as previous research irrespective to prior experience, shows that coherence generally drops as participants get older, except in the beta band (Moezzi et al., 2019; Vysata et al., 2014). There were significant effects of MLD in the alpha and gamma band and significant effects of lifestyle in theta and low beta. Coherence between ROIs were widely distributed, with more significant coherence between frontal regions and between anterior and posterior regions. Model 2 investigated whether the same explanatory variables could account for WM performance and the results revealed a strong negative correlation with age, as expected. An interaction between age and MLD also showed that MLD positively counteracts the effect of age, which was also predicted. An exploratory post-hoc analysis on whether rs-EEG coherence would correlate revealed that no such relationship existed. Band specific results will be discussed in turn.

5.1 EEG results discussion

5.1.1 Alpha band

As evident from the theoretical background, the alpha band has a central role when it comes to measuring potential neurocognitive adaptations and especially so for executive processes and attentional control. Recall that all case studies found significant results in the alpha band, thus I predicted more significant results within this band, especially when considering each participant had their own individualized alpha frequency. Between RFT-LP, MLD predicted a negative change in coherence across the whole age range. This stands in contrast to previous findings from Pereira-Soares et al (2021), where bilinguals with increased dual-language use both at home and in social settings exhibited greater alpha coherence between MF-RFT and LP-RP. Pereira Soares' age range was limited to an adult population, so perhaps less coherence in alpha band could be explained by a wider age range in this sample. This thesis utilizes EEG data from both younger, middle aged and older adults, so both the diminishing effects of age in general, coupled with data from the young and middle age populations may complicate the effect of age on coherence.

In order to further understand this potential relationship, a conditional effect plot was created (see Appendix A). The graph looks at the relationship between age and coherence across different MLD groups. The graph reveals that for participants with a high and medium MLD, coherence does not fall as sharply with age when compared to the low MLD group, i.e. MLD flattens the downwards trajectory of age. Keep in mind that this graph must be interpreted with particular caution, as the regression model that looked at this same interaction proved statistically insignificant with a p-value of 0.06. Nevertheless, much of the bilingualism and aging literature indicate that certain forms of engaging dual-language use, such that the MLD measures helps flatten the decrease in functional connectivity in the later stages of life, which is exactly what the BAPSS model postulates (J. G. Grundy et al., 2017) According to the model, bilinguals are able to more efficiently recruit posterior networks due to a lifetime of conflict resolution, which is why the lack of significant alpha results in general is quite surprising, especially in the posterior region. The significant effect of MLD was across the hemispheres, stemming from the right frontal to the left posterior, which could indicate enhanced connectivity between these two regions, a finding that was confirmed by the predictions. The BAPSS model also stresses that bilinguals would recruit more posterior regions, so significant correlations between posterior brain regions was predicted, but not found in the analysis. But again, this should be taken with a grain of salt, as the spatial resolution with EEG is quite poor, making it difficult to make assumptions about which areas of the brain that are interconnected.

Another point worth noting about the lack of significant results from alpha band, was the rejection of IAF calculations for 4.95% of all coherence pairings, which essentially means that alpha coherence across these participants, suffered from less statistical power. In spite of this, utilizing individualized alpha frequencies is still a better idea than using a fixed alpha bandwidth, as fixed bands do not account for individual differences in alpha power, a fact that has been well-established in the literature (Corcoran et al., 2018). As a sponge-based EEG system was used for data collection, this may also have added to the level of noise in the data as the impedance threshold that was used was quite a bit higher than other rs-EEG studies (see section 5.4 for details).

The second prediction for RQ1 stated that lifestyle-score would positively correlate with alpha coherence. Recall that predictions were ordered by likelihood, so in an ideal world, the lack of correlations could be explained by the more impactful role of MLD, as one of the principal goals and novel elements of this study was to examine the effects of bilingual language engagement, independently from other lifestyle-variables. In alpha band there were no significant correlations in any of the ROIs between coherence and lifestyle score. This is surprising, as the composite lifestyle score includes both mentally stimulating activities and other factors such as diet and exercise. For example, Mentally stimulating activities has previously shown to be a very robust indicator of CR, when other predictors such as SES and IQ were accounted for (Valenzuela & Sachdev, 2006). Thus, the lifestyle scores comprise of an exhaustive measure of each participants lifestyle, not necessarily limited by previous studies that only included verbal IQ and years of education, like Fleck et al (2017) did.

5.1.2 Beta band

Previous studies highlighted in this paper have shown that beta band occupies a relatively less significant position in the bilingualism literature, when compared to alpha or theta band. That is, its presence has rather been more associated with native language proficiency, rather than being associated with specific exponents of bilingualism. Recall that for example, that Bice (2020) found increased beta coherence for bilinguals, but post-hoc analyses rather revealed that beta oscillations were more strongly associated with native language proficiency. Calvo et al (2023) also found increased beta coherence for frontal and frontotemporal electrodes for monolinguals, relative to bilinguals, which also happen to coincide with the BAPSS model. In the present thesis, beta band produced by far the least number of significant correlations, with no significance found in high beta. This frequency band was predicted to correlate positively with MLD, akin to the results found in alpha frequency. Pereira-Soares also found that AoA for the L2 correlated with higher beta coherence and power for bilingual participants, but this result is not directly comparable to this study, as they utilized mostly late and heritage bilinguals. This result makes sense in the context that rs-EEG beta oscillations seem to be more prevalent during L2 learning, which aligns with their participant profile (Prat et al., 2016, 2019). Since all of the participants utilized in this thesis were early sequential bilinguals with comparatively similar L2 AoA, it was not included as a predictor variable.

A negative correlation between lifestyle score and low beta coherence was also predicted, following findings from Pereira-Soares et al (2021). The opposite was found in this thesis, together with a negative correlation of age, which is to be expected when using older participants. The positive correlation between lifestyle and low beta coherence also represents the only positive prediction from the whole EEG analysis, which means that a higher lifestyle score results in increased coherence. As this is the opposite of what was predicted, it makes this result a perplexing finding. One possibility is that using a composite score may have reversed the potential negative effect SES, as the third prediction builds of a negative relationship between SES and beta-coherence that Pereira-Soares et al (2021) found. Recall that lifestyle score is comprised of several life-style factors and experiences thought to benefit CA and contribute to resilience against the effects of aging. SES was also included in this measure but could have been obscured by the rest of the variables also included in the composite score. Nevertheless, lifestyle score was rather included to control for other lifestyle factors, not necessarily to examine the effects that these measures might exert on rs-EEG functional connectivity.

To sum up the findings from beta coherence, the lack of results is most likely due to beta oscillations being associated with native language proficiency, as Bice et al (2020) concluded. Although the participants employed here all reported high proficiency in the native language, as is the case with most native speakers of any language, the participants were also highly proficient in their second language. Combine this with a large age range and a narrow MLD score for the majority of the participants, the lack of significant beta results becomes clearer.

5.1.3 Gamma band

Assessing the role of gamma band oscillations in general should be treated with caution, as role of gamma in bilingualism research is not very clear. For example, Bice et al (2020) found a marginal increase in gamma band coherence for the bilingual group but did not provide an explanation for the result. Gamma oscillations seem to be implicated with motor-functions, both as it occurs and when imagined (Amo Usanos et al., 2020; Ulloa, 2021). There is some limited evidence of the role of gamma when exponents of bilingualism is considered. Recall that Pereira-Soares et al (2021) found a significant correlation between AoA of the L2 and gamma coherence, which means that early acquisition of the L2 predicts increased gamma coherence. The authors interpreted this as reflecting inter-regional local communication within ROIs, so an early exposure to a second language means more efficient local processing. Previous work on the role of gamma oscillations has revealed its importance for local processing, as gamma is classified as a short-wave frequency (von Stein & Sarnthein, 2000). In the context of the results from model 1 in this thesis, the results cannot be interpreted in this manner as gamma band only produced negative correlations between the predictors variables and coherence.

Age had an expected negative effect for coherence between MF-RFT and MF-RP. Interestingly, the negative effect of age was only present in the right hemisphere. This result is also the inverse finding from Fleck et al (2017), who found increased gamma coherence for older participants high in CR. This result could stem from the fact that Fleck et al only utilized middle-aged to older participants and ran coherence separately for *younger* and older participants. A trend in the results and subsequent interpretation is that having such a large age range may have obscured how age differentially affects coherence in individuals high in CR, either through MLD or lifestyle score.

Moving back to the principal finding, namely how MLD affects rs-EEG coherence. The graphs in the appendix show that the interaction between age and MLD was almost significant for the gamma band. This same result was also found in alpha, but between different ROIs (LP-RFT, p-value = 0.06). When plotted through a conditional effects plot, using different levels of MLD, a tendency for MLD to negate the age-effect reveals itself (see Appendix, B, C, D). The effect is most pronounced between MF-RP and for the high MLD group, the downwards regression line seems to completely flatten. This type of pattern represents the ideal result in understanding how language use specifically, affects intrinsic brain patters in an aging population. This trend is not immediately apparent when running a regression analysis for all participants, as linear regression models require one solid regression line, which marginalizes the effect of age on the various age brackets. Again, I want to emphasize that the results presented in this paragraph did not prove significant, thus the interpretation should be treated only as a hypothetical *ideal* scenario, one that the present analysis failed to capture. Since a similar trend was also found in alpha, this indicates that future studies might encounter this pattern again. This flattening effect of MLD on age should be approached with a more sophisticated analysis for future studies or by using age-groups like Fleck et al (2017) did. What is interesting, is that model 2 seemed to capture the statistical significance of this relationship, albeit with a different outcome measure.

5.1.4 Theta band

Quite a few significant results were found in the theta band, mostly negative correlations between age and coherence. Again, this was to be expected as rs-EEG coherence decreases as a function of age. It was predicted that there would be a positive correlation between coherence and MLD, stemming from the findings from Pereira-Soares et al (2021). No such effect was found in the theta band. As evident from table 1, the p-values for MLD were quite high, indicating that there were no trends towards a relationship. The lack of significant MLD effects taken together with six negative correlations between age and coherence, these results could indicate that: (i) theta coherence does not necessarily modulate bilingual experiences in this participant sample (ii) MLD was not a sufficient measure to capture potential neurocognitive adaptions (iii) Including older participants with decreasing coherence in the participant pool, could muddy the effect of MLD on coherence for all participants.

(i)

The notion that theta oscillatory dynamics are modulated by bilingual exponents is not well explored in the literature. In the presented case studies, only Pereira-Soares et al found a modulatory effect for theta when regressed with non-societal language use, which was evident in MF-RFT and RFT-LFT. As their study included participants with heritage languages, the results obtained in their study, could indicate that theta is implicated with a greater degree of inhibition from living in a society where the heritage language is constantly suppressed. This stands in contrast when considering the homogeneity of the participants in the present thesis, as one of the admission requirements was to be a native Norwegian speaker. All 90 participants were also living in Norway and therefore had fewer opportunities to inhibit the native language.

(ii) The MLD range for the participants was quite limited, which resulted in a quite homogenous MLD score, with a mean MLD of 1.007 on the range 0.85-1.05. Recall that the possible MLD scores obtainable lies on the 0-2 range, which means that all participants were fairly bilingual and nuances in differential language use would be hard to capture with this sample. This limits the kinds of inferences that can be made for bilingual language engagement and possibly explains the lack of MLD significance.

(iii) The two case studies that found significant results in theta band related to bilingualism (Pereira-Soares et al 2021) and CR (Fleck et al 2017) utilized different age groups. Although the two studies are not directly comparable on their own, the results for both are highly relevant for the present study, as both bilingualism and CR are included as independent variables. The mean age for the respective studies differed considerably, with Pereira Soares utilizing younger and middle-aged participants (mean=28.34, SD=12.34), while Fleck et al tested older participants (mean=58.51, SD=4.37). The present thesis uses participants within both ranges, so if MLD is partly responsible for a compensatory effect on coherence in older participants, the effect of such a result would not be captured. Recall that for alpha and gamma, the near-significant trend for MLD in the other frequency bands is that higher MLD flattens the negative effect of age.

As for prediction 2, theta band was found quite prominently in Fleck et (2017) and together with alpha, reflected an age-related shift in hemispheric coherence across the age groups.

Thus, the predictions for this study reflected this finding at it was expected to find greater coherence between RFT-RP/MF-RP that was positively predicted by lifestyle score and age. This was not confirmed by the results. Akin to the findings from Fleck, we also expected to find a negative correlation for age between LFT-LP/MF-LP, which was confirmed. Although an interesting finding, the crux of this thesis is to independently assess the effect bilingualism when other life-style factors are controlled for, so I will not go into detail on why our sample did not find any positive correlations with lifestyle score and coherence.'

5.2 Behavioral Results

Model 2 attempted to the explain the variance in working memory performance through the same variables utilized in model 1. The literature is not in agreement on the presupposed *bilingual advantage,* with valid arguments on both sides. This thesis is not suited for examining the bilingual advantage debate in the sense of whether bilinguals outperform monolingual peers in tasks that tap into executive functioning. However, the present dataset and analysis adds an element of novelty in understanding how exponents of bilingualism may exert some influence on EF performance, above and beyond other lifestyle factors. Recall the section on aging and how the gradual build-up of CR may manifest themselves to preserve normal cognitive functioning in the face of aging. WM and other fluid abilities is one of the first components of EFs to be affected by age-related degradation at around age 30 (Ferguson et al., 2021). This decline in WM performance for this dataset is exemplified in figure 5.

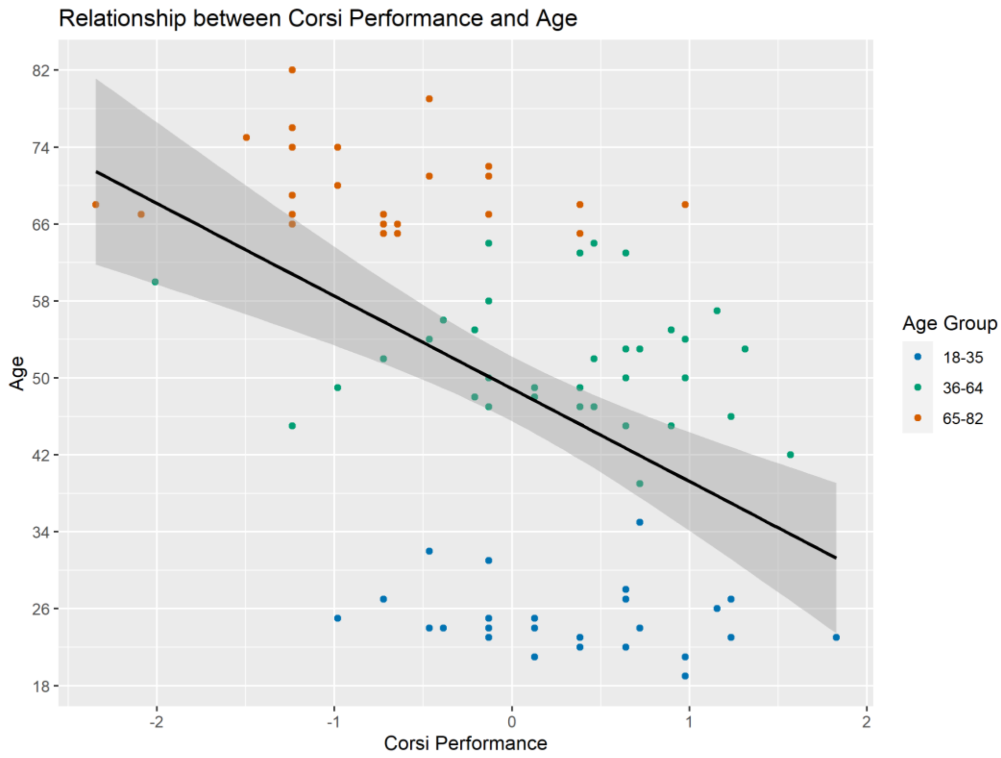


Figure 5: Raw Corsi performance correlated against age

The results revealed first and foremost that age has a substantial negative effect on WM performance and the negative coefficient of -0.449 confirmed this. It was predicted that MLD on its own would correlate positively with WM performance. This result was not found, as the correlation between MLD and WM performance was not statistically significant. Akin to the rs-EEG coherence results, there is a trend in the results that MLD on its own is not very informative in assessing the role of bilingual language engagement due to the nature of regression models and the large age range. Furthermore, the age distribution was uneven as 30% of participants aged 60-70 and 26% of all participants aged 20-30. In an ideal world, the participant profile would consist of an equal number of participants in age brackets to increase statistical reliability. Fortunately, model 2 also revealed the first tangible interaction between MLD and age.

This interaction was predicted based on increased inhibitory demands stemming from non-selective language access, also known as dual language activation. Provided enough exposure with both passively and actively inhibiting either language, this gradual experience will manifest itself later in life through increased performance in a WM task. As described in section 2.2., whether this experience benefits EFs overall has not produced any conclusive evidence. However, when examining the effect that bilingualism has on working memory specifically, one meta-analysis found a slight positive effect and another found a tangential advantage for bilinguals relative to monolinguals (J. Grundy & Timmer, 2017; Monnier et al., 2022). There were however some conflicting results when it comes to the moderator variables in each review. Grundy & Timmer (2017) found that the bilingual advantage was strongest in the verbal domain, which means that the strongest effect lies within verbal working memory, as they performed better on a linguistic WM task. Monnier et al (2022) did not find any effect of verbal vs non-verbal WM memory but found that the strongest predictor was in what language the tasks were administered, which was an effect we accounted for in this experiment. As a non-linguistic visuo-spatial WM task was used in the present thesis, this might shed some light on which specific subsections of WM that bilingualism affects, which are not necessarily linguistic in nature.

Grundy & Timmer (2017) also predicted that they would observe an age effect on WM performance, specifically that children and young adults would show the largest effect size, due to being tested at peak cognitive performance. They also expected to observe increased WM performance for older adults, due to increased experience with managing two languages, which was not directly visible in the results. The results from this thesis may shed some light on this, specifically the interaction between age and MLD. Looking at the effects plot from figure 4, we can observe how various levels of MLD linearly improves WM performance in the aging trajectory. Take for example the dotted red line, representing the lowest possible MLD scores, we can see how their performance on the Corsi Blocks drops sharply as age increased, not unlike the regression line from the scatter plot displayed in figure 5. This suggests that MLD counteracts the effect that increased has on the deterioration of WM performance, but it does not necessarily improve WM performance throughout the lifespan. This finding confirms research question 2, which sought to answer whether multilingual engagement modulates WM performance, when other lifestyle factors are accounted for.

5.3 General Discussion

The final research question that this thesis attempted to answer is whether there exists a measurable relationship between WM performance and the brains intrinsic activity at rest. So far, the results have been addressed separately, as conducting an investigation into the relation between two outcome measures presents the opportunity to dive deeper into each of them. In order to tie these two outcome measures together, a post hoc exploratory correlation analysis was run on the significant results that model 1 produced. Since model 1 revealed a few frequency bands and ROI pairings that produced a significant relationship with MLD, it was hypothesized that a similar correlation would be found in these ROI pairings and WM performance. Model 3 revealed that no such relationship existed however, which subsequently answered RQ3.

Although I could not find any previous studies that directly related rs-EEG coherence with performance on a visuospatial WM task, it was predicted that such a relationship might exist in the alpha and theta bands, specifically across hemispheres (frontal to posterior). This builds off one study that found increased alpha and theta connectivity when performing a task thought to tap into the central executive (Sauseng et al., 2005). As demonstrated above, theta and alpha bands are widely studied and has been linked to both WM and exponents of bilingualism in the past, making it a suitable candidate. As have been a central point so far, alpha seems to be a very prominent frequency band and in relation to RQ3, alpha peaks has been tied to increased WM performance in a digit-span task (Richard Clark et al., 2004). Again, this study did not examine resting state activity, which is a recurring theme in the literature (Anderson & Perone, 2018).

There could be a few reasons for these null results, with the first possibility being that the spontaneous electricity that the brain elicits during wakeful rest has no impact whatsoever on performance in visuospatial task. The lack of any literature seems to indirectly support this. More realistically, the utilization of rs-EEG coherence as methodology has only recently gained popularity, so it might simply be too soon for any articles to have emerged, which is especially true when it comes to including bilingualism as a potential moderator variable (Rossi et al., 2023). The few articles relating WM performance with an EEG analysis did not specifically test visuo-spatial WM either, as Sauseng et al (2005) used allocentric WM and Richard Clark et al (2004) used the digit-span test, which is rather a measure of WM capacity of numbered information. Under Baddeley's model of WM, digit span is a measure of the phonological loop (Baddeley & Logie, 1999). Thus, the second possibility is that visuo-spatial WM specifically does not have a relationship between rs-EEG coherence, but if another WM task was utilized such as the digit span task, a correlation might emerge. Nevertheless, this exploratory approach on whether prior experience can account for adaptations in intrinsic brain activity advocates a more holistic approach going forward.

As for RQ 1: Does bilingual language engagement modulate rs-EEG coherence patterns throughout the lifespan, when other lifestyle factors are controlled for? In terms of significant results, it would not seem that bilingual language engagement does not modulate coherence, at least not in a statistically significant manner. As seen above, MLD only negatively predicted coherence between frontal regions in gamma and across RFT-LP in alpha band. Nevertheless, we saw a near-significant trend on how age interacts with MLD to flatten this decrease in the two bands. This was only a trend in the data and thus we cannot determine whether this relationship actually exists with the current dataset. As mentioned, the MLD in this case lies on a restrictive range, as all of the participants had a very similar score.

The participants were all native speakers of Norwegian and the vast majority rated their L2 proficiency quite high. The early recruitment process also advertised that the experiment itself would consist of two parts with two different languages, to account for possible confounding effect of language mode (section 2.3.2). This preliminary information may have inadvertently conveyed a message that you had to be quite fluent in English in order to participate and could have discouraged participants less proficient in English from participating. Also, the Norwegian school system introduces the English language fairly early at age 6-7-8 depending on when the participant was born. English as a language is also very prevalent at the societal level, for example, roughly every fourth university course is taught in English and tv-shows in English are often more prevalent than Norwegian (Medietilsynet, 2020; Svarstad, 2022). This resulted in a quite homogenous MLD values across the board.

Another potential problem with MLD, is the use of proficiency to calculate the final score. The MLD score is somewhat of a hybrid entropy score. What I mean by this is that MLD calculates the relative use of each participants language in various communicative contexts, measured through hours spent using the L1/L2 in these contexts. This is precisely the kind of data that is highly relevant in determining whether prior experience may have an impact on rs-EEG as it quantifies past use. As seen with Pereira-Soares et al (2021), different contexts of language use alter how the brain recruit networks during wakeful rest. The problem in this case, is that this valuable contextual information is calculated together with each participants proficiency. For the reasons highlighted in the previous paragraph, the contextual information loses its significance as the proficiency dictates the final MLD score, more so than how they used their languages. In other words, the high proficiency scores diminish the information on language use. The MLD relies on a sequential calculation of scores: First the dominance for each participant is calculated, which is based off the self-rated proficiency scores and frequency of usage of different components of language. These includes in what contexts you use any of your languages (socially, at home, work/school) and with whom you use the language with. Together with the self-reported proficiency score, a Proportion of Dominance score is calculated and represents the degree of dominance relative to their language use. The crux here however, is that this usage is obscured by the self-reported proficiency, which is probably why the MLD score lies on such a narrow range. For example, when you look at English proficiency on it’s own for the dataset, the mean proficiency is 0.75 out of 1 (SD = 0.12). When compared to the mean for Norwegian proficiency of 0.95(SD=0.08), it becomes evident that the participants utilized are quite balanced in their bilingualism. Fleck et al (2017) also reported this problem with their measure of CR. Recall that they used verbal IQ and years of education as CR proxies and the authors state that most all participants had completed high school or equivalent, which truncated the CR score.

Even though the MLD proved to be a potentially problematic measure of bilingual language engagement, it nevertheless had a significant interaction with age in Model 2. This interaction was also helpful in answering research question 2. The answer for RQ2 seems to be yes, although this result needs to be replicated with a better measure of bilingual language engagement, namely a measure that is separate from proficiency. Although proficiency has and continues to be a very important variable in any study pertaining to SLA and bilingualism, it does not necessarily capture how a bilingual uses their languages. As Gullifer et al., (2021) argues, at the most basic level proficiency only measures the ability to apply your understanding of a language to comprehend and produce sentences. It does not necessarily reveal the context or manner in which your proficiency was acquired. It is this contextual information on individual differences of language exposure and use, that is critical in being able to determine whether prior language engagement can predict and modulate neurocognitive outcomes, as Pereia-Soares et al (2021) observed.

The use of self-rated proficiency may also be problematic, as the reliability of self-reported measures can be compromised in a number of ways. The participant might not understand the questionnaire or simply not be bothered by reading the questions. This issue was somewhat circumvented by conducting the questionnaire part of the experiment with an interviewer, but human errors may still occur. It has also been shown that culture plays a role in self-rated proficiency in particular, as one study investigating the validity of self-reported proficiency questionnaires, found large discrepancies for different language combinations (Tomoschuk et al., 2019). This means that the language combinations of the bilinguals dictated proficiency, rather than the actual proficiency, which was verified by a language proficiency task. Including a standardized proficiency test together with a measure of differential language use in different contexts, may prove fruitful in future research.

5.4 Limitations and further research

I mentioned that the MLD score may be considered a *hybrid* entropy score, as it includes proficiency in the calculation. It would therefore be prudent to rather calculate bilingual language engagement separate from proficiency, through a dedicated language engagement score. This could for example be achieved using the up-and-coming concept of language entropy (Gullifer & Titone, 2020). Incorporating the concept from information theory, language entropy attempts to quantify language exposure by calculating the likelihood of a certain type of language exposure. This would result in an entropy score ranging from 0-1 for various contexts. For example, if you had a bilingual participant report that they only used their L1 in different communicative contexts (school, home, work etc..), the entropy score would be 0, as the likelihood of using the L2 in this context, for this participant, would be very low. If you had another participants that reported a 50/50 usage of the L1 and L2, the entropy score would be 1, signifying an equal possibility of using both languages within this communicative context (Gullifer et al., 2021). If you were to calculate entropy scores for various language context and treated these as a composite score or latent variable separate from proficiency, this would likely result in a more accurate model and further our understanding of how individual language use affects our minds and brains. Another addition for relevant contexts is also calculating entropy scores for contexts where language mixing and code-switching are rampant.

Another alternative to using an entropy score can be the use of a bilingualism quotient (Marian & Hayakawa, 2021). Inspired by the classic measure of general intelligence (IQ), the bilingualism quotient is a novel way to measure the degree of bilingualism in a given participant by deriving the shared variance between several indices of dual language use, into a single value. The measurement of IQ and bilingualism share many features, as the authors point out. Namely that it is a highly complex construct with many interconnected parts that often correlate with each other and the end-product, either IQ or the bilingualism quotient is considered a latent variable. The concept of a bilingualism quotient is still in its infancy, but future studies may benefit from using such a score in tandem with a separate score for dua-language use.

The second point I want to address is that of the lifestyle score. Although not central to the research question, this study controls for lifestyle factors thought to promote the accrual of cognitive reserves. There is disagreement in the literature to what specific lifestyle factors and cognitive tests that may be considered as a proxy for CR (Chapko et al., 2018; Nogueira et al., 2022). The lack of an agreed upon framework has resulted in less reliability to both the measurement and the very existence of the concept. Since CR cannot be directly observed or measured and is considered a latent variable, thus any use of CR must be considered with great care. For example, one point of criticism against Fleck et al (2017) was that the authors used two measures of CR: verbal intelligence and education. Although these two measures are solid indicators of CR, they included no data on mentally stimulating activities, diet, exercise or other factors used in this thesis. This makes it difficult to compare results, as it is not known for certain if these two measures are sufficient to gauge CR. Further research that attempts to measure or use cognitive and brain reserves would benefit from following a recent whitepaper that attempts to unify the use of CR within one framework. (Stern et al., 2020)

Another limitation that I have briefly touched upon was the use of a regression model. Since regression models rely on only a single regression line it presupposes a linear relationship between the dependent and independent variables, which possibly obscured the effect of age and MLD on coherence. The sample size of 90 was just about not sufficient to run a more sophisticated analysis, such as a structural equation model, as was done by Carter et al., (2023). SEM modelling is a combination of a path analysis and confirmatory factor analysis, which are two early statistical methods used to assess complex relationships among latent variables. As the composite lifestyle-score may be considered a latent variable, SEM modelling can also be fitted to test the assumptions of a theoretical model such as the BAPSS against the dataset. But the major benefit of SEM is its ability to operate with several dependent variables. That means that the two outcome variables in this thesis could be used in the same model, which would eliminate the need for model 3. Further research into experience-dependent adaptations to the brain should therefore have a sample size that is adequate for such an analysis.

A sponge-based EEG system was also used in favor of a more stable gel-based system, as the 32 Channel Wet-Sponge R-Net system that was used operates with a relatively high milli-amp threshold of 100 kΩs. As a point of reference, the milli-amp threshold is the impedance of each electrode and before a given experiment can start, all electrodes must be 100 kΩs. As the ability of the sponges to conduct electricity diminishes over time and is generally less stable than its gel-based counterpart, this might lead to noisier data that might obscure the frequencies and IAF calculation. For reference, Pereira-Soares et al (2021) set this threshold at 25 kΩs, Fleck et al (2017) and Calvo et al (2023) had an impedance threshold set at 50 kΩs. This means that for these studies, they recorded the EEG signal with an impedance level that is less sensitive to noise. Future studies should take this into consideration to ensure the best possible data quality.

6 Conclusion

In summary, this thesis attempted to understand how bi-multilingual language engagement impacts neurocognitive outcomes. Firstly, I attempted to uncover the unique role of bilingual language engagement on spontaneous brain activity during wakeful rest and for working memory performance, while simultaneously controlling for other lifestyle-factors throughout the lifespan. I found a near-significant trend in the rs-EEG data that MLD flattens the downwards trajectory of age on coherence across hemispheres in alpha frequency and within frontal areas in the gamma frequency. However, this same interaction was significant for WM performance, suggesting that increased multilingual engagement over time, also aids executive functioning for individuals with higher MLD scores. These principal results confirmed that multilingual language engagement positively contributes to WM performance, but this cannot be established for rs-EEG coherence without follow-up studies that utilize a more diverse set of bilinguals and a more sophisticated statistical analysis. Secondly, I correlated rs-EEG coherence with WM performance to see if a link exists between the two. An exploratory post-hoc analysis was performed in the same ROIs where a significant effect of MLD was found, but there was no correlation between WM performance and coherence. These null results may be explained as a lack of a relationship between FC assessed with rs-EEG. It is also possible that visuo-spatial WM does not necessary correlate with rs-EEG, but if another measure of WM or executive functioning was used instead, this relationship might emerge.

This study contributes to the emergent literature on bilingualism and aging by showcasing that differential multilingual language engagement positively affects CA, especially in maintaining working memory performance for older bilinguals. To my knowledge, this is the first study that attempts to dissociate bilingualism and its exponents from other mentally stimulating activities also thought to yield a compensatory effect on CA. As the world has enjoyed advancements in quality of life and a longer lifespan, this also means that the elderly population prone to the degenerative effects of aging, will rise to unsustainable levels in the near-future (Bialystok et al., 2016). Therefore, understanding the protective significance of bi-multilingualism may provide benefits to policymakers concerned with public health and in making informed decisions from clinicians whose hands suffer the burden of *alleviating* this public health crisis. This thesis further advocates a similar holistic approach for future studies on aging and bilingualism.

Bibliography

Abud, T., Kounidas, G., Martin, K. R., Werth, M., Cooper, K., & Myint, P. K. (2022). Determinants of healthy ageing: a systematic review of contemporary literature. *Aging Clinical and Experimental Research*, *34*(6), 1215–1223. https://doi.org/10.1007/s40520-021-02049-w

Addams, J. (2005). *1001 smartest things ever said* (S. Price (ed.)). Rowman & Littlefield.

Adler, N. E., Epel, E. S., Castellazzo, G., & Ickovics, J. R. (2000). Relationship of subjective and objective social status with psychological and physiological functioning: preliminary data in healthy white women. *Health Psychology : Official Journal of the Division of Health Psychology, American Psychological Association*, *19*(6), 586–592. https://doi.org/10.1037//0278-6133.19.6.586

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development*, *77*(6), 1698–1716.

Amarya, S., Singh, K., & Sabharwal, M. (2018). *Ageing Process and Physiological Changes* (G. D'Onofrio, A. Greco, & D. Sancarlo (eds.); p. Ch. 1). IntechOpen. https://doi.org/10.5772/intechopen.76249

Amo Usanos, C., Boquete, L., de Santiago, L., Barea Navarro, R., & Cavaliere, C. (2020). Induced gamma-band activity during actual and imaginary movements: EEG analysis. *Sensors*, *20*(6), 1545.

Amzica, F., & Lopes da Silva, F. H. (2017). 20C2 Cellular Substrates of Brain Rhythms. In D. L. Schomer, F. H. Lopes da Silva, D. L. Schomer, & F. H. Lopes da Silva (Eds.), *Niedermeyer's Electroencephalography: Basic Principles, Clinical Applications, and Related Fields* (p. 0). Oxford University Press. https://doi.org/10.1093/med/9780190228484.003.0002

Anderson, A. J., & Perone, S. (2018). Developmental change in the resting state electroencephalogram: Insights into cognition and the brain. *Brain and Cognition*, *126*, 40–52. https://doi.org/10.1016/J.BANDC.2018.08.001

Ardila, A., Bernal, B., & Rosselli, M. (2016). The Role of Wernicke's Area in Language Comprehension. *Psychology & Neuroscience*, *9*. https://doi.org/10.1037/pne0000060

Baddeley, A. (2011). Working Memory: Theories, Models, and Controversies. *Annual Review of Psychology*, *63*(1), 1–29. https://doi.org/10.1146/annurev-psych-120710-100422

Baddeley, A., & Logie, R. (1999). *Working memory: The multiple-component model.*

Belsky, D. W., Caspi, A., Houts, R., Cohen, H. J., Corcoran, D. L., Danese, A., Harrington, H., Israel, S., Levine, M. E., Schaefer, J. D., Sugden, K., Williams, B., Yashin, A. I., Poulton, R., & Moffitt, T. E. (2015). Quantification of biological aging in young adults. *Proceedings of the National Academy of Sciences*, *112*(30), E4104–E4110. https://doi.org/10.1073/pnas.1506264112

Berger, H. (1929). Hans Berger on the electroencephalogram of man. *Arch F Psychiatry*, *87*, 527–570.

Bialystok, E., Abutalebi, J., Bak, T. H., Burke, D. M., & Kroll, J. F. (2016). Aging in two languages: Implications for public health. *Ageing Research Reviews*, *27*, 56–60. https://doi.org/10.1016/j.arr.2016.03.003

Bialystok, E., Luk, G., Peets, K. F., & YANG, S. (2010). Receptive vocabulary differences in monolingual and bilingual children. *Bilingualism: Language and Cognition*, *13*(4), 525–531. https://doi.org/DOI: 10.1017/S1366728909990423

Bialystok, E., Poarch, G., Luo, L., & Craik, F. I. M. (2014). Effects of bilingualism and aging on executive function and working memory. *Psychology and Aging*, *29*(3), 696.

Bice, K., Yamasaki, B. L., & Prat, C. S. (2020). Bilingual Language Experience Shapes Resting-State Brain Rhythms. *Neurobiology of Language*, *1*(3), 288–318. https://doi.org/10.1162/nol_a_00014

Brazier, M. A. (1961). Preliminary proposal for an EEG terminology by the Terminology

Committee of the International Federation for Electroencephalography and Clinical Neurophysiology. *Electroencephalography and Clinical Neurophysiology*, *13*, 646–650. https://doi.org/10.1016/0013-4694(61)90186-9

Broadway, J. M., & Engle, R. W. (2011). Individual differences in working memory capacity and temporal discrimination. *PloS One*, *6*(10), e25422. https://doi.org/10.1371/journal.pone.0025422

Brysbaert, M. (2021). Power considerations in bilingualism research: Time to step up our game. *Bilingualism: Language and Cognition*, *24*(5), 813–818.

Calvo, N., Grundy, J. G., & Bialystok, E. (2023). Bilingualism modulates neural efficiency at rest through alpha reactivity. *Neuropsychologia*, *180*, 108486. https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2023.108486

Carter, F., DeLuca, V., Segaert, K., Mazaheri, A., & Krott, A. (2023). Functional neural architecture of cognitive control mediates the relationship between individual differences in bilingual experience and behaviour. *NeuroImage*, *273*, 120085. https://doi.org/https://doi.org/10.1016/j.neuroimage.2023.120085

Chapko, D., McCormack, R., Black, C., Staff, R., & Murray, A. (2018). Life-course determinants of cognitive reserve (CR) in cognitive aging and dementia – a systematic literature review. *Aging & Mental Health*, *22*(8), 921–932. https://doi.org/10.1080/13607863.2017.1348471

Cleghorn, C. L., Harrison, R. A., Ransley, J. K., Wilkinson, S., Thomas, J., & Cade, J. E. (2016). Can a dietary quality score derived from a short-form FFQ assess dietary quality in UK adult population surveys? *Public Health Nutrition*, *19*(16), 2915–2923. https://doi.org/10.1017/S1368980016001099

Cohen, S., Doyle, W. J., Skoner, D. P., Rabin, B. S., & Gwaltney, J. M. (1997). Social ties and susceptibility to the common cold. *Jama*, *277*(24), 1940–1944.

Colombo, B., Antonietti, A., & Daneau, B. (2018). The Relationships Between Cognitive Reserve and Creativity. A Study on American Aging Population. *Front Psychol*, *9*, 764. https://doi.org/10.3389/fpsyg.2018.00764

Corcoran, A. W., Alday, P. M., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2018). Toward a reliable, automated method of individual alpha frequency (IAF) quantification. *Psychophysiology*, *55*(7), e13064. https://doi.org/10.1111/psyp.13064

Corsi, P. M. (1972). *Human memory and the medial temporal region of the brain.* (Vol. 34, p. 891). ProQuest Information & Learning.

Cox, S. R., Ritchie, S. J., Tucker-Drob, E. M., Liewald, D. C., Hagenaars, S. P., Davies, G., Wardlaw, J. M., Gale, C. R., Bastin, M. E., & Deary, I. J. (2016). Ageing and brain white matter structure in 3,513 UK Biobank participants. *Nature Communications*, *7*(1), 13629. https://doi.org/10.1038/ncomms13629

Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J. F., & Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity. *Medicine and Science in Sports and Exercise*, *35*(8), 1381–1395. https://doi.org/10.1249/01.MSS.0000078924.61453.FB

Daselaar, Sm., Veltman, D. J., Rombouts, S., Raaijmakers, J. G. W., & Jonker, C. (2003). Neuroanatomical correlates of episodic encoding and retrieval in young and elderly subjects. *Brain*, *126*(1), 43–56.

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2008). Que PASA? The posterior-anterior shift in aging. *Cerebral Cortex (New York, N.Y. : 1991)*, *18*(5), 1201–1209. https://doi.org/10.1093/cercor/bhm155

Del Maschio, N., Fedeli, D., & Abutalebi, J. (2018). Bilingualism and aging. Why research should continue. *Linguistic Approaches to Bilingualism*, *11*. https://doi.org/10.1075/lab.18032.del

Della Rosa, P. A., Videsott, G., Borsa, V. M., Canini, M., Weekes, B. S., Franceschini, R., & Abutalebi, J. (2013). A neural interactive location for multilingual talent. *Cortex*, *49*(2), 605–608.

DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function.

Proceedings of the National Academy of Sciences of the United States of America, *116*(15), 7565–7574. https://doi.org/10.1073/PNAS.1811513116/SUPPL_FILE/PNAS.1811513116.SAPP.PDF

Dennis, N. A., Daselaar, S., & Cabeza, R. (2007). Effects of aging on transient and sustained successful memory encoding activity. *Neurobiology of Aging*, *28*(11), 1749–1758.

Dhana, K., Evans, D. A., Rajan, K. B., Bennett, D. A., & Morris, M. C. (2020). Healthy lifestyle and the risk of Alzheimer dementia: Findings from 2 longitudinal studies. *Neurology*, *95*(4), e374–e383. https://doi.org/10.1212/WNL.0000000000009816

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Donnelly, S., Brooks, P. J., & Homer, B. D. (2019). Is there a bilingual advantage on interference-control tasks? A multiverse meta-analysis of global reaction time and interference cost. *Psychonomic Bulletin & Review*, *26*(4), 1122–1147. https://doi.org/10.3758/s13423-019-01567-z

Dunn, A., & Fox Tree, J. (2012). More on language mode. *International Journal of Bilingualism*, *18*, 605–613. https://doi.org/10.1177/1367006912454509

Ferguson, H. J., Brunsdon, V. E. A., & Bradford, E. E. F. (2021). The developmental trajectories of executive function from adolescence to old age. *Scientific Reports*, *11*(1), 1382. https://doi.org/10.1038/s41598-020-80866-1

Fingelkurts, A. A., Fingelkurts, A. A., & Kähkönen, S. (2005). Functional connectivity in the brain—is it an elusive concept? *Neuroscience & Biobehavioral Reviews*, *28*(8), 827–836. https://doi.org/https://doi.org/10.1016/j.neubiorev.2004.10.009

Finnigan, S., & Robertson, I. H. (2011). Resting EEG theta power correlates with cognitive performance in healthy older adults. *Psychophysiology*, *48*(8), 1083–1087. https://doi.org/https://doi.org/10.1111/j.1469-8986.2010.01173.x

Fleck, J. I., Kuti, J., Mercurio, J., Mullen, S., Austin, K., & Pereira, O. (2017). The impact of age and cognitive reserve on resting-state brain connectivity. *Frontiers in Aging Neuroscience*, *9*(DEC), 392. https://doi.org/10.3389/FNAGI.2017.00392/BIBTEX

Fox, J., & Weisberg, S. (2018). *An R companion to applied regression*. Sage publications.

Frahm, J., Merboldt, K.-D., & Hänicke, W. (1993). Functional MRI of human brain activation at high spatial resolution. *Magnetic Resonance in Medicine*, *29*(1), 139–144. https://doi.org/https://doi.org/10.1002/mrm.1910290126

Frangou, S., Modabbernia, A., Williams, S. C. R., Papachristou, E., Doucet, G. E., Agartz, I., Aghajani, M., Akudjedu, T. N., Albajes-Eizagirre, A., Alnæs, D., Alpert, K. I., Andersson, M., Andreasen, N. C., Andreassen, O. A., Asherson, P., Banaschewski, T., Bargallo, N., Baumeister, S., Baur-Streubel, R., … Dima, D. (2022). Cortical thickness across the lifespan: Data from 17,075 healthy individuals aged 3–90 years. *Human Brain Mapping*, *43*(1), 431–451. https://doi.org/https://doi.org/10.1002/hbm.25364

Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences*, *3*(11), 410–419. https://doi.org/https://doi.org/10.1016/S1364-6613(99)01388-1

Genesee, F. (2015). Myths about early childhood bilingualism. *Canadian Psychology*, *56*(1), 6–15. https://doi.org/10.1037/A0038599

Grosjean, F. (1988). Exploring the recognition of guest words in bilingual speech. *Language and Cognitive Processes*, *3*(3), 233–274.

Grosjean, F. (1998). Studying bilinguals: Methodological and conceptual issues. *Bilingualism: Language and Cognition*, *1*(2), 131–149. https://doi.org/DOI: 10.1017/S136672899800025X

Grundy, J. G., Anderson, J. A. E., & Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences*, *1396*(1), 183–201. https://doi.org/10.1111/nyas.13333

Grundy, J., & Timmer, K. (2017). Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second Language Research*, *33*, 325–340.

https://doi.org/10.1177/0267658316678286

Gullifer, J. W., Kousaie, S., Gilbert, A. C., Grant, A., Giroud, N., Coulter, K., Klein, D., Baum, S., Phillips, N., & Titone, D. (2021). Bilingual language experience as a multidimensional spectrum: Associations with objective and subjective language proficiency. *Applied Psycholinguistics*, *42*(2), 245–278. https://doi.org/DOI: 10.1017/S0142716420000521

Gullifer, J. W., & Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism: Language and Cognition*, *23*(2), 283–294. https://doi.org/DOI: 10.1017/S1366728919000026

Hafkemeijer, A., Altmann-Schneider, I., de Craen, A. J. M., Slagboom, P. E., van der Grond, J., & Rombouts, S. A. R. B. (2014). Associations between age and gray matter volume in anatomical brain networks in middle-aged to older adults. *Aging Cell*, *13*(6), 1068–1074. https://doi.org/10.1111/acel.12271

Harman, D. (2001). Aging: Overview. *Annals of the New York Academy of Sciences*, *928*(1), 1–21. https://doi.org/https://doi.org/10.1111/j.1749-6632.2001.tb05631.x

Harris, S. E., & Deary, I. J. (2011). The genetics of cognitive ability and cognitive ageing in healthy older people. *Trends in Cognitive Sciences*, *15*(9), 388–394. https://doi.org/10.1016/j.tics.2011.07.004

Hartline, D. K., & Colman, D. R. (2007). Rapid conduction and the evolution of giant axons and myelinated fibers. *Current Biology*, *17*(1), R29–R35.

Hosoda, C., Tanaka, K., Nariai, T., Honda, M., & Hanakawa, T. (2013). Dynamic neural network reorganization associated with second language vocabulary acquisition: A multimodal imaging study. *Journal of Neuroscience*, *33*(34), 13663–13672.

Jabès, A., Klencklen, G., Ruggeri, P., Antonietti, J.-P., Banta Lavenex, P., & Lavenex, P. (2021). Age-Related Differences in Resting-State EEG and Allocentric Spatial Working Memory Performance. *Frontiers in Aging Neuroscience*, *13*, 704362. https://doi.org/10.3389/fnagi.2021.704362

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Research Reviews, 53*(1), 63–88. https://doi.org/10.1016/j.brainresrev.2006.06.003

Klimova, B., Novotny, M., & Kuca, K. (2018). Anti-Aging Drugs - Prospect of Longer Life? *Current Medicinal Chemistry*, *25*(17), 1946–1953. https://doi.org/10.2174/0929867325666171129215251

Kroll, J. F., Bobb, S. C., & Hoshino, N. (2014). Two languages in mind: Bilingualism as a tool to investigate language, cognition, and the brain. *Current Directions in Psychological Science*, *23*(3), 159–163. https://doi.org/10.1177/0963721414528511

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychological Bulletin*, *144*(4), 394–425. https://doi.org/10.1037/bul0000142

Leoń, I., Garciá-García, J., & Roldań-Tapia, L. (2014). Estimating Cognitive Reserve in Healthy Adults Using the Cognitive Reserve Scale. *PLoS ONE*, *9*(7), 102632. https://doi.org/10.1371/JOURNAL.PONE.0102632

Li, P., Zhang, F., Yu, A., & Zhao, X. (2020). Language History Questionnaire (LHQ3): An enhanced tool for assessing multilingual experience. *Bilingualism: Language and Cognition*, *23*(5), 938–944. https://doi.org/DOI: 10.1017/S1366728918001153

Linck, J. A., Osthus, P., Koeth, J. T., & Bunting, M. F. (2014). Working memory and second language comprehension and production: a meta-analysis. *Psychonomic Bulletin & Review*, *21*(4), 861–883. https://doi.org/10.3758/s13423-013-0565-2

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2011). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes, 27*(10), 1479–1488. https://doi.org/10.1080/01690965.2011.613209

Lupker, S. J., & Kinoshita, S. (2003). *Masked Priming: State of the Art* (1st. Ed). Hove: Taylor and Francis. https://doi.org/10.4324/9780203502846

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences of the United States of America*, *97*(8), 4398–4403. https://doi.org/10.1073/PNAS.070039597/ASSET/247BC48B-5406-453D-806D-0D3872A1DA58/ASSETS/GRAPHIC/PQ0700395003.JPEG

Marian, V., & Hayakawa, S. (2021). Measuring bilingualism: The quest for a "bilingualism quotient." *Applied Psycholinguistics*, *42*(2), 527–548. https://doi.org/DOI: 10.1017/S0142716420000533

Marinazzo, D., Riera, J. J., Marzetti, L., Astolfi, L., Yao, D., & Valdés Sosa, P. A. (2019). Controversies in EEG source imaging and connectivity: modeling, validation, benchmarking. In *Brain Topography* (Vol. 32, pp. 527–529). Springer.

Medietilsynet. (2020). *Delrapport 8: språk og medievaner barn og medier*. https://doi.org/978-82-91977-99-7

Miller, E. K., Lundqvist, M., & Bastos, A. M. (2018). Working Memory 2.0. *Neuron*, *100*(2), 463–475.

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

Moezzi, B., Pratti, L. M., Hordacre, B., Graetz, L., Berryman, C., Lavrencic, L. M., Ridding, M. C., Keage, H. A. D., McDonnell, M. D., & Goldsworthy, M. R. (2019). Characterization of Young and Old Adult Brains: An EEG Functional Connectivity Analysis. *Neuroscience*, *422*, 230–239. https://doi.org/https://doi.org/10.1016/j.neuroscience.2019.08.038

Monaco, M., Costa, A., Caltagirone, C., & Carlesimo, G. A. (2013). Forward and backward span for verbal and visuo-spatial data: standardization and normative data from an Italian adult population. *Neurological Sciences*, *34*(5), 749–754. https://doi.org/10.1007/s10072-012-1130-x

Monnier, C., Boiché, J., Armandon, P., Baudoin, S., & Bellocchi, S. (2022). Is bilingualism associated with better working memory capacity? A meta-analysis. *International Journal of Bilingual Education and Bilingualism*, *25*(6), 2229–2255.

Murman, D. L. (2015). The Impact of Age on Cognition. *Seminars in Hearing*, *36*(3), 111–121. https://doi.org/10.1055/s-0035-1555115

Nogueira, J., Gerardo, B., Santana, I., Simões, M. R., & Freitas, S. (2022). The Assessment of Cognitive Reserve: A Systematic Review of the Most Used Quantitative Measurement Methods of Cognitive Reserve for Aging. In *Frontiers in psychology* (Vol. 13, p. 847186). https://doi.org/10.3389/fpsyg.2022.847186

Oeppen, J., & Vaupel, J. W. (2002). Demography. Broken limits to life expectancy. *Science (New York, N.Y.)*, *296*(5570), 1029–1031. https://doi.org/10.1126/science.1069675

Olsen, R. K., Pangelinan, M. M., Bogulski, C., Chakravarty, M. M., Luk, G., Grady, C. L., & Bialystok, E. (2015). The effect of lifelong bilingualism on regional grey and white matter volume. *Brain Research*, *1612*, 128–139. https://doi.org/10.1016/J.BRAINRES.2015.02.034

Opdebeeck, C., Martyr, A., & Clare, L. (2016). Cognitive reserve and cognitive function in healthy older people: a meta-analysis. *Aging, Neuropsychology, and Cognition*, *23*(1), 40–60. https://doi.org/10.1080/13825585.2015.1041450

Pereira Soares, S. M., Kubota, M., Rossi, E., & Rothman, J. (2021). Determinants of bilingualism predict dynamic changes in resting state EEG oscillations. *Brain and Language*, *223*, 105030. https://doi.org/https://doi.org/10.1016/j.bandl.2021.105030

Prat, C. S., Yamasaki, B. L., Kluender, R. A., & Stocco, A. (2016). Resting-state qEEG predicts rate of second language learning in adults. *Brain and Language*, *157*, 44–50.

Prat, C. S., Yamasaki, B. L., & Peterson, E. R. (2019). Individual differences in resting-state brain rhythms uniquely predict second language learning rate and willingness to communicate in adults. *Journal of Cognitive Neuroscience*, *31*(1), 78–94.

Prince, M., Bryce, R., Albanese, E., Wimo, A., Ribeiro, W., & Ferri, C. P. (2013). The global prevalence of dementia: A systematic review and metaanalysis. *Alzheimers Dement*, *9*(1), 63-75.e2. https://doi.org/10.1016/j.jalz.2012.11.007

Richard Clark, C., Veltmeyer, M. D., Hamilton, R. J., Simms, E., Paul, R., Hermens, D., & Gordon, E. (2004). Spontaneous alpha peak frequency predicts working memory performance across the age span. *International Journal of Psychophysiology*, *53*(1), 1–9. https://doi.org/https://doi.org/10.1016/j.ijpsycho.2003.12.011

Rook, J. (2022). *Individual differences in bilingualism affect resting-state brain coherence in (older) adulthood (MSc Thesis)*.

Rossi, E., Soares, S. M. P., Prystauka, Y., Nakamura, M., & Rothman, J. (2023). Riding the (brain) waves! Using neural oscillations to inform bilingualism research. *Bilingualism: Language and Cognition*, *26*(1), 202–215.

Rothman, J., Bayram, F., DeLuca, V., Di Pisa, G., Duñabeitia, J. A., Gharibi, K., Hao, J., Kolb, N., Kubota, M., Kupisch, T., Laméris, T., Luque, A., van Osch, B., Pereira Soares, S. M., Prystauka, Y., Tat, D., Tomić, A., Voits, T., & Wulff, S. (2022). Monolingual comparative normativity in bilingualism research is out of " control ": Arguments and alternatives. In *Applied psycholinguistics* (pp. 1–14). https://doi.org/10.1017/S0142716422000315

Sauseng, P., Klimesch, W., Schabus, M., & Doppelmayr, M. (2005). Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International Journal of Psychophysiology, 57*(2), 97–103.

Shackman, A. J., McMenamin, B. W., Maxwell, J. S., Greischar, L. L., & Davidson, R. J. (2010). Identifying robust and sensitive frequency bands for interrogating neural oscillations. In *NeuroImage* (Vol. 51, pp. 1319–1333). Elsevier Science. https://doi.org/10.1016/j.neuroimage.2010.03.037

Soares, S. M. P., Prystauka, Y., DeLuca, V., & Rothman, J. (2022). Type of bilingualism conditions individual differences in the oscillatory dynamics of inhibitory control. *Frontiers in Human Neuroscience, 16*.

Spivey, M. J., & Marian, V. (1999). Cross talk between native and second languages: Partial activation of an irrelevant lexicon. In *Psychological Science* (Vol. 10, pp. 281–284). Blackwell Publishing. https://doi.org/10.1111/1467-9280.00151

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the International Neuropsychological Society*, *8*(3), 448–460.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*(10), 2015–2028. https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2009.03.004

Stern, Y., Albert, M., Barnes, C. A., Cabeza, R., Pascual-Leone, A., & Rapp, P. R. (2023). A framework for concepts of reserve and resilience in aging. *Neurobiology of Aging*, *124*, 100–103. https://doi.org/https://doi.org/10.1016/j.neurobiolaging.2022.10.015

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., Ewers, M., Franzmeier, N., Kempermann, G., Kremen, W. S., Okonkwo, O., Scarmeas, N., Soldan, A., Udeh-Momoh, C., Valenzuela, M., Vemuri, P., Vuoksimaa, E., & and the Reserve, R. and P. F. P. I. A. E. D. and C. F. W. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's & Dementia*, *16*(9), 1305–1311. https://doi.org/https://doi.org/10.1016/j.jalz.2018.07.219

Stocco, A., & Prat, C. S. (2014). Bilingualism trains specific brain circuits involved in flexible rule selection and application. *Brain and Language*, *137*, 50–61.

Stone, J. L., & Hughes, J. R. (2013). Early history of electroencephalography and establishment of the American Clinical Neurophysiology Society. *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society*, *30*(1), 28–44. https://doi.org/10.1097/WNP.0b013e31827edb2d

Strobel, C., & Engedal, K. (2009). Norsk revidert mini mental status evaluering (MMSE-NR). *Demensutredning i Kommunehelsetjenesten. Aldring Og Helse–Nasjonalt Kompetansesenter. Helsedirektoratet*.

Svarstad, J. (2022, April 25). Mer enn hvert fjerde emne undervises på engelsk: – Går greit, men blir ikke like bra som på norsk. *Khronos*. https://khrono.no/mer-enn-hvert-fjerde-emne-undervises-pa-engelsk-gar-greit-men-blir-ikke-like-bra-som-pa-norsk/726788

Thompson, J. M., Hamilton, C. J., Gray, J. M., Quinn, J. G., Mackin, P., Young, A. H., & Nicol Ferrier, I. (2006). Executive and visuospatial sketchpad resources in euthymic bipolar disorder: Implications for visuospatial working memory architecture. *Memory*, *14*(4), 437–451. https://doi.org/10.1080/09658210500464293

Tomoschuk, B., Ferreira, V. S., & Gollan, T. H. (2019). When a seven is not a seven: Self-ratings of bilingual language proficiency differ between and within language populations. *Bilingualism: Language and Cognition*, *22*(3), 516–536.

Ulloa, J. L. (2021). The Control of Movements via Motor Gamma Oscillations. *Frontiers in Human Neuroscience*, *15*, 787157. https://doi.org/10.3389/fnhum.2021.787157

Valenzuela, M. J., & Sachdev, P. (2006). Brain reserve and cognitive decline: a non-parametric systematic review. *Psychological Medicine*, *36*(8), 1065–1073. https://doi.org/DOI: 10.1017/S0033291706007744

Van de Steen, F., Faes, L., Karahan, E., Songsiri, J., Valdes-Sosa, P. A., & Marinazzo, D. (2019). Critical Comments on EEG Sensor Space Dynamical Connectivity Analysis. *Brain Topography*, *32*(4), 643–654. https://doi.org/10.1007/s10548-016-0538-7

Voits, T., DeLuca, V., & Abutalebi, J. (2022). The nuance of bilingualism as a reserve contributor: Conveying research to the broader neuroscience community. *Frontiers in Psychology*, *13*.

von Stein, A., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology*, *38*(3), 301–313. https://doi.org/https://doi.org/10.1016/S0167-8760(00)00172-0

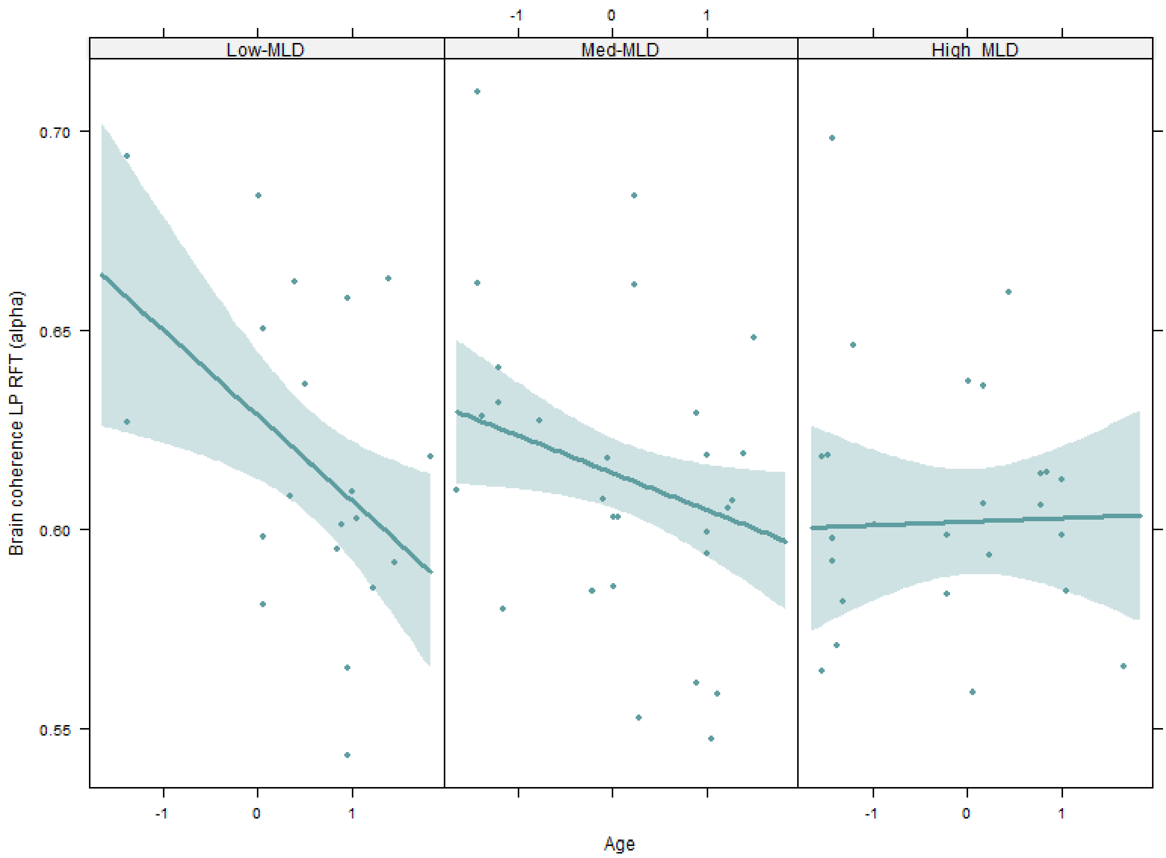
Vysata, O., Kukal, J., Prochazka, A., Pazdera, L., Simko, J., & Valis, M. (2014). Age-related changes in EEG coherence. *Neurol Neurochir Pol*, *48*(1), 35–38. https://doi.org/10.1016/j.pjnns.2013.09.001

Wen, Y., & van Heuven, W. J. B. (2017). Non-cognate translation priming in masked priming lexical decision experiments: A meta-analysis. *Psychonomic Bulletin and Review*, *24*(3), 879–886. https://doi.org/10.3758/s13423-016-1151-1

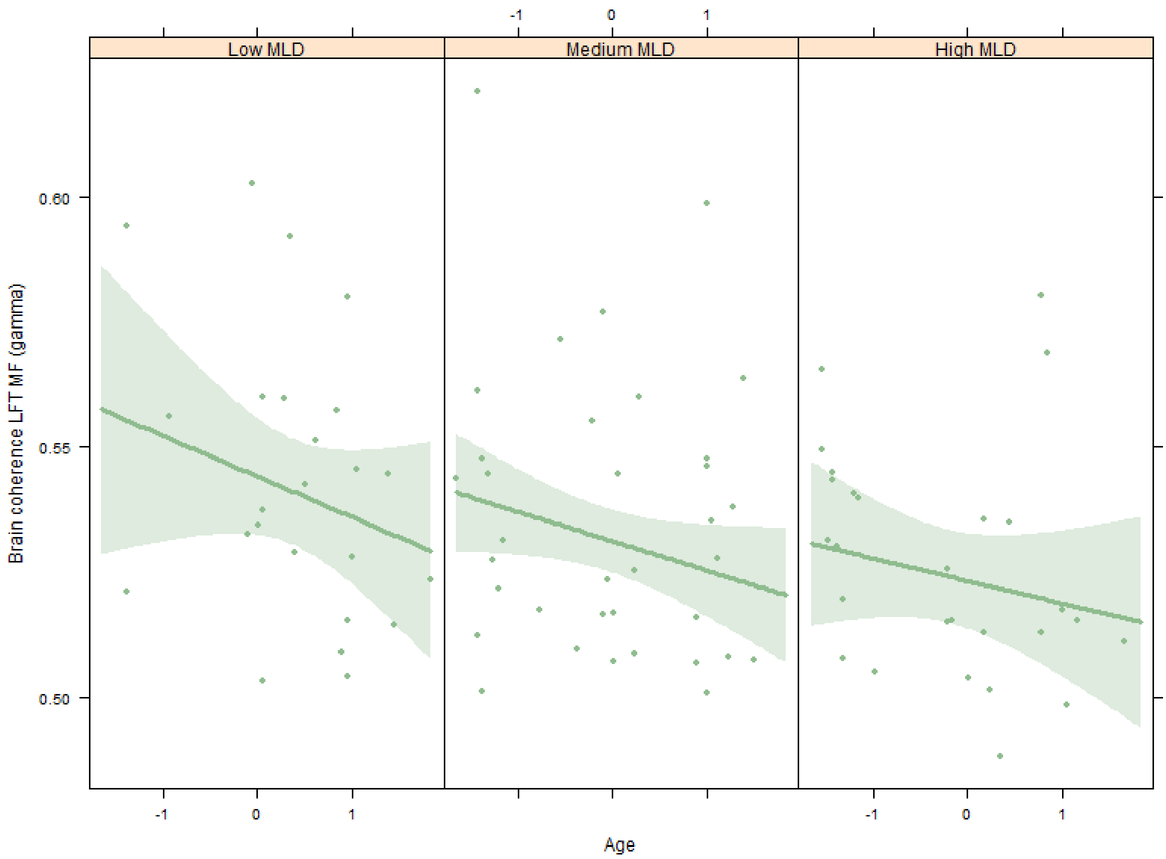
WHO. (2023). *Aging and Health*. https://www.who.int/news-room/fact-sheets/detail/ageing-and-health

Appendix

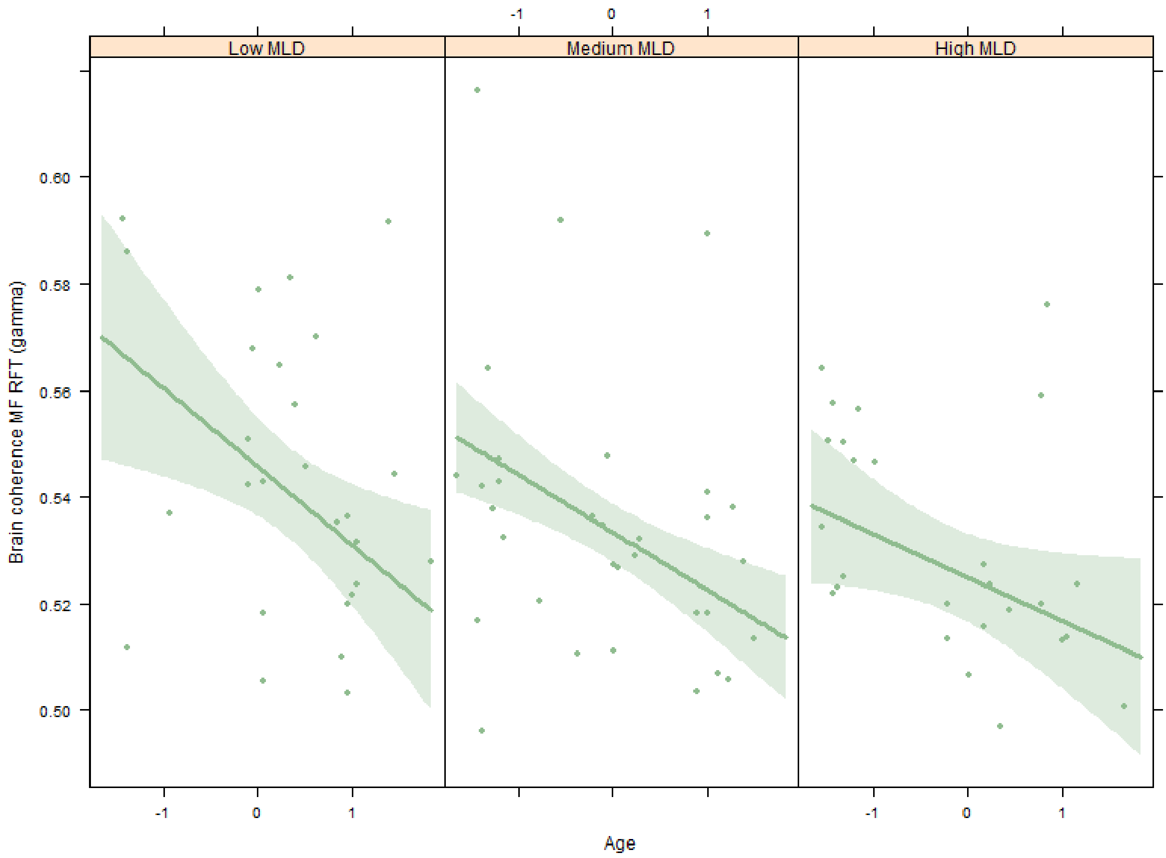
A Conditional effects plot of Age on LP-RFT alpha coherence, conditioned and grouped by MLD level.



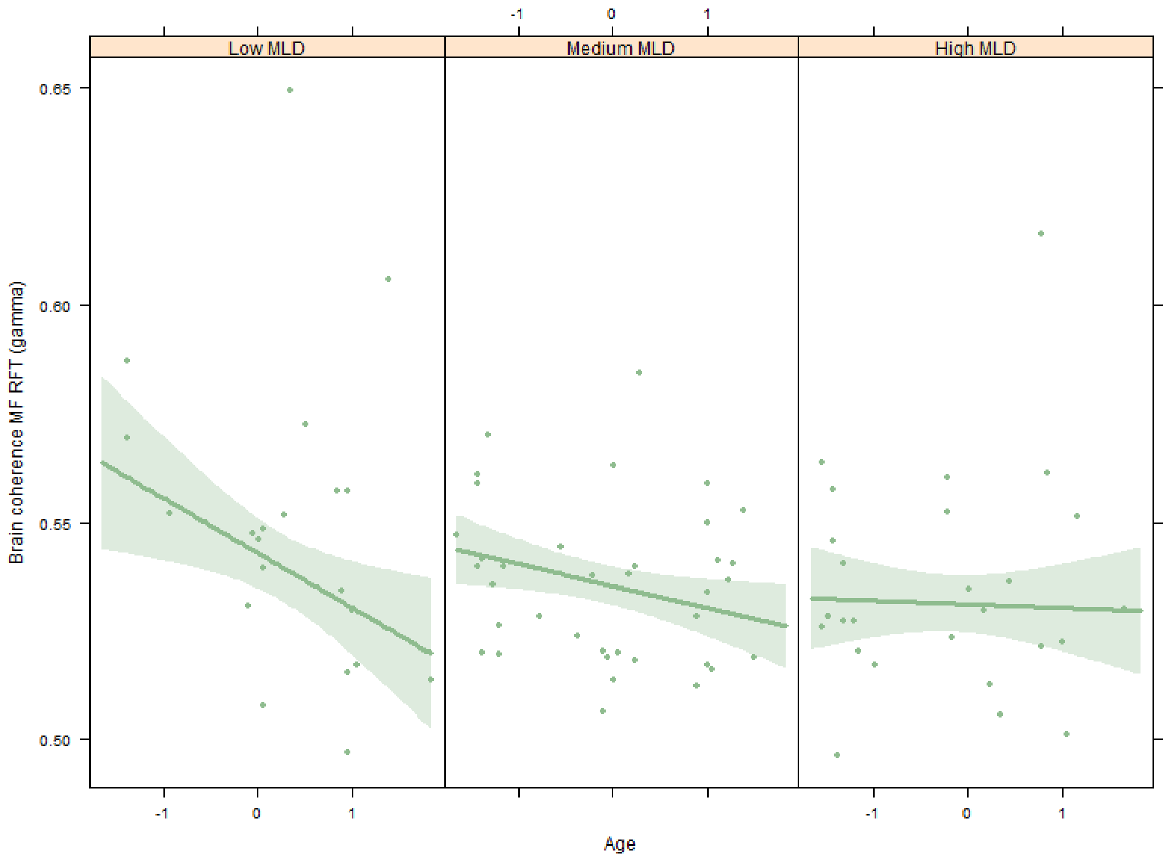
B Conditional effects plot of Age on Gamma LFT-MF coherence, conditioned and grouped by MLD level.



C. Conditional effects plot of Age on gamma MF-RFT coherence, conditioned and grouped by MLD level.



D Conditional effects plot of Age on Gamma MF-RP coherence, conditioned and grouped by MLD level.



Model 1 Significant Results

	Alpha LP-RFT			Alpha MF-RFT			Lowbeta LFT-MF			Lowbeta MF-RP			Gamma LFT-MF			Gamma MF-RFT			Gamma MF-RP		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.615	0.606 – 0.624	**<0.001**	0.613	0.599 – 0.627	**<0.001**	0.556	0.549 – 0.564	**<0.001**	0.563	0.558 – 0.568	**<0.001**	0.533	0.526 – 0.539	**<0.001**	0.535	0.530 – 0.541	**<0.001**	0.536	0.532 – 0.541	**<0.001**
Age c[, 1]	-0.010	-0.019 – -0.001	**0.032**	-0.020	-0.035 – -0.006	**0.007**	-0.008	-0.015 – -0.000	**0.047**	-0.004	-0.009 – 0.002	0.185	-0.006	-0.013 – 0.000	0.066	-0.011	-0.017 – -0.006	**<0.001**	-0.006	-0.011 – -0.002	**0.009**
MLD c[, 1]	-0.011	-0.021 – -0.001	**0.027**	-0.007	-0.022 – 0.009	0.396	-0.007	-0.015 – 0.000	0.061	-0.002	-0.008 – 0.003	0.389	-0.008	-0.015 – -0.001	**0.019**	-0.009	-0.015 – -0.003	**0.004**	-0.005	-0.009 – 0.000	0.054
Lifestyle Score c[, 1]	-0.005	-0.014 – 0.003	0.203	-0.003	-0.017 – 0.011	0.714	0.002	-0.005 – 0.009	0.495	0.006	0.000 – 0.011	**0.036**	-0.001	-0.007 – 0.005	0.824	-0.005	-0.010 – 0.001	0.088	0.001	-0.003 – 0.005	0.654
Age c[, 1] × MLD c[, 1]	0.009	-0.001 – 0.019	0.063	0.000	-0.017 – 0.017	0.981	0.002	-0.006 – 0.011	0.589	0.001	-0.006 – 0.007	0.834	0.001	-0.006 – 0.009	0.702	0.003	-0.004 – 0.009	0.404	0.005	-0.001 – 0.010	0.094
Observations	73			85			86			84			86			85			84		
R^2	0.160			0.125			0.061			0.035			0.096			0.103			0.000		

E Significant model 1 results.