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Bi-multilingual Language Engagement Shapes the Brain’s Functional Connectivity

An Aging Study on Resting State Brain Rhythms Correlated to Executive Functions

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Abstract

Bi-multilingualism have been argued to help maintain cognitive functioning in aging through increased resilience to cognitive decline, known as cognitive reserves (CR). Researchers have argued that bi-multilingualism imposes unique cognitive demands that can change the brain's structural and functional integrity. In order to investigate the effects of multilingual engagement on cognition, behaviourally and neurologically, resting state (RS) oscillations were collected through electroencephalography (EEG) in healthy Norwegian-English bi-multilingual adults in various stages of adulthood. Additionally, behavioural responses in terms of reaction times (RT) were captured through a non-linguistic flanker task and further correlated to RS dynamics. Negative main effects of language experience, operationalised as multilingual diversity (MLD), were found in the alpha and gamma bands, while also indications in said frequency bands indicated a flattening effect of age-related cognitive decline for those with a higher MLD. The MLD did not indicate increased flanker efficiency, where only older age significantly increased RTs. No correlations were found between the RS functional connectivity and flanker performance. These findings might suggest that higher multilingual engagement will slow down the age-related decline in the brain's functional connectivity, as this negative main effect of MLD is likely due to no CR trade-off for the younger participants.

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ACH	Adaptive Control Hypothesis
AD	Alzheimer’s Disease
BAPSS	Bilingual Anterior-to-Posterior and Subcortical Shift
BR	Brain Reserve
CR	Cognitive Reserve
CRS	Cognitive Reserve Scale
EBF	Experience-based Factors
EEG	Electroencephalography
EF	Executive functions
ERP	Event-Related Potential
FFT	Fast-Fourier Transformation
fMRI	Functional Magnetic Resonance Imaging
GM	Grey Matter
IAF	Individualised Alpha Frequency
IC	Inhibitory Control
ITI	Inter-trial Interval
KCL	Potassium Chloride
LFT	Left Frontal Temporal
LHQ3	Language History Questionnaire 3.0
lm	Linear Mixed Model
lmRob	Robust Linear Regression Model
LP	Left Posterior
L1	First Language
L2	Second Language
2L1	Two languages from birth
MF	Medial Frontal
MMSE	Mini Mental State Examination
MRI	Magnetic Resonance Imaging
MSSSS	MacArthur Scale
NSD	Norwegian Centre for Research Data
RFT	Right Frontal Temporal
ROI	Region of Interest

RP	Right Posterior
RS	Resting State
rs-EEG	Resting State Electroencephalography
SFFQ	Short Form Dietary Questionnaire
WM	White Matter

1. Introduction

The field of language research is progressing where increasing attention and important findings over the last few decades have led the field in different directions which consequently means that the field is becoming wider where researchers are investigating very different aspects language. Bi- and multilingualism (henceforth referred to as bi-multilingualism) have especially been of particular interest. During the last two decades, researchers have investigated more thoroughly if being a bilingual can affect cognition, both behaviourally and neurologically. However, the link between bi-multilingualism and cognitive effects is still poorly understood and unresolved (see Bialystok, 2021 for a review / opinion paper). The basis of these investigations lays within that bi-multilingualism entails unique demands for the brain, which consequently can result to changes in the brain's functional and structural integrity (De Frutos-Lucas et al., 2020; Costumero et al., 2015; Green & Abutalebi, 2013). This has led to an explosion of studies where several studies have found evidence for that bi-multilingualism can lead to effects on neurocognition (see for example Pliatsikas, 2019, for a review). However, there is currently a wealth of variation in the behavioural findings of bi-multilingual effects in executive function (EF) tasks (Lehtonen et al., 2018).

The research on the matter have been conducted in different age groups, and it have been suggested that long-term bilingualism can result in a more cognitively healthy aging process through the strengthening of cognitive reserves (CR; Stern, 2009; Craik et al., 2010). These reserves are argued to be a mechanism that are built over time through effortful and stimulating activities and serves as a cognitive resilience in the event of cognitive decline, which can help maintain cognitive functioning at an older age. Since the world is aging (WHO, 2022), the understanding of these effects on cognitive decline and cognitive functioning is becoming increasingly important to explore further.

The majority of the previous research have investigated bilingualism in comparison to monolingualism, where monolinguals serve as a 'control group'. Through this, one can investigate whether there are differences between these groups, both behaviourally and neurologically. Recent research has taken a step back and argued that this default investigation method might not be as optimal as previously thought. Bi-multilingualism is rather a dynamic spectrum where differences in multilingual engagement, experience, and opportunity is important to acknowledge (DeLuca et al., 2019). These speakers are not all identical since some have more opportunities and engages more in multilanguage contexts than others, and thus are more exposed to these situations, which can potentially lead to stronger effects on cognition. Increased bilingual engagement have been shown to affect neurocognition, where no monolinguals have served as a control group (e.g., Soares et al., 2021). However, there are no current studies on whether differences in bi-multilingualism as a dynamic spectrum can affect cognition across the lifespan while controlling for other lifestyle factors. This thesis therefore aims to partake in filling this gap in the literature by investigating differences in bi-multilingual engagement and whether it affects brain functionality and EF throughout the lifespan while also controlling for other demographic lifestyle factors.

2. Theoretical Background

2.1 Bilingualism and cognitive decline

2.1.1 Bilingualism

Human language is universal and language experience varies but half of the world's population are now speaking more than one language (Grosjean, 2014) and research on bilingualism has become increasingly important. The research covers a lot of aspects of bilingualism, from language acquisition to what role bilingualism plays on brain structure and function where the latter has found effects due to bilingualism in later years (Bice et al., 2020; Voits et al., 2022; Calvo & Bialystok, 2021). It is however ironic that there is no clear-cut definition of bilingualism. Early definitions of bilingualism stated that one must have "native-like control of two languages" (Bloomfield, 1933), however this excludes all of the non-balanced bilinguals, and there would be a problem with labelling all the people that speak more than one language but with different levels of proficiency. Additionally, it is difficult to know the proficiency level of these speakers with 'native-like control' as well because it is arduous to measure. The discussion has also taken a turn to be defined dependent on language use, for instance, that bilinguals are "people who use two (or more) languages (or dialects) in their everyday lives" (Grosjean, 1997), however, not all bilinguals actually use two or more languages (or dialects) in their daily lives. The discussion about bilingualism therefore often regards the grade of knowledge and use of another language or dialect to be considered a bilingual, however a clear-cut definition of bilingualism still remains undisclosed.

Researchers have therefore begun to view bilingualism as a spectrum where individuals with varied experience and engagement in a second language are still accounted for (DeLuca et al., 2019; Rossi et al., 2022). The spectrum of bilingualism is wide in terms of bilingual experience and use; however, bilinguals are often separated in groups in terms of age and manner of acquisition. These groups are often regarded as twofold, 'simultaneous bilinguals' are speakers who learn two languages from birth and 'sequential bilinguals' are speakers who acquire the second language after the first is acquired. However, this separation is nuanced where differences in language use, experience, and opportunity shines. For instance, heritage speakers are bilinguals who acquire a ethnical minority language at home (e.g., learning English at home in Norway) either simultaneous with the societal majority language or a short period after (Montrul & Ionin, 2012). The overall use and proficiency of their minority language is very individual in this group of bilinguals, it is therefore important acknowledge the spectrum that bilingualism is, based on experiences and opportunity, and it is not a solid state of being. Some recent researchers have therefore tried to urge a shift in the research norm i.e., the bilingual vs. monolingual comparison, and rather consider bilinguals under experienced-based factors (EBF) and view the results in light of these factors (DeLuca et al., 2019).

2.1.2 Cognitive decline

With decreasing birth rates and an overall aging population it is becoming increasingly important to conduct research on the older population in order to find evidence for factors that can improve the overall quality of life to these individuals as their cognitive and physical abilities progressively deteriorate (WHO, 2022; Vollset et al., 2020). As for the brain itself, deterioration is clearly identifiable by investigating the physical and anatomical change in the brain with the use of MRI scans. These scans can quantify grey matter (GM) volume and white matter (WM) integrity and have been frequently used in studies on aging (Voits et al., 2022; Farokhian et al., 2017; see Bettio et al., 2017 for review). Even though the cognitive abilities deteriorate with age, the trajectory of cognitive decline still varies where some suffer with neuropathological diseases like dementia and Alzheimer's disease (AD) while others are more resilient to cognitive decline. The determinants of this rapid decline and also why some are more resilient to cognitive aging is yet to be fully understood in the literature. Contributing factors to a healthier aging trajectory have been proposed in the literature, for instance, genetic differences, a healthy diet, physical exercise, longer education, greater cognitive stimulation, and later research have argued that active bilingualism can also be a contributing factor to healthier cognitive aging (see Bettio et al., 2017; Cabeza et al., 2018).

This resilience to cognitive aging is often explained in the literature by the concepts of cognitive reserve (CR) and brain reserve (BR). CR is regarded as a protective mechanism that can help maintain cognitive functioning in the event of cognitive decline, which follows the damage to the brain in terms of older age, injury or through other neuropathological diseases like dementia (Fleck et al., 2017), an individual with a higher CR is therefore more resilient to neural atrophy (Stern, 2009). CR focuses on the efficiency of neural networks in how people process different tasks where CR is often measured by lifetime experiences such as educational attainment, socioeconomic status, grade of leisure activities, IQ, and also language history. BR is differences in the inter-individual brain's anatomy and is often measured quantitively in terms of neural tissue, more neurons, or synapses, as a structural reinforcement of the brain (Stern, 2009). Differences in life experiences can therefore tap into the aging trajectory where some activities that are effortful and stimulating can be prone to a healthier aging process since it enforces the reserves.

Fleck and colleagues (2017) investigated this concept of CR and brain oscillations in middle-aged adults where they recorded brain oscillations at wakeful rest, both with eyes closed and eyes open, using electroencephalography (EEG). They used brain oscillations to capture functional connectivity, or coherence. This measure can show whether different brain regions, in set frequency bands, are in synchrony with each other and discloses whether they are connected (Bowyer, 2016). The participants in Fleck et al. (2017) (n=90) were cognitively healthy adults between the ages of 45 and 64. These participants were categorised into low-CR and high-CR groups based on CR scores through a median split, meaning that participants with a score below the median split were placed in the low-CR group and vice versa. The CR score was calculated through two measures, socio-economic status, and verbal IQ scores. The results showed that younger participants had greater left-hemisphere functional connectivity (coherence) than in the right hemisphere, whereas for the older group, it was the opposite. There was a general finding of higher coherence in the eyes-closed condition than in the eyes-open condition, and that the high CR group exhibited greater coherence than the low CR group in the alpha frequency band (8-12 Hz), regardless of their age, in the eyes closed condition. Findings also revealed that younger participants in the low-CR group had higher mean coherence than the high-CR group, whereas this was shifted to the opposite in the older group, and this was most evident in the right-hemisphere in the alpha (8-12 Hz) and theta (4-8 Hz) frequency bands. However, the study does not investigate the coherence between the hemispheres, only intra-hemispheric coherence measures were made. The findings therefore suggests that higher CR can maintain the functional connectivity for the older participants, which might result in a healthier aging trajectory.

In order to investigate the older population, it is incredibly important to separate individuals with neuropathological diseases like AD and other dementia types and those that do not. This task has been proven to be a more complex task than it might seem. With age, the brain deteriorates, and it might be difficult to separate these groups since the anatomy is nonetheless changing regardless of a present disease. The aging trajectory of the brain without a present neuropathological disease where both structural and functional changes in several regions and domains change is often referred to as ‘normal aging’ (Farokhian et al., 2017).

The onset of the aging process varies inter-individually, where some can experience decline as early as in their 50s while others experience it later, most prominently it occurs around age 60 (Nyberg et al., 2012). Typical processes that are negatively affected with age are for instance processing speed and selective attention, where the processing speed peaks in the third decade in life and then slowly decreases with age. The decline in selective attention, the ability to focus on specific information while ignoring irrelevant information in noisy environments, is also noticeable with age (Harada et al., 2013). Studies have also found that some brain regions are more vulnerable to normal non-pathological deterioration, such as the prefrontal, insular, cingulate cortices, and the hippocampus while other regions are more robust to age-related effects such as the occipitoparietal areas and subcortical regions (e.g., Farokhian et al., 2017; Voits et al., 2022; Feng et al., 2020). It is yet to be fully understood why these regions are so vulnerable to deterioration where the hippocampus, responsible for memory, is especially vulnerable. It is therefore expected that cognitive and physical abilities are reduced in older age even without a present neuropathological disease, however, certain activities can help the aging process as presented above.

As opposed to normal aging, there are the incidences of dementia or other neuropathological diseases which have been heavily researched but there is yet to be fully understood what exactly causes a minority of the population to develop dementia, like AD. There has been suggested a magnitude of risk factors for developing dementia, however, the individual differences between patients makes it difficult to know why such a large percentage of the world’s older population is living with dementia, which is estimated to be around 10 percent for people above age 70 (Freedman et al., 2021; See Solomon et al., 2014 for review). Dementia is the umbrella term of various types of diseases that involve loss of memory, language, problem-solving, and reduction of other cognitive abilities. Dementia is caused by abnormal brain changes where the brain cells are damaged over time which eventually affects daily life (Alzheimer’s Association, 2023). The most typical symptom of dementia is loss of memory, and it is often the first noticeable symptom before it progressively gets worse. There is currently no cure for dementia, but researchers are trying to find a form of medication that can prevent or slow down this cellular damage, especially in relation to AD (Ma et al., 2022). Healthy habits and better lifestyle choices has also been suggested to prevent or delay onset of AD and dementia where it is believed that individuals with greater reserves can cope better in the face of a neuropathological disease. AD and dementia cannot be considered as normal aging since it severely reduces cognitive and physical abilities in a considerably shorter time frame than normal aging.

2.1.4 Bilingualism modulates cognitive decline?

Bilingualism have been suggested to have an impact on the brain, both functionally and structurally. Researchers have argued that bilingualism imposes some extra unique demands that the brain have to manage, and it is believed to be the reason behind these structural and functional changes in the brain (Bogulski et al., 2019; Seo & Prat, 2019). Linguistically, the bilingual has to acquire and maintain two separate, yet interconnected, language systems and prevent language interference between the languages. Cognitively, the bilingual has to select the appropriate language according to the given context and manage them appropriately. These unique demands are cognitively challenging which trains the brain and is believed to generate greater reserves in the long-term. It could be assumed that more active dual-language use and experience may result in even greater reserves since it is more cognitively demanding by frequently being exposed to such situations. However, there is a limited number of studies on this matter since the magnitude of active bilingual language use is often not accounted for. It is therefore important to conduct studies which account for inter-group differences in dual-language use and experience and how it correlates to structural and functional changes in the brain and/or reserves.

Studies on bilingualism has found evidence for a neural network shift from the frontal regions of the brain to the posterior regions which correlates to bilingual experience, which has been termed the "*bilingual anterior-to-posterior and subcortical shift*" (BAPSS; Grundy, Anderson & Bialystok, 2017). They report that bilinguals who rely on frontal regions tend to show decreased dual-language performance as opposed to those who have recruited the posterior regions. This seems to stem from the fact that this posterior recruitment correlates to efficiency in the second language (L2). More efficient networks and involvement of posterior regions relates to CR and can further reinforce the brain to delay the onset of severe neuropathological diseases. Some findings support this suggestion where Craik et al. (2010) investigated older individuals who had been diagnosed with probable AD. They collected data from 211 patients where 109 were monolinguals and 102 were bilinguals, where the bilinguals had to have used the L2 regularly in the majority of their life, and as a minimum from their early adulthood. There was a support for a bilingual effect where the bilinguals were diagnosed 4.1 years later than the monolinguals and the onset of AD symptoms were reported 5.3 years later. There were no apparent effects of other factors they collected such as educational attainment, occupational status, or immigration, and the authors argue that lifelong bilingualism contributes to greater CR which let them cope better with neuropathology.

The functional connectivity (or coherence) between brain regions with age have been shown to decrease more in the posterior regions compared to the anterior regions which also experience some increases (Jones et al., 2011; López-Sanz et al., 2017). This connectivity decrease in the posterior regions is accelerated when investigating AD patients, however, it decreases in healthy aging as well. Interestingly, this is not consistent with the previously mentioned studies who are suggesting that the anterior regions and the hippocampus are particularly vulnerable to age-related effects (Farokhian et al., 2017; Voits et al., 2022; Feng et al., 2020). The effect of bilingualism and the BAPSS model (Grundy et al., 2017) implies that the connectivity in the posterior regions are strengthened for bilinguals who are frequently involved in dual-language use which can positively modulate their CR. The involvement of the posterior regions can therefore contribute to resilience of the seemingly more apparent disconnection problem of the posterior regions in dementia and modulates their reliance on the anterior regions.

Altogether, bilingualism seem to contribute to healthy aging and modulates the reserves, both structurally and functionally. The additional and unique demands the brain have to manage seems to cause strengthened networks, more frequent recruitment of posterior brain regions, increased brain volumes in terms of GM and WM in several brain regions, and these modulations can help with delaying neuropathological diseases with several years.

2.2 Executive functions and bilingualism

2.2.1 Executive functions in bilingualism research

Executive function (or EF) is an umbrella term for multiple cognitive processes which involves inhibition, attention, monitoring, shifting, working memory, and fluency (Lehtonen et al., 2018). These functions have been heavily studied in relation to bilingualism in later years. The bilingualism and EF link have been made because of the additional and unique demands that bilingualism entails, and consequently it has been suggested whether bilingualism can modulate these functions (Green & Abutalebi, 2013). Since both languages in a bilingual's mind are always active (Guo et al., 2012), bilingualism has been directly tied to inhibition since the bilingual speaker always has to inhibit the irrelevant language according to the context, and it has therefore been suggested whether greater inhibitory demands through bilingualism can also modulate inhibition skills in domain-general contexts as well (Green, 1998). Recent research has therefore investigated bilinguals versus monolinguals in non-linguistic cognitive tasks, such as the flanker task (Eriksen & Eriksen, 1974), which tests inhibitory control and selective attention, in order to see differences between these groups. This belief has often been regarded to be a part of the so-called ‘bilingual advantage’, which suggests that bilinguals have an advantage in cognitive control, however, the topic is controversial and there is a wealth of variation in the findings in different studies (Lehtonen et al., 2018).

One of the early works on bilingualism and inhibitory control proposed the inhibitory control (IC) model (Green, 1998), which revolves around language selection. The model proposes a mechanism for bilinguals to avoid inappropriate non-target language interference, which is argued to be monitored by a ‘supervisory attentional system’ that reacts to top-down cues which further leads to inhibition of the non-target language. This model was then further extended and proposed that these processes also could modulate inhibitory control in other non-linguistic cognitive domains as well. This model has gotten considerable attention in the field and has also received a lot of criticism as well, where findings suggest there is an applicability problem of the model on inhibitory control in other non-linguistic domains (see Hilchey & Klein, 2011 for review).

Lehtonen and colleagues (2018) conducted an extensive meta-analysis of the previous literature on EF in relation to bilingualism and included 152 studies and all of the sub-categories of EF. They only included studies that had at least five different samples in the task-inclusion paradigm (i.e., monolingual versus bilingual comparisons), and they only included studies that investigated healthy adults above 18 years of age. They further grouped the participants from the collected studies into two sub-groups of ‘younger’ (aged 18-59) and ‘older’ (age 60 and above) in order to account of age-related effects. Only behavioural data were collected from these studies and consequently, neuroimaging data was excluded from further analysis. Additionally, publication bias was also accounted for. The results of this extensive metanalysis revealed that there was no advantage in the behavioural data for the bilinguals after the publication bias was accounted for. However, prior to this correction, there was a small positive effect for inhibition, shifting, and working memory, but monitoring and attention remained insignificant. This further reveals that the effects from bilingualism on EF might not be observed in behavioural data alone, there might be more to discover if one also includes how the information is processed which is especially important for the older participants because there is generally less research on healthy bilingual seniors.

Another study on EF and bilingualism was conducted by Kousaie and Phillips (2017) where they investigated neural oscillations through EEG on 21 monolinguals and 22 bilinguals while they were performing three cognitive interference tasks, specifically, Stroop, Flanker and Simon. The participants were in the older age range, between 60 and 83. The bilinguals self-reported themselves as highly proficient in their L2 French and they were also tested in an animacy judgement task, as an objective measure of L2 proficiency, which corresponded to their self-assessment. The monolinguals had minimal exposure to any additional language. The results were task dependent where there was only found a clear correlation between bilingualism and behavioural performance in the Stroop task where the bilinguals were more accurate and faster in the incongruent condition. No behavioural effects were found in the Simon task, whereas in the flanker task, bilinguals had greater accuracy in general but there was no correlation in reaction times. As for the EEG material, which was analysed through event-related potentials (ERP), the results also vary to some extent. The bilingual group was better at detecting conflict and allocated fewer resources in the Stroop task, which indicated better performance. In the Simon task, the results indexed better performance for the bilingual group, where the monolinguals kept monitoring for conflict in both trial conditions and bilinguals were also faster in categorisation and allocated fewer resources than the monolinguals. In the flanker task, there were some indications for better performance for bilinguals, the bilinguals seemed to be better at conflict monitoring in the incongruent trials, and there were some small processing differences between the groups where the bilinguals were better. Because of the variation in the findings between the tasks, they argue that the tasks struggle to prove their convergent validity. However, there were language group differences in each task, whereas only a clear behavioural correlation was found in the Stroop task, which further strengthens the argument that behavioural data alone might not always account for potential changes in cognition in relation to bilingualism.

Because of the inconsistencies in behavioural data across studies, it should probably be used as a complementary factor to neuro-related research in relation to bilingualism, where the main focus is investigating how information is processed or correlating behavioural data to neuro-imagery measures. These potential differences were not captured by Lehtonen and colleagues (2018). Multiple studies have investigated said differences and found correlations between bilingualism and structural and/or functional changes in the brain, especially in comparison to monolinguals (Costumero et al., 2015; see Bialystok et al., 2012 for review), however, there is limited work in comparison to differences in interindividual bilingual experiences and engagement throughout the lifespan.

2.2.2 Adaptive control in bilingualism

A hypothesis on adaptive control in bilingualism was proposed by Green and Abutalebi (2013), where they propose that bilingual brain adaptations are based on different language experiences. This hypothesis, the adaptive control hypothesis (ACH), specifically include three conversation contexts and creates a theoretical approach to predicting the outcomes of both efficiency in language production and in cognitive tasks (e.g., Stroop task), both behaviourally and neurologically. The first context is a single-language context where one language is used in a specific environment and the other in another environment, for instance, a non-societal language at home, meaning that a different language is used as home as than in the society. The second context is a dual-language context, where both languages are (typically) used with different speakers. The third context is within a dense code-switching context where the language switches within utterances, and speakers can also morphosyntactically modify words in between languages, meaning that the morphosyntax from one language can attach to a word from the other language. These three language situations are argued to utilise different cognitive control processes, where for instance, interference suppression, is utilised more in single – and dual-language contexts than in dense code-switching contexts since they need to inhibit language interference. Whereas opportunistic planning, which means using whatever comes to mind to reach the goal, is prominent in code-switching contexts.

It is therefore argued that these conversational contexts each impose different cognitive processes that can cause certain brain adaptations which depends on what situation the bilingual speaker engages in. In terms of goal maintenance, interference suppression and conflict monitoring, it is argued that dual-language contexts require the greatest implementations of these processes since both languages are present in this situation and language interference is to be avoided. Theoretically, one can therefore investigate certain regions of interests (ROI) dependent on how the bilingual engages in conversations. If a bilingual engages more in dual-language contexts, for instance an interpreter, could there be visible brain adaptations in the left prefrontal cortex and inferior cortex, that they argue to be related to interference control?

There are of course limitations to this theoretical framework, where it can be tedious, in a practical sense, to separate between the language use parameters when asking participants, and additionally, that it can be difficult for the participant to give a reliable estimation. Recent research has also struggled to find support for the ACH where for instance a large-scale study investigated behavioural performance in four interference tasks (e.g., antisaccade, Stroop, go/no-go, stop-signal task), where they tested 195 bilinguals with Polish as their first language (L1) and English as their second language (L2). They controlled for dual-language contexts but found no correlations between their results and the ACH (Kałamała et al., 2020). A recent review by Paap, Mason and Anders-Jefferson (2021) also struggled to find compelling evidence in favour of the ACH, which they mention is “at best, inconsistent”.

2.2.3 Bilingualism and attentional control

The argument of increased attentional control as a measure of bilingualism is based on the idea that bilinguals need to divert attention to the target language, and also manage two languages that are both active. One can see that the idea behind the believed enhanced attentional control is very similar to the other arguments of the other executive control functions. The issue with inhibition as Bialystok et al., (2012) and Bialystok and Craik (2022) argues is that some previous evidence has shown that the bilinguals have a general advantage in both task conditions i.e., congruent and incongruent trials, and therefore it becomes difficult to say that they have an advantage because of inhibition, since there is nothing to inhibit in congruent trials. They therefore suggest that bilinguals, rather than inhibiting stimuli, are better at allocating attentional resources in conflict monitoring. The argument of attentional control and inhibition is therefore closely related.

A study that shows this is an older study by Bialystok et al. (2004) where they conducted three investigations on bilinguals compared to monolinguals. The participants in the first and second study included younger to middle-aged adults aged between 30-58 and older seniors aged between 60-88. Whereas the third study only included younger to middle-aged adults aged between 30-55. There was a total of 154 participants across these studies, where the first had 40 participants, the second had 94 participants, and the third had 20 participants. All of these studies presented the Simon task, where they measured the Simon effect, which is a measure of the mean reaction time of incongruent and congruent trials, and then subtracts the congruent trials by the incongruent ones to find a Simon effect. The study designs varied to a certain degree, the first Simon design in the first study was replicated from a previous study which was meant to be testing children, and it therefore consisted of fewer trials (n=28). This was then increased for the second study to a more standard approach (n=192). For the third study, they wanted to see if the Simon effect and reaction times would converge after sufficient practice and therefore found a new group of bilinguals and monolinguals where they included 10 blocks of 24 trials each and used two of the same conditions presented in the second study which was side-2 and center-4.

The results from the first study showed a general effect of longer reaction times for the incongruent trials than congruent ones and a smaller Simon effect for the bilinguals and younger adults. There was however no correlation between bilingualism and Simon effect in the older group, and there was still a speed advantage for bilinguals in congruent trials as well. For the second study, there was a reliably smaller Simon effect for the bilinguals, but not in the younger bilingual group. With increased age, there was a positive effect of bilingualism on the Simon effect. For the final study, the Simon effect and reaction times converged with increased practice, where the bilinguals were faster and showed smaller Simon effects in the beginning. The Simon effects converged in the sixth block for each group, and then the bilinguals became better from block seven through nine, and then converged again with the monolinguals in the final block. The bilinguals had better reaction times throughout the task except for in the final block, where the monolinguals had gotten enough practice and went down towards the bilinguals' level. Altogether, these studies show the advantages seen in bilingual children are preserved through adulthood and that bilinguals might be more resilient in cognitive decline on EF. However, the results also show that the bilinguals do not only outperform monolinguals on incongruent trials, but also in congruent ones, which can be tied to better attentional allocations rather than only better inhibitory control. This suggestion has also been shown in other studies as well (Bialystok et al., 2005).

2.3 Measures of bilingualism

2.3.1 Behavioural interference tasks and resting state

Different tasks to investigate cognitive control have been used for decades and there has been an upsurge with the use of these cognitive tasks in relation to bilingualism in later years. Typical behavioural interference tasks are for instance, the Stroop task (Stroop, 1935), the

Simon task (Craft & Simon, 1970), and the flanker task (Eriksen & Eriksen, 1974), which tests the participants’ ability to avoid interference and conflict in certain contexts by supressing irrelevant information. The flanker task is of particular interest in this thesis, and it presents the stimuli with a set of arrows where the participants are asked to only focus on the central arrow which is surrounded by ‘flanker’ arrows which serves as a distraction. The surrounding arrows can either be congruent, incongruent, or neutral. In congruent trials, the surrounding ‘flanker’ arrows point in the same direction as the central arrow; in incongruent trials, the surrounding arrows point in the opposite direction as the central arrow; and in neutral trials, no ‘flanker’ arrows are present. These trials test the participants’ ability to cope with interference from the ‘flankers’ and they are asked to respond as quickly as possible while remaining high accuracy. Incongruent trials are generally known to result in slower reaction times and less accurate responses than congruent and neutral trials, because of the interference. It is however uncertain whether behavioural data alone i.e., reaction times and accuracy, can represent a bilingual effect with the use of the flanker task since it only measures efficiency and accuracy, and not how they process the information which can be further explored using neuroimaging measures.

Resting state (RS) is a measure of brain activity in a task-free setting which can measure brain function and connectivity in wakeful rest and can be utilised as a baseline and compared to on-task contexts. However, little is known about the links between RS brain activity and brain activity in on-task contexts, and as well whether it correlates with behavioural task performance (Anderson & Perone, 2018). Resting state EEG (rs-EEG) measures intrinsic brain activity of firing neurons, and can therefore capture dynamic and spontaneous oscillations that the brain produces (Bice et al., 2020). Neuroelectric activity changes during the lifespan, where the general indication is that power slowly decreases with age and that the functional connectivity becomes more organised in adolescence and adulthood, however, less is known for the older population (see Anderson & Perone, 2018 for review). In shorter periods of time, the brain waves remain relatively stable and can therefore be utilised to correlate them with previous life experiences and, of course, investigate how they change across the lifespan.

2.3.2 Neural oscillations

Electroencephalography (EEG) has proven to be a very important tool in neuroscience in general, but it has also been frequently used in psycholinguistics and research on bilingualism. EEG measures the brain's neuroelectric activity in real time through a non-invasive a cap of electrodes that is placed on the scalp. Because of its high temporal resolution, EEG can be used to examine how the brain responds or to certain stimuli, like language processing or non-linguistic general cognitive processing, and it can also capture the brain's functional connectivity in stimuli-free settings i.e., rs-EEG. EEG can therefore capture differences in the neural oscillations between individuals and correlate it to previous life experiences, for instance, if the additional and unique cognitive demands that bilingualism entails change the brain's functional integrity and how it processes information, it should be captured by EEG. Previous work has compared monolinguals versus bilinguals and has reported differences between the two groups based on their neuroelectric activity at rest (Bice et al., 2020), and during task performance (Kousaie & Phillips, 2017). However, one should be able to capture differences inside the bilingual group itself based on dual-language (or multilanguage) use and experience as well since the active bilinguals are exposed more frequently to cognitively challenging dual-language situations.

There are five main frequency bands that have been discovered in the literature: delta (1–4 Hz), theta (4–8 Hz), alpha (8-12 Hz), beta (13–30 Hz) and gamma (30–150 Hz) and they have been connected to multiple cognitive processes for each band. These frequencies have been defined in very early EEG work and they are based on 'cycles' per second (i.e., frequency), morphology, topology, and abundance (Brazier et al., 1961). The delta band is therefore the slowest frequency band since it is cycles only one to four times per second (i.e., 1-4 Hz) and it is usually seen during sleep (Dang-Vu et al., 2005). However, there is a wealth of variability in where to set the boundaries of the frequency bands in the literature, where some splits particular frequency bands into subgroups, for instance, low alpha (7-10 Hz) and high alpha (10-13.5 Hz) (Klimesch et al., 2007). Notice that the frequency band is also extended in this instance from 8 to 12 Hz to 7 to 13.5 Hz.

The alpha band is definitely one of the most researched frequency bands and has been connected to inhibitory control of irrelevant information and 'inhibition timing', which is argued to be closely related to attentional control (Klimesch et al., 2007; Klimesch, 2012), re-allocation of attentional resources (van Diepen & Mazaheri, 2017), and some studies also mention it has an impact on task performance (Bice et al., 2020; W. Klimesch et al., 1999; Doppelmayr et al., 2005; Sauseng et al., 2005) but the results on the latter varies (van Diepen & Mazaheri, 2017). Bilingualism and its relation to alpha activity has also been researched where, for instance, Bice and colleagues (2020) researched neural activity at rest from 91 monolinguals and 106 bilinguals and also attempted to correlate it to a Simon task. The results show there was a correlation between alpha power and performance, but only for the monolinguals, likely to be due the fact that the bilinguals already had significantly more alpha activity, in terms of power and coherence. They also showed that higher alpha activity was related to “more second-language use, higher native-language proficiency, and earlier age of second-language acquisition” (Bice et al., 2020).

Alpha band oscillations are characteristic since it is argued that the oscillations operates differently than other frequency bands (except for low beta (13-20 Hz)), in terms of the functions of increase and decrease in power (Klimesch et al., 2007). Other frequency band oscillations (except theta) are characterised by an increase in power, known as synchronisation, but responses in the alpha frequency can also be characterised when the power is decreasing, known as desynchronisation, or suppression (Klimesch et al., 2007; Klimesch, 2012). Simply speaking, when a band is synchronising it means that different neurons are firing synchronously, and the power is increasing, whereas in desynchronisation, the synchrony is lost, and the power is decreasing. The synchronisation and desynchronisation are argued are argued to play different roles in stimulus processing and/or task demands, and whether the eyes are open or closed (Klimesch, 2012; Klimesch, 1999). Klimesch (2012) argues that the alpha synchronisation (increase in power) works as an inhibitory filter, whereas the desynchronisation (decrease in power) is a complex process that entails a release of inhibition and relates to active cognitive processing. This is particularly visible in memory tasks used in an older study by Klimesch and colleagues (1999) where they investigated short-term memory in semantic processing. They used a modified Sternberg task where the participants had to memorise a sting of five or ten characters which was presented for 3000ms, then, after 2000ms, they were presented with a probe, and they had to decide whether this probe was a part of the previous string. Results showed that in there was a strong synchronisation during encoding and retention and a strong and consistent desynchronisation during retrieval. For RS contexts, it is generally known that synchronisation is large during eyes closed conditions, whereas the alpha oscillations desynchronise in eyes open conditions. These findings suggests that the synchronisation and desynchronisation are responsible for two different processes.

The beta frequency band is set in the parameters between 13 and 30 Hz, however, the frequency boundaries vary here as well, where it could also be split into two subgroups, often regarded as low beta (13-20 Hz) and high beta (18-30 Hz) (e.g., Rossi et al., 2022). The beta frequency band has been tied to different, and important, cognitive processes such as a maintenance role of the current cognitive state (Engel & Fries, 2010) and semantic and syntactic unification through beta band synchronisation (Bastiaansen & Hagoort, 2006). In terms of language learning, L2 learning rates and eagerness to speak in the L2 were found to correlate with beta power distributions over the right hemisphere and lower beta power, respectively (Prat et al., 2016; Prat et al., 2019). Additionally, Bice and colleagues (2020) found a positive correlation between beta power and native-language proficiency, for both monolinguals and bilinguals. However, there were some qualitative differences in the beta distribution between the groups where beta activity could only be seen in the left frontal region in the monolingual group as opposed to the bilingual group, where it was also present in the right frontal regions which they argue could be due to the extra demands with dual-language use. They also found that bilinguals had overall greater beta coherence than monolinguals, which they related to faster L2 learning rate. The findings that bilingualism affects neuroelectric beta activity has been seen across multiple studies, Soares and colleagues (2021) also found bilingualism effects on beta power, but this was dependent on age of acquisition of the L2 or the two L1s (2L1), rather than native-language proficiency.

Opposed to alpha and beta, theta (4-8 Hz) has been less researched in the field of bilingualism and neurocognition. Theta activity has often been related to long range communication between brain areas such as between prefrontal cortex and posterior cortex, and von Stein and Sarnthein (2000) found evidence for theta activity between frontal and parietal regions during working memory retention and argues it functions as a top-down processing mechanism. Different studies have also correlated theta long range activity to bilingualism (Soares et al., 2021) and interference control (Tafuro et al., 2019). In terms of bilingualism, Soares and colleagues (2021) conducted a study on eyes closed RS oscillations and investigated 103 bilingual speakers, where almost half were L1 Norwegian L2 English speakers (n=46), and the remaining participants had different language repertoires, such as L1 German L2 English (n=30) or 2L1 German-Italian (Italian as heritage language; n=25) or L1 Norwegian L2 Swedish/Spanish (n=2). The results showed significant correlations for both greater non-societal language use and proficiency with theta coherence over different brain regions. The results suggests that greater use and proficiency in the non-societal language modulates the functional connectivity (coherence) between brain regions that might not be directly connected to each other. There was however no correlation between theta power and any of the variables, where power correlations were only found in the beta and gamma band which was related to age of onset of L2/2L1. These results are not in line with Bice and colleagues's study (2020) where they report that monolinguals had significantly higher theta power in frontotemporal electrodes in the left hemisphere and marginally greater theta coherence in the medial frontal region compared to bilinguals.

The gamma band (30-150 Hz) is the highest and fifth frequency band. The oscillations in this frequency band therefore cycles rapidly and has been tied to local processing, especially through the sensory systems (von Stein & Sarnthein, 2000). This means that the gamma band can facilitate processing information through, for instance, the visual sensory system, which underlies the bottom-up processing category. Research has also suggested that gamma activity mainly processes information locally, as opposed to the long-range communication that the alpha and theta band are known for (von Stein & Sarnthein, 2000). Gamma activity has also been related to motor control which goes beyond the actual process of performing physical movements (Ulloa, 2021). Less is known in relation rs-EEG and bi-multilingualism, where there is nothing to process. For instance, Soares et al. (2021) and Bice et al. (2020) both found correlations between gamma activity and language background, specifically that earlier age of acquisition of an L1/2L1 modulated gamma activity and that bilinguals had better functional connectivity between specific brain regions than monolinguals, respectively. However, their interpretations of these results are limited or non-existent, especially in terms of functional connectivity, and it is therefore difficult to decipher any potential results through the gamma band, potential results in the gamma band should therefore be treated with caution in the present thesis.

In order to accommodate this issue with varying boundaries for fixed frequency bands and the fact that the frequencies vary individually, Klimesch (1997) was one of the first to advocate for individualised frequency bands (i.e., individualised alpha frequency (IAF)). This method captures the individual alpha peaks on the whole head spectrum, which is predominantly during eyes closed RS, and it relies heavily on the occipital regions to capture the synchronous alpha peaks. Once the alpha frequency has been identified for the individual, the other frequency bands are set depending on the IAF. Recall that the alpha frequency is typically identified between 8-12 Hz, however, a hypothetical individual with 11 Hz as their alpha peak has then set the alpha frequency between 9-13.5 Hz. The IAF has also been shown to be related to cognition, for instance, processing speed (Klimesch et al., 2007). IAF is also included in the present thesis in order to capture this variation in the frequency boundaries.

In sum, EEG measures neuroelectric activity and has shown to be an important tool in research on neurocognition and bilingualism. The different frequency bands have shown to be responsible for different processes, however, the boundaries of which these bands are set varies across studies and therefore IAF have been incorporated.

2.3.3 Coherence

A measure commonly used in EEG is the mathematical method of functional connectivity (henceforth referred to as coherence). Coherence is a measure that can show whether the neurons in the brain fires synchronously through quantifying the frequency and amplitude of the synchronous neural oscillatory patterns between different brain regions (Bowyer, 2016). Coherence is measured within a set frequency band, and through this, one can see whether different recording locations (electrodes) captures consistent and synchronous oscillations. Coherence is different from ‘phase’ since it aims to measure the consistency of synchronous activity rather than capture it in a short period of time. Phase synchrony is often used to investigate the cycles over a short period of time in relation to trials (i.e., phase-locked) or through pairing up recording sites or by only one single electrode (Bowyer, 2016). Though coherence can capture whether two sites are firing synchronously and therefore they might be connected to each other, it does not explain the directionality of the signal, which is known as effective connectivity. For instance, if the right frontal temporal and the left frontal temporal are firing synchronously in a set frequency band, it only says that these regions are firing in the same manner and might be connected to each other, but it does not provide information of what direction the signal is going (Bowyer, 2016). Coherence is therefore used to investigate whether different and spatially separated electrodes are in synchrony, if so, the different brain regions are communicating with each other. However, correlating a single electrode to a specific brain region can be misleading since the electric activity spreads as it rises to the surface of the head. Therefore, a single electrode can capture electric activity from adjacent brain regions and these signals adds to the sum of all captured electric activity in that electrode (Bowyer, 2016). Regardless of this fact, several studies still use this method in their research (e.g., Bice et al., 2020; Soares et al., 2021).

2.4 The present study

The goal of this thesis is to investigate L1 Norwegian L2 English bi-multilinguals and further contribute to research on whether long-term bi-multilingualism modulates the functional aspect of the brain at rest and whether this correlates to domain-general task performance. The participants included here are either bi- or multilinguals, but they all have Norwegian as their L1 and English as their L2, with most reporting ability to communicate in additional languages, hence the term bi-multilingual. Previous research has shown that neuroimaging measures in relation to bilingual effects on cognition has been a very important tool since there are inconsistencies in behavioural findings. Neuroimaging findings show more consistently that bilingualism modulates the functional and/or structural changes in the brain, however, the debate is still ongoing. The present paper therefore investigates healthy Norwegian-English bi-multilinguals in different stages of their adult life to provide more important research to the ongoing debate about bi-multilingual effects on neurocognition across the lifespan.

2.4.1 Research questions

1. Do differences in bi-multilingual engagement, above and beyond other lifestyle enrichment factors, affect resting state oscillations across the lifespan?
2. Do differences in bi-multilingual engagement, above and beyond other lifestyle enrichment factors, affect cognitive task performance across the lifespan?
3. Is there a correlation between resting state brain rhythms and task performance, if so, is it as a function of long-term bi-multilingualism (greater cognitive reserves)?

2.4.2 Predictions

Previous research has shown that there is a correlation between rs-EEG mean coherence patterns and non-societal language use in the theta, alpha and gamma band (Soares et al., 2021), and correlations with the alpha band and language control, and also the correlation with beta coherence and faster and better learning of a new language (Bice et al., 2020). Additionally, recent research has also shown important correlations between rs-EEG oscillations and CR in general, depending on age (Fleck et al., 2017). With this all in mind, the predictions for the first research question are threefold, and presented in an hierarchical manner. First, participants with greater multilingual diversity scores (MLD), as a measure of multilingual engagement, will generally exhibit greater coherence patterns than those with a lower MLD score in the alpha, beta, theta, and gamma bands. Recall that the BAPSS model suggests that bilinguals who recruit posterior brain regions tend to show better dual-language performance than to those who rely on anterior regions. Second, though not extensively tested in the literature, it is predicted that the MLD difference will be more pronounced in the older participants since lifelong bi-multilingualism might build greater CR, and therefore those with higher MLD scores might have better coherence patterns in the posterior brain regions in line with the BAPSS model (Grundy et al., 2017). Third, those with higher CR (measured through an aggregate lifestyle score) will generally have increased coherence in the alpha band which is based off the findings reported in Fleck et al. (2017), where they reported higher coherence for high CR groups within the eyes-closed RS condition, which is also the chosen condition in the present thesis. Remember that MLD and CR are controlled for in this thesis and that they are separate scores.

The argument of better inhibitory control have been challenged by Calvo and Bialystok (2021; Bialystok et al., 2012). This criticism is based on the findings from monolingual versus bilingual research where the bilinguals outperformed monolinguals in both conditions, rather than in only in incongruent trials that requires inhibitory control. Since bilinguals were more efficient in both conditions, they argued that they were better at allocating their attentional resources because there is nothing to inhibit in congruent trials. This approach should be extendable to within-group bi-multilingual differences, I would argue in accord with degree of individual engagement with bilingualism (DeLuca et al., 2019). The prediction is that there will be three possible outcomes of the flanker analysis, first, that there will be a correlation between greater MLD scores and efficiency in the flanker task, especially in the older group of participants, since they are not at their cognitive peak and greater MLD scores will show itself as a facilitating effect on cognitive performance. Second, if the first prediction is insignificant, better lifestyle scores, as a measure of CR, will be pronounced in the older group of participants, where better CR equals significantly better performance. Third, if the previous predictions fail to show significant effects, there will only be an age correlated effect where older participants will perform worse in relation to younger ones.

There is a large gap in the literature with correlating RS dynamics and task performance, there has only been a few studies that have attempted this where the methods and results vary (e.g., Gordon et al., 2018; Xie et al., 2021; Bice et al., 2020). In a literature review on rs-EEG, Anderson and Perone (2018) hypothesise whether it can provide insight “into the nature of the interactivity within and between brain regions that should, in principle, be linked to their engagement in a task" (i.e., interactivity between frontal and posterior sites). This has yet to be tested to a great extent. Since alpha, theta, and beta have been connected to EF processes, which is also argued to be strengthened through active bi-multilingualism. Therefore, it is predicted that alpha, theta, and beta coherence is correlated to task performance, where participants with greater RS coherence in these frequency bands between frontal and posterior sites perform better in the flanker task.

3. Materials and Methods

3.1 Participants

Data was collected from 93 bi-multilingual individuals who had Norwegian as their L1 and English as their L2, any additional languages beyond these were also welcome. Three participants had to be excluded due to excessive noise in the EEG data, leaving 90 participants (Female=61, mean age = 48.88, age range = 19-82). The participants were recruited through different methods, from social media to posters placed in various locations in Tromsø, Norway, which was the location of the study. To be included in the study, the participants had to be at least a L1 Norwegian L2 English bilingual which was controlled for in a one-to-two-hour interview conducted in English prior to the lab session, additionally, the participants had to fill out various forms on their language background, diet, social status, and other demographic lifestyle factors. All participants were cognitively healthy bi- or multilinguals and did not have any history of major brain injuries or neurological disorders, as well as no use of any psychotropic medications. They were either right- or left-handed individuals with either corrected or uncorrected vision. At the end of the lab session, the participants received a 500 NOK gift card.

3.2 Materials

3.2.1 Resting state

A RS session and a non-linguistic flanker task was used for the experiment. The resting state recording was stimuli free where the participants were seated in a dim lit and sound isolated room in front of a 27-inch monitor with a white fixation cross in the middle of the screen with an otherwise black background. They were asked to limit physical movement and to close their eyes during the 5-minute recording.

3.2.2 Flanker task

For the non-linguistic flanker task (Eriksen & Eriksen, 1974), the stimuli were presented by using Presentation® software (Version 23.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) where the arrows were white on an otherwise black background displayed on the same 27-inch monitor. The instructions were written in Norwegian in order to reduce L2 activation. The task started with twelve practice trials in line with the previous given instructions. The trials consisted of four congruent trials where all the arrows pointed the same direction (e.g., > > > > >), either left or right, four incongruent trials where the middle arrow pointed in the opposite direction as the surrounding arrows (e.g., > > < > >), and four neutral trials where there was only one arrow pointing either left or right (e.g., <). The practice trials also had response values whether the participant's response was incorrect, displayed by a red X, or correct, displayed by a green check mark. Excluding the practice round, the main experimental task consisted of 240 trials which were separated into two blocks with a break in between and consisted of 80 trials for each condition. The manual responses were recorded with two buttons on a keyboard with 20 horizontal cm in between the buttons, and they were asked to use one hand for each button. Before each trial, a white fixation cross was shown in a randomised time frame of 400-1600ms. Thereafter, a completely black screen appeared for 200ms after the cross disappeared. The flanker set was then displayed until the participant responded for a maximum time of 1500ms, if no response was recorded, it moved on to the next trial. In order to prevent any transfer in between the conditions a 2000ms inter-trial interval (ITI) was shown.

3.3 Procedure

The present thesis is a part of a bigger project in the PoLaR lab at UiT – the Arctic University of Norway, and the study was approved by the Norwegian Centre for Research Data (NSD). There were two sessions for each participant, of which one was an interview session, and the other was in the lab for the EEG recordings. These sessions had to be done on separate days in order to account for dual-language activation. The interview was conducted in English and begun with asking the participants to fill out a screening form where they were asked whether they have had any major head injuries (concussions etc.), if they were suffering from any neurological disorders, and if they were taking any psychotropic medication as these factors can cause unwanted noise in the data. Any participant answering yes to any of these screening questions were politely excluded from further testing. Included participants were asked to sign a consent form which briefly informed them about the purpose of the project and about their rights, for instance, that they could withdraw at any point. They were then asked to fill out a Language History Questionnaire 3.0 (LHQ3) (Li et al., 2020), and a short form dietary questionnaire (SFFQ) (Cleghorn et al., 2016). After these had been filled out, the participants were asked to select a time and date for the lab session.

The lab session was carried out exclusively in Norwegian in order to reduce L2 activation since all languages are active in a bi-multilingual’s brain (Guo et al., 2012). The lab session begun with measuring their head for selecting an appropriate size for the 32 Channel Wet-sponge R-net cap for LiveAmp (BrainProducts, Inc.). Meanwhile the cap was soaking in potassium chloride (KCL) mixed water for 15 minutes, the participants were asked to fill out a Cognitive Reserve Scale (CRS) (Leoń et al., 2014) which captures different lifestyle factors and their involvement in cognitively challenging activities. Subsequently, they were asked to self-report their own socioeconomic status using a MacArthur scale (MSSSS) (Adler et al., 2000). The participants were then capped with the selected 32 Channel Wet-sponge R-net cap for LiveAmp (BrainProducts, Inc.) and seated in a sound-isolated room in front of a computer where the distance to the screen varied from 40-80cm. They were also asked to not have any smart-devices (phones and smart-watches etc.) with them into this sound-isolated room. Once the R-net cap was connected computer, the impedance levels were checked and improved in order to get the best signal as possible. The participants were then familiarised with important factors of the EEG system and how it reacts to blinks and general movement, subsequently, they were given instructions to close their eyes and limit movement during the 5-minute RS recording.

After the RS recording, they moved on to the flanker task of which Presentation® (Version 23.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) provided the stimuli. They were instructed to read and familiarise themselves with the instructions presented on the screen, written in Norwegian Bokmaal. Potential questions were also answered and further explained to the participant. They were instructed to use one hand for each of the two buttons on the keyboard, if the central arrow pointed left, they would use their corresponding left hand to press the left button and vice versa. Since response time is an important measurement, they were also asked to answer as quickly as possible while remaining high accuracy. Finally, the participants were encouraged to take a break in between the blocks consisting of 120 trials each and were given the opportunity to ask questions about the task during the break. After completing an additional task, which is beyond the scope of this thesis, they were also asked to partake in an mini mental state examination (MMSE) (Strobel & Engedal, 2009) in Norwegian. At the end of the session, the participants were compensated for their time with a 500 NOK gift card at a local shopping mall.

3.4 Data collection

The recordings were collected by using the 32 Channel Wet-sponge R-net cap for LiveAmp (BrainProducts, Inc.), and the cap was placed according to the 10-10 system and recorded from ground (Fpz). The impedances were checked prior to the tasks, the electrodes could not extend 100 KΩ and the most important electrodes, ground (Fpz) and reference (FCz), could not extend 50 KΩ. Brain Vision Recorder was used to collect the data with a sampling rate at 512 Hz.

3.5 EEG pre-processing

3.5.1 Resting state EEG pre-processing

For the rs-EEG material, in Brain Vision Analyzer 2.0 (BrainProducts, Inc), the data was first down-sampled to 128 Hz from the original 512 Hz. The data was then segmented to a total of 270 seconds and the start of the sample was dependent of when the signal was settling down, but an average around 30-60 seconds into the recording. A new reference was then applied to the data which was an average of all electrodes and then the data passed through a band-pass filter from 1 to 45 Hz with a notch filter of 50 Hz. In order to remove potential blinks and eye movement, the independent component analysis (ICA) was performed on the whole data with a total of 512 steps and using the infomax restricted algorithm with an average of 2.17 removed components per participant. Finally, the pre-processed data was exported to R-studio for further analysis where the data followed an adapted R-script (Soares et al., 2021).

3.6 Data analysis

3.6.1 Survey data

Recall that the different questionnaires served to create aggregate scores for the multilingual diversity, or MLD, and lifestyle score. As for the calculations of these scores, the MLD score is based on the LHQ3 introduced by Li et al. (2020) which thoroughly collects data from the participants' language background, such as general language use for all of their languages and self-reported proficiency in each language. These two factors are set to calculate overall language dominance. This has further been extended to an aggregate score of these factors to a MLD score which was inspired by Gullifer & Titone (2020). The MLD score ranges from 0 to 2, and since the LHQ3 can account for up to four languages, a score of two would mean that the multilingual speaker with four languages would be equally dominant in each of their languages. In sum, the MLD score calculates dominance, based on self-reported proficiency and usage of all of their languages, and then again calculates the language dominance of each language into a MLD score.

The calculation of the lifestyle score was based on different questionnaires presented to each participant, specifically, the CRS (Leoń et al., 2014), SFFQ (Cleghorn et al., 2016), and MSSSS (Adler et al., 2000). These consisted of the different scores, for instance, their social network index, physical activity, diet, socioeconomic status, and participation in cognitive challenging activities. The scores of these questionnaires were then calculated into a composite lifestyle score, which is able to capture their CR. The range of this aggregate score was set between 0 and 1.

3.6.2 Resting State analysis

The RS pre-processed data was first passed through an adopted script from Prat et al. (2016) by Soares et al. (2021) which can calculate coherence and power in the respective frequency bands[1]. The script utilises Individualised Alpha Frequency (IAF) bands, meaning that it can account for individualised frequency bands rather than using fixed frequency bandwidths which this script categorises as the following: delta as 0-4 Hz, theta as 4-8 Hz, alpha as 8-12.5 Hz, low beta as 12.5-18 Hz, high beta as 18-30 Hz and gamma 30-40 Hz. The script therefore categorises the frequency bands based on a whole-head IAF which is based on the alpha peaks in each individual on the whole-head spectrum. The other frequency bands were defined as follows: delta IAF-6 Hz, theta between IAF-6 Hz and IAF-2 Hz, alpha between IAF-2 Hz and IAF+2.5 Hz, low beta between IAF+2.5 Hz and IAF+8 Hz, high beta between IAF+8 Hz and IAF+20 Hz, and gamma between IAF+20 Hz and 40 Hz. If the script could not find a detectable alpha peak in the two occipital electrodes, O1 and O2, then the IAF would not be calculated and then it would automatically set the peak at 10 Hz.

For the script processes, it starts off with removing long-term signal drifts by using a linear regression. The data then is divided into two time series segments of 2 seconds with a 25% overlap where the default sliding is 0.75. Segments with artifacts and blinks not detected during the ICA is removed from the pipeline through removing segments exceeding 100

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[1] Adapted from their GitHub website. For a systematic walkthrough of the script see: https://github.com/UWCCDL/QEEG

microvolts. The segments that pass this quality control is then passed through a Fast-Fourier Transformation (FFT), which further maintains and squares the real output. Subsequently, the FFT spectra is then averaged out and returns a mean spectrogram, and then it is log-transformed to represent power in decibels. Then, the alpha peak is identified in each channel which is the highest value in a very liberal alpha range, specifically between 7 Hz and 14.5 Hz, and this highest peak is surrounded by two lower values. Further, a spectrogram is created for each region and placed in a spectra file by averaging all the good channels within that region, and then the power is calculated and added to the summary files. Finally, coherence is calculated in every channel pairing through the same cleaning procedure, and then further calculated between and within the specific region of interests (ROI) (which are left frontal temporal (LFT), left posterior (LP), right frontal temporal (RFT), right posterior (RP), and medial frontal (MF)) by averaging it with channel pairings between or within all of the frequency bands.

The exclusion criteria followed the guidelines in Soares et al. (2021) of which channels exceeding an average log power of ±2.5 standard deviations to the average of all channels were removed, which resulted in removing 49 channels (2.14% of all data). For the IAF calculation, channels with no peak were also removed, which resulted in removing 113 channels (4.95% of all data). In line with their work, the channels with no peak were only removed for the IAF analysis but further included for the average coherence analysis. The third criteria involved excluding participants that had less than 80% of remaining channels (i.e., less than 24 channels) which resulted in excluding three participants.

As for brain region pairings and coherence, some brain regions lacked a coherence measure (11.33% of the whole data), but this was still included for the coherence analysis. The coherence data including the survey data and important participant information was fed into a robust linear regression model (*lmRob*) from the *robustbase* (Maechler et al., 2023) package in R-Studio. This model type, opposed to other linear regression models, is more sensitive to outliers and suboptimal normal residuals, and brain data is often not normally distributed, which makes it a good fit for this type of data. Two models were made for each brain region in each of the frequency bands of which the bandwidth depended on the individual's IAF, which resulted in 100 models since there were 10 brain region pairs and 5 frequency bands (i.e., theta, alpha, low beta, high beta, and gamma). The independent variables had also been centred beforehand, in order to get them on the same scale. These models only varied in which frequency band and brain region they were applied to.

1. lmRob(Coherence ~ Age.c + Lifestyle_Score.c)

MLD was subsequently added to the models as an interaction with age in order to account for multilingual engagement on its own and whether it interacts with age.

2. lmRob(Coherence ~ Age.c * MLD + Lifestyle_Score.c)

These two models were therefore used for each frequency band and brain region pair, and they were then tested with an ANOVA in order to compare the model fitting and whether one was better than the other. All of these models were also tested for multicollinearity.

3.6.3 Flanker analysis

Only behavioural data was collected for the flanker analysis which consisted of 240 trials for each of the 90 participants and there were initially three trial conditions, congruent, incongruent, and neutral. The neutral trials were then removed from the data set, specifically 7200 trials. Then it was trimmed using the trimr package (Grange, 2015) in R-Studio where trials that were either incorrect, below a reaction time of 150ms and above 2.5 standard deviations per dataset were removed from further analysis, which resulted in removing 659 trials. A flanker effect was then calculated through calculating the mean reaction time of the congruent and incongruent trials for each participant and then subtracting the mean reaction time of the incongruent trials with the mean of the congruent trials. This left one row per participant and was then merged with the main data frame that consisted of the survey data and EEG coherence material. Two linear mixed regression models (*lm*) were then passed onto the data frame where all of the independent variables had been centred in order to get them on the same scale.

1. lm(Flanker_effect ~ Age.c + Lifestyle_Score.c)

A second model was then created in order to see if there was an interaction between MLD and age.

2. lm(Flanker_effect ~ Age.c * MLD.c + Lifestyle_Score.c)

Subsequently, these were compared through an ANOVA in order to compare the model fitting and if one is better than the other. The models were also tested for multicollinearity.

4. Results

4.1 Resting state EEG results

4.1.1 Alpha coherence

The coherence results varied across frequency bands where significant correlations with age generally proved to be negative. In the alpha band, coherence between the LP and RFT (*E* = -0.009, *SE* = .004, *p* = .031) and between MF and RFT (*E* = -0.020, *SE* = .007, *p* = .006) correlated negatively with age. Brain coherence between LP and RFT also correlated negatively with MLD (*E* = -0.011, *SE* = .004, *p* = .027) which can be seen in figure 1 below. The interaction between age and MLD was insignificant but indicated a significance (*E* = .009, *SE* = .004, *p* = .063), seen in figure 2. No additional significant results were found in the alpha band.

Figure 1 Alpha coherence by MLD between LP & RFT

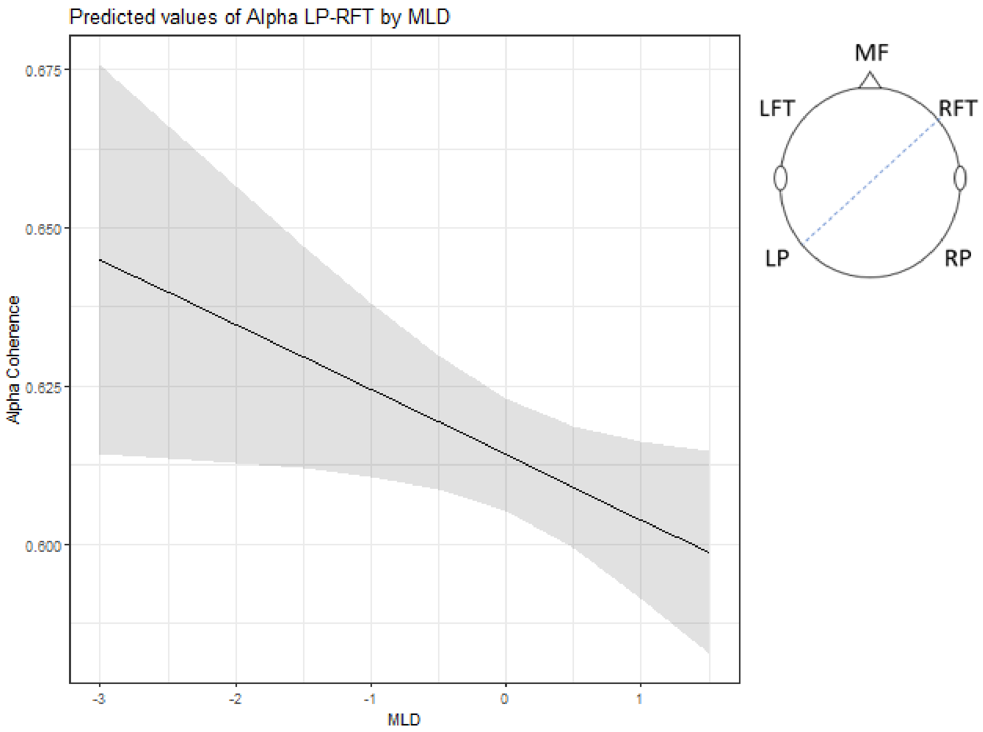
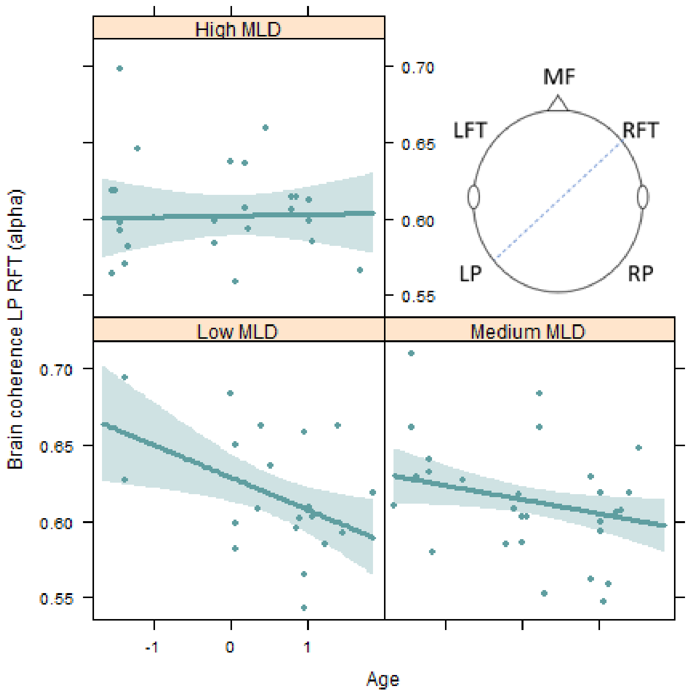


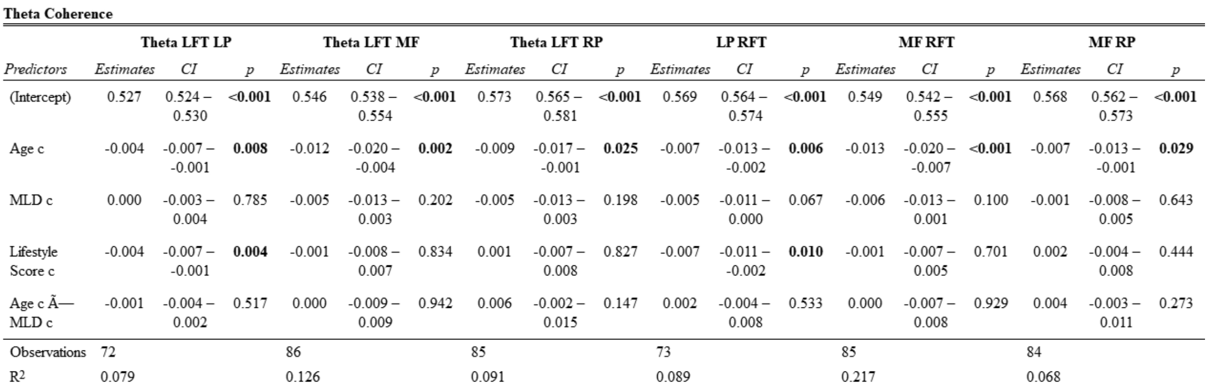
Figure 2 Alpha coherence by MLD and age between LP & RFT



4.1.2 Theta coherence

There was a strong and widespread tendency that age negatively predicted coherence in the theta band. Coherence between LFT and LP (*E* = -0.004, *SE* = .001, *p* = .007), LFT and MF (*E* = -0.012, *SE* = .003, *p* = .002), LFT and RP (*E* = -0.009, *SE* = .004, *p* = .025), LP and RFT (*E* = -0.007, *SE* = .002, *p* = .006), MF and RFT (*E* = -0.013, *SE* = .003, *p* < 0.001), and MF and RP (*E* = -0.006, *SE* = .004, *p* = .031) were all negatively modulated by age, as depicted in table 1. Additionally, coherence between LFT and LP (*E* = -0.004, *SE* = .001, *p* = .004), and LP and RFT (*E* = -0.006, *SE* = .002, *p* = .009) were negatively modulated by lifestyle scores, shown in figure 3 and 4, respectively. No other significant correlations were found.

Table 1 Overview of significant results with age in theta



Theta Coherence

	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	-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	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	-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 Ã— MLD c	-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		

Figure 3 Theta coherence by lifestyle score between LFT & LP

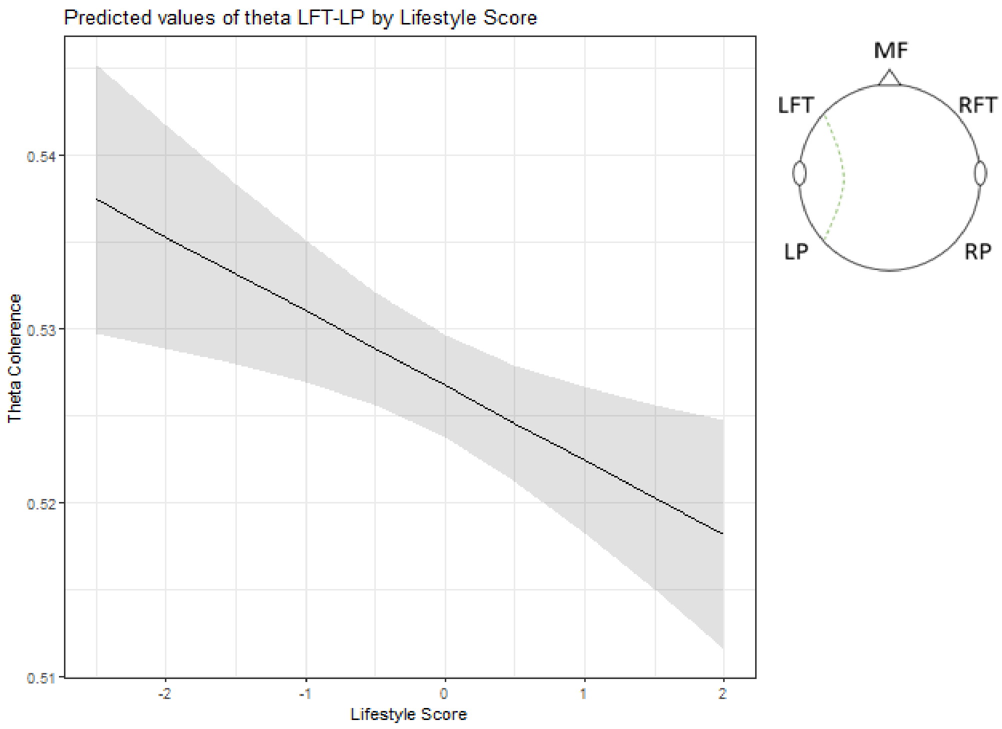
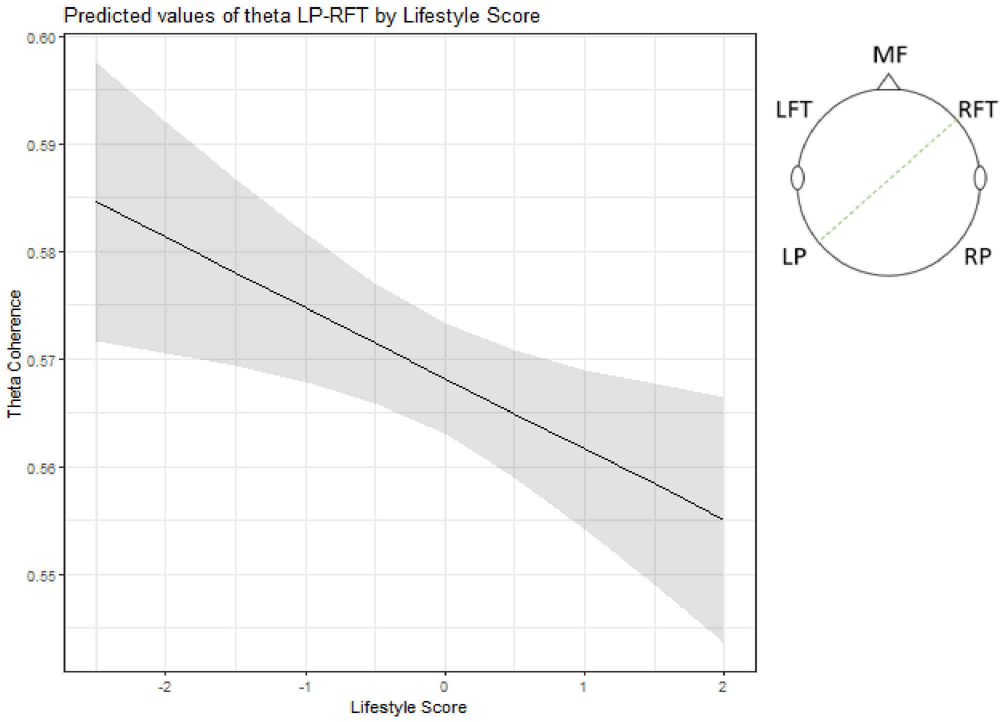


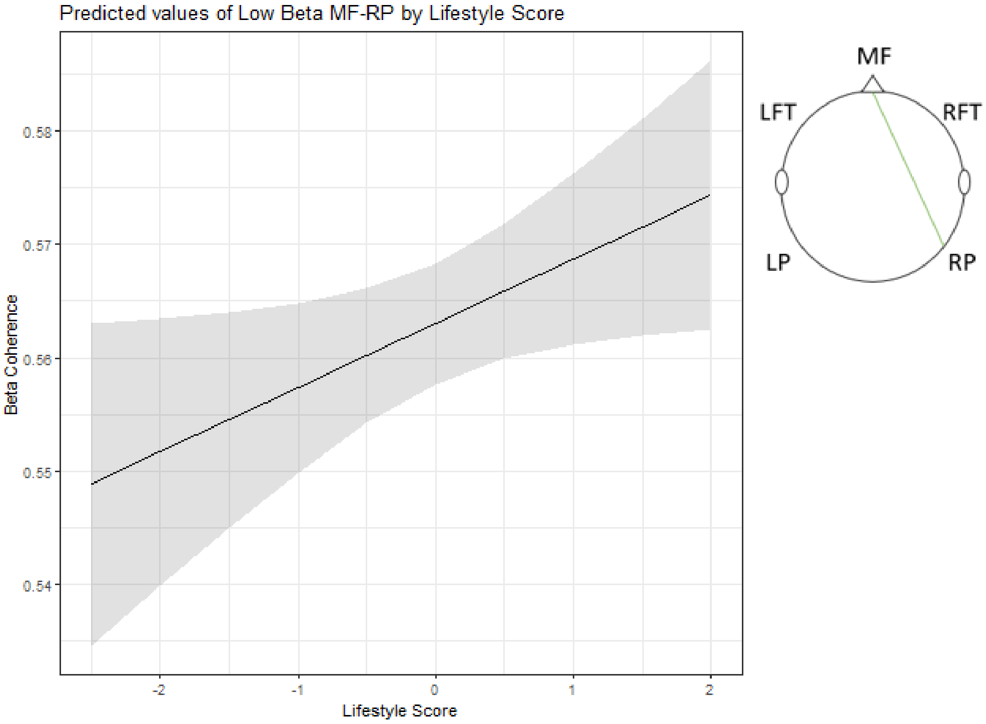
Figure 4 Theta coherence by lifestyle score between LP & RFT



4.1.3 Beta coherence

Significant results were only found in the low beta band, where coherence between LFT and MF (*E* = -0.007, *SE* = .003, *p* = .047) was negatively modulated by age. Coherence between MF and RP (*E* = .005, *SE* = .002, *p* = .035) was positively modulated by lifestyle scores (as seen in figure 5 below), but not modulated by age. There were no significant results in high beta or between any additional brain region pairs in low beta.

Figure 5 Low beta coherence by lifestyle score between MF & RP



4.1.4 Gamma

Finally, significant results were found between three brain region pairs in the gamma band. Coherence between MF and RFT, and MF and RP were both negatively modulated by age. Additionally, coherence between LFT and MF (*E* = -0.008, *SE* = .003, *p* = .019) and between MF and RFT (*E* = -0.008, *SE* = .002, *p* = .003) were both negatively modulated by MLD, as depicted in figure 6 and 7 below, respectively. How they interacted with age and MLD is shown in figure 8 and 9 as well. No other significant results were found.

Figure 6 Gamma coherence by MLD between LFT & MF

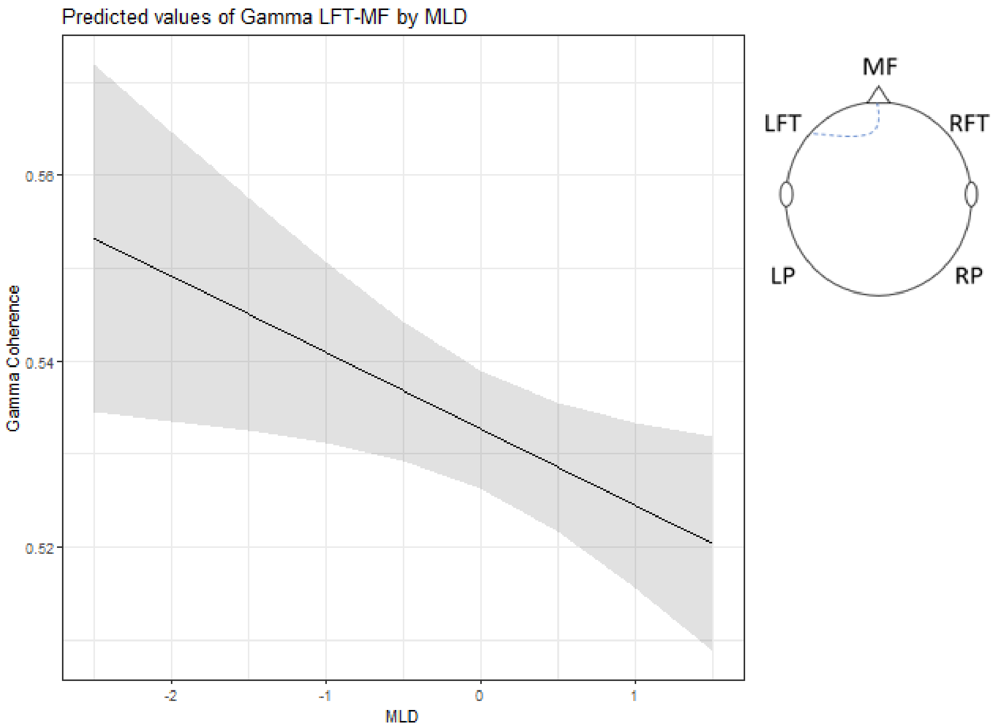


Figure 7 Gamma coherence by MLD between MF & RFT

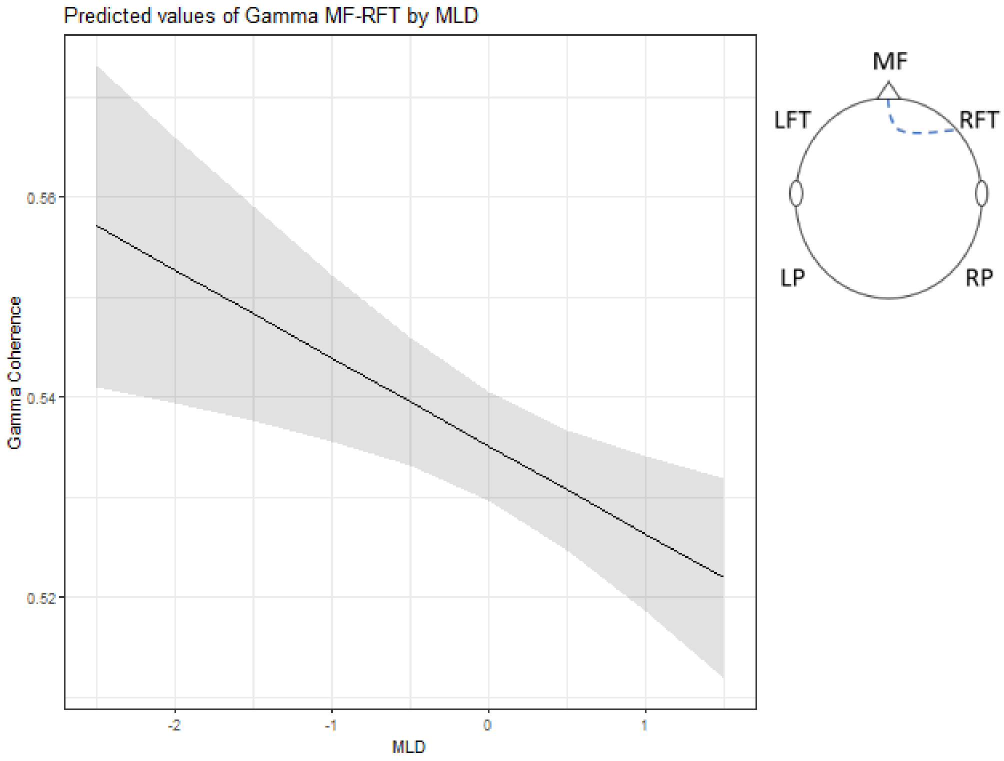


Figure 8 Gamma coherence by age and MLD between LFT & MF

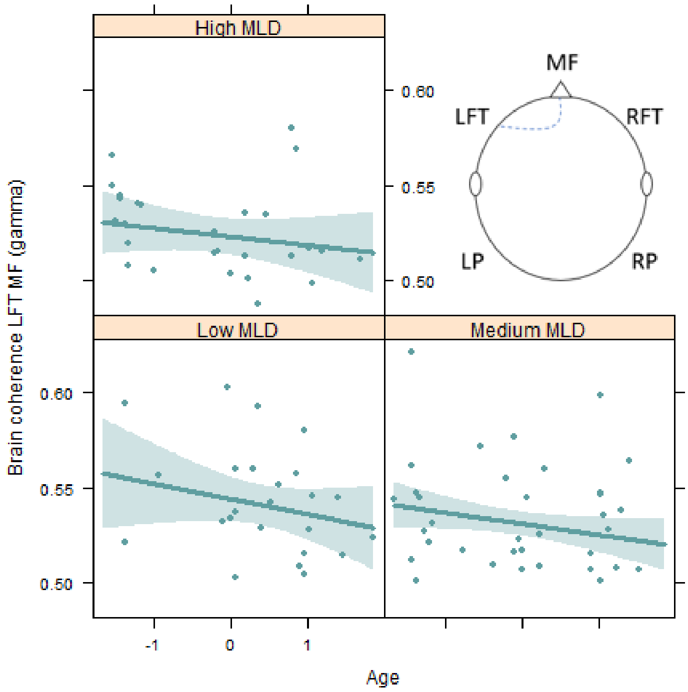


Figure 9 Gamma coherence by age and MLD between MF and RFT

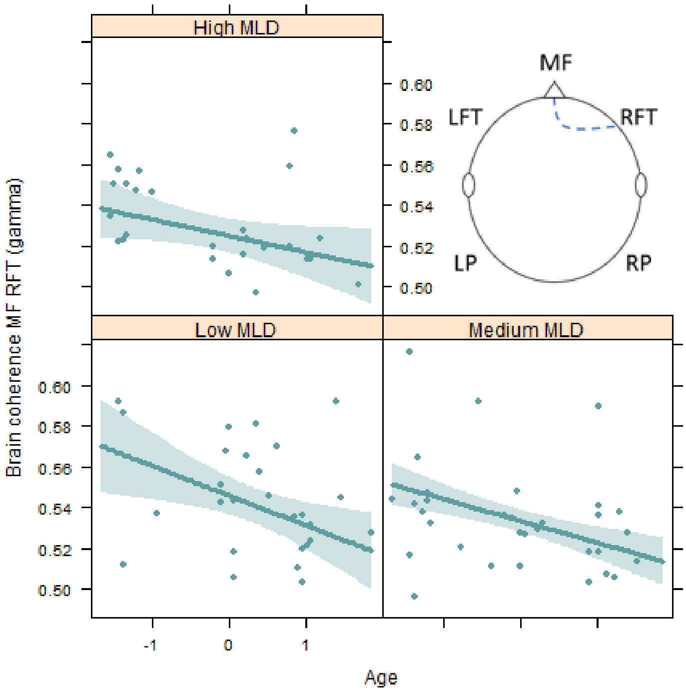


Figure 10 Coherence map with all of the significant results

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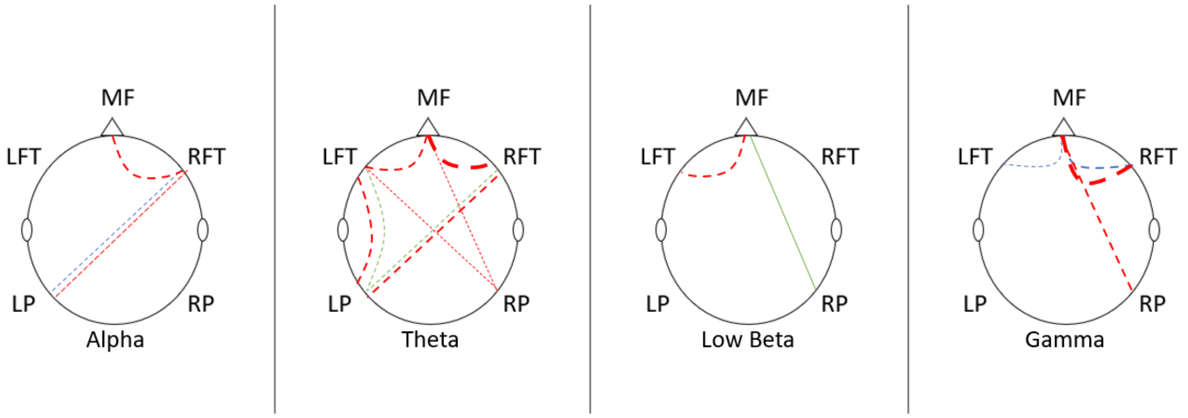
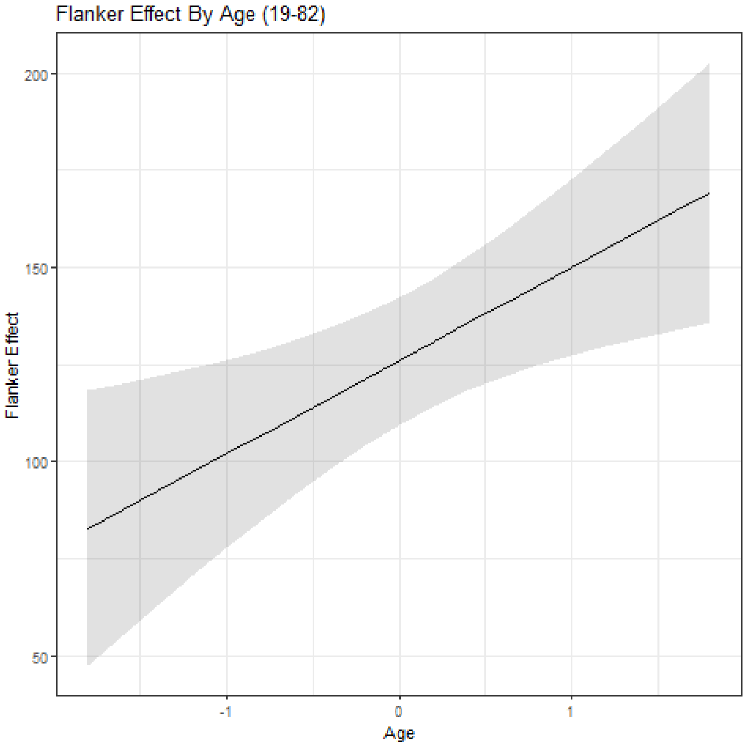


Coherence map of all significant correlations between brain region pairs with the different predictor variables (age, MLD, and lifestyle score). The boldness of the lines represents the significance, where the thickest lines are the most significant findings. The colour of the lines represents the variables where age is red, MLD is blue, and lifestyle score is green. Dotted lines represent negative correlations and normal solid lines represent positive interactions.

4.2 Behavioural flanker data

The behavioural data analysis of the flanker task did not reveal any correlations between MLD and task performance, or between CR and task performance, and the interaction between MLD and age was also insignificant. However, there was a positive correlation with age (*E* = 23.982, *SE* = 8.455, *p* = .005), as seen in figure 11.

Figure 11 Flanker performance by age



4.3 Post-hoc analysis of flanker performance and coherence

4.3.1 Data analysis

A post-hoc analysis was done after the coherence and flanker analysis. Flanker performance and coherence was utilised for this analysis where flanker performance (i.e., flanker effect) and the coherence pairs that was significant with MLD in the coherence analysis were gathered for further inspection. This resulted in investigating the LP and RFT coherence pair in the alpha band as well as the coherence pairs between LFT and MF, and MF and RFT in the gamma band. The flanker effect was combined with the data frame containing the RS coherence material and was then grouped into the respective coherence pairs. For the models, the coherence material was treated as an independent variable since it is set to explain the variation in the flanker performance. Then, as previously done for the other independent variables, it was centred. Through R-studio, one simple robust linear regression model was passed onto the data for each brain region pair, in order to see if there was an interaction between the two outcome variables. Since there was only one model for each brain region pair and these models only contained one independent variable, an ANOVA could not be performed. However, they were checked for multicollinearity.

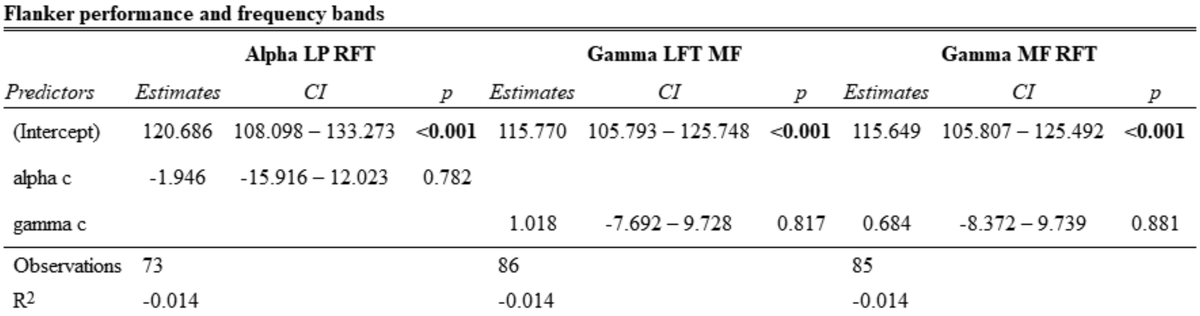
1. lmRob(Flanker_effect ~ Coherence)

A correlation matrix was also performed as a precautionary measure to investigate whether there was an interaction at all. This correlation method attempts to correlate every column in the data frame with each other, if there is no correlation, the output is blank. Recall that the subsets in the coherence analysis represented one coherence pair, these were split into additional subsets, which contained the subject number column (even though this is not necessary), flanker effect column, and the coherence column.

4.3.2 Post-hoc results

The interaction between behavioural flanker performance and RS coherence, in the frequency bands and brain region pairs that was previously correlated with MLD, revealed no significant interactions, depicted in table 2 below.

Table 2 Flanker performance by coherence

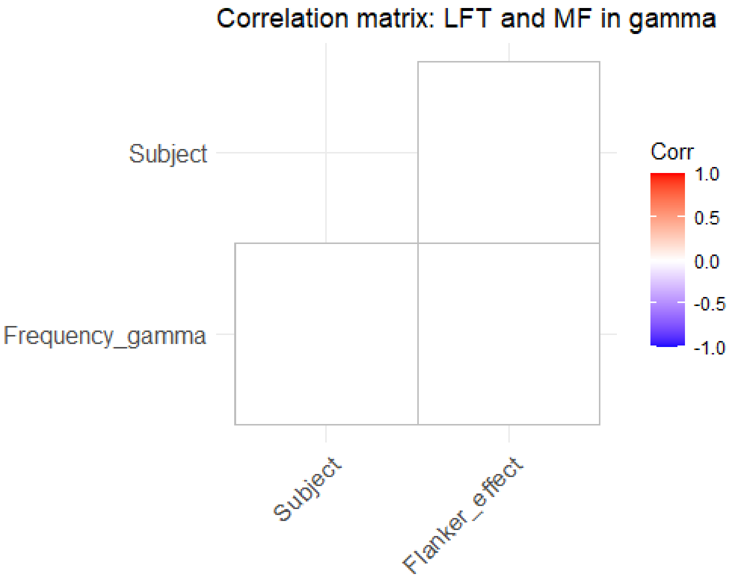


Flanker performance and frequency bands

	Alpha LP RFT			Gamma LFT MF			Gamma MF RFT		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	120.686	108.098 – 133.273	**<0.001**	115.770	105.793 – 125.748	**<0.001**	115.649	105.807 – 125.492	**<0.001**
alpha c	-1.946	-15.916 – 12.023	0.782						
gamma c				1.018	-7.692 – 9.728	0.817	0.684	-8.372 – 9.739	0.881
Observations	73			86			85		
R^2	-0.014			-0.014			-0.014		

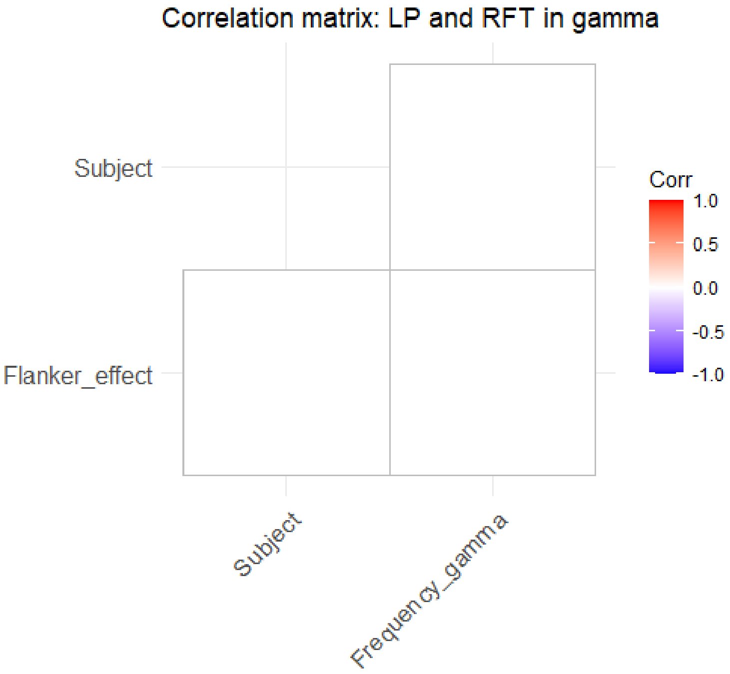
The correlation matrix revealed no significant correlations between flanker effect and coherence in none of the coherence pairs that were significant with MLD, as depicted in the figures below where blank is insignificant.

Figure 12 Correlation matrix: LFT and MF in gamma



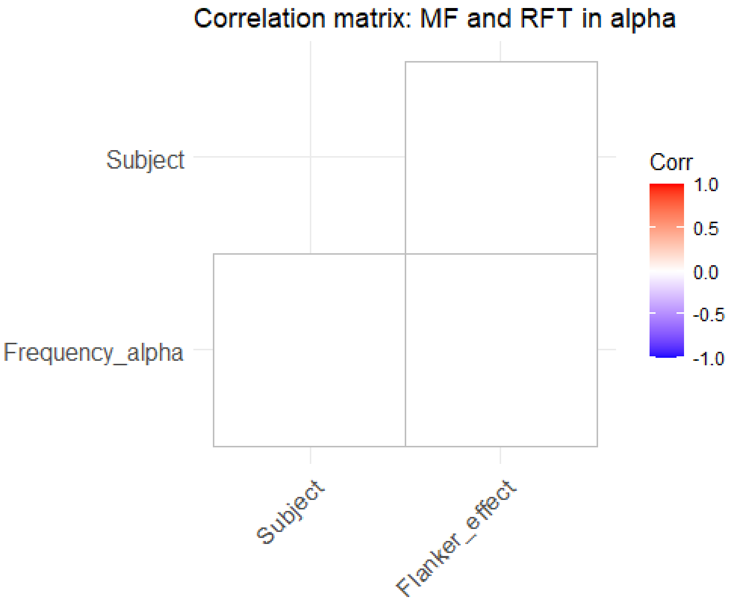
Correlation matrix in the Left Frontal Temporal and Medial Frontal coherence pair in gamma correlated with flanker performance.

Figure 13 Correlation matrix: LP and RFT in gamma



Correlation matrix in the Left Posterior and Right Frontal Temporal coherence pair in gamma correlated with flanker performance.

Figure 14 Correlation matrix: MF and RFT in alpha



Correlation matrix in the Medio Frontal and Right Frontal Temporal coherence pair in alpha correlated with flanker performance.

5. Discussion

The present thesis aimed to investigate brain functionality in relation to bi-multilingual engagement and correlate it to EF throughout the lifespan. This type of research is rather new and have not been explored well enough in the current literature. Previous research has found correlations between brain functionality and bilingualism through rs-EEG measures (e.g., Soares et al., 2021; Bice et al., 2020). However, there is no current studies on the healthy senior population and how the functionality changes across the lifespan, and whether lifelong bi-multilingualism as a dynamic spectrum, above and beyond other lifestyle factors, can modulate this. The basis of this functional architecture modulation lays within that a multilingual's languages are always active in their minds and have to manage them properly (Guo et al., 2012; Bogulski et al., 2019; Seo & Prat, 2019). This entails controlling for interference from other non-target languages according to each language context, which earlier works suggested could strengthen the bilinguals' inhibitory skills (Green, 1998), but has now also been explored further in relation to other EF (Calvo & Bialystok, 2021; Green & Abutalebi, 2013). Previous studies have therefore often compared bilinguals to monolinguals, but bi-multilingualism is rather a dynamic spectrum, and this remains an understudied subject. In order to investigate these bi-multilingual effects on cognition, three investigations were implemented. First, brain oscillations in Norwegian-English bi-multilingual adults in various stages of adulthood were collected through EEG in a task-free setting. Second, these adults performed a flanker task where their brain oscillations and behavioural responses were recorded, but only the behavioural data was used for further analysis. Third, as a post-hoc investigation, the brain region pairs (in their respective frequency bands) that exhibited significant results between bi-multilingual engagement and coherence were then correlated to the flanker task performance.

First, the results showed a general trend of a negative correlation between brain coherence and aging across all frequency bands, where younger participants had greater coherence than the older participants (see figure 10). Second, they revealed a negative effect of MLD on coherence, meaning that participants with a higher MLD score had lower coherence, which was the opposite of the predicted outcome. Recall it was predicted that the MLD correlations would be found in the alpha, theta, and gamma bands, but no correlation was found in theta, only in alpha and gamma. However, it was partially confirmed that better MLD scores facilitated to flattening the age-related decline in coherence for the older participants in the alpha and gamma band, but this was not only between posterior regions (see figure 2, 8 and

9), as the prediction suggested would be the most pronounced regions. Third, the prediction about the correlation between lifestyle scores and brain coherence in alpha was not confirmed, where significant results were only found in the theta and beta band, and not alpha. Moreover, the results indicated that greater lifestyle scores were related to worse coherence in theta and greater coherence in low beta. In the low beta band, greater lifestyle scores indicated higher coherence between MF and RP (see figure 5). In the theta band, higher lifestyle scores indicated worse coherence between the LFT and LP and between LP and RFT (see figure 3 and 4). Fourth, the flanker analysis only confirmed the prediction that higher age would slow the reaction times down, no significant results were found with MLD and the other lifestyle factors. Finally, the prediction for the post-hoc analysis was not confirmed since no significant results were found between flanker performance and coherence.

5.1 Resting state coherence

5.1.1 Bi-multilingual engagement affects alpha rhythms

Alpha activity is one of the most researched frequency bands in EEG research and several studies have found that alpha activity (both coherence and power) is responsible for a wealth of cognitive processes, such as inhibitory control (Green, 1998), language control (Bice et al., 2020), re-allocation of attentional resources (van Diepen & Mazaheri, 2017), and that alpha activity operates differently than other frequency bands (except theta) through that synchronisation and desynchronisation represent two different processes (Klimesch, 2012). These cognitive processes have been related to bi-multilingualism in recent years because of the proposed unique cognitive demands bi-multilingualism entails. This has caused researchers to investigate these cognitive processes in, predominantly, bilinguals where significant effects have been found (e.g., Kousaie & Phillips, 2017). New and innovative research has also begun to investigate whether these effects extend to at-rest oscillations as well. Some of the few studies that have explored this idea have found significant correlations in, among others, the alpha band where the differences are pronounced and clear. Recall that Bice et al., (2020) and Soares et al., (2021) both found correlations between language control and alpha activity. Alpha activity has therefore been of particular interest in this thesis where rs-EEG coherence measures revealed a main age-related effect, a main effect of an aggregated MLD score, and a trending effect in the interaction between age and MLD.

Functional connectivity has been shown to decrease with increased age (Vysata et al., 2014) and thus it is not surprising that this effect was indeed found here as well, specifically between MF and RFT and between LP and RFT. As previously presented age-related effects are known to occur, even without any pathological diseases like dementia. Previous research have not investigated healthy bi-multilingual seniors to the same degree as individuals with dementia or other pathological diseases. Soares et al., (2021) suggested that this type of investigation should be researched and whether bi-multilingualism can help maintain cognitive functionality. The MLD interaction with age found here in the alpha band, although Soares et al., (2021) and Bice et al., (2020) found more widespread interactions with non-societal language use and language control, shows an indication that MLD might slow down the age-related cognitive trajectory. However, recall that the interaction between age and MLD output was insignificant (only close to significance (p = .063), see figure 2), and the estimate value with the main MLD effect was negative. The trending indication suggests that those with a lower MLD score appear to have decrease in coherence with higher age, but this drastic decrease stagnates a bit for those that are in the ‘medium’ range, and completely stagnates and can be on the verge of increasing for those with a higher MLD score (see figure 2). This can potentially suggest that increased multilingual use and higher non-native language proficiency, which the MLD score is composited of, can contribute to a healthier aging process. Recall that the BAPSS model (Grundy et al., 2017) suggests that the bilinguals that have recruited the posterior regions can show increased dual-language performance as opposed to those that rely more on their anterior regions. This trending effect of MLD and age is indeed between the left posterior and right frontal temporal, and it can indicate that it is line with the BAPSS model since MLD can help maintain the communication between these regions which is especially important considering that the posterior regions are especially vulnerable to decline when aging. One reason there might only be indicating significance for the interaction with age and MLD can be the cause of a very limited MLD range which was between 0.895 and 1.059 out of 0 and 2. As for the negative main effect of MLD, it may be that the younger participants are driving it down since the younger participants with a higher MLD is actually below the lower MLD group in coherence measures in the same age range, which is in line with Fleck et al. (2017) since multilingual engagement can potentially build stronger CR (Craik et al., 2010) and these participants are too young to have any CR trade-off.

Overall, the MLD score was negatively affecting coherence between LP and RFT, where those with higher MLD scores had worse coherence, which may be a cause of that the younger participants drives it down. The trending interaction between age and MLD was only close to significance, and it cannot be confirmed whether MLD can affect the aging process through looking at the alpha band, thus, it is not in line with the prediction. The lifestyle score was also expected to be significant in the alpha band, but no significant interactions were found, and hence the third prediction is not confirmed.

5.1.2 Age and lifestyle scores negatively modulates theta coherence

Theta activity has generally been less researched in the literature than the alpha and beta bands. The theta band has been linked to long-range communication that are not necessarily connected to each other, and have been further linked to bilingualism (Bice et al., 2020), CR (Fleck et al., 2017), interference control (Tafuro et al., 2019), and it has been argued to facilitate with top-down processing (von Stein & Sarnthein, 2000). Recent evidence has found contrastive evidence for greater coherence in theta, recall that Bice et al. (2020) found that monolinguals had marginally greater coherence than bilinguals within the medial frontal electrodes, but Soares et al. (2021) found that more non-societal language use and higher self-rated proficiency in the societal language correlated with theta coherence between the frontal regions. This therefore entails further research in order to see whether increased multilingual engagement can have an effect on coherence, and especially in relation to aging, as it was not researched by either of these studies.

As opposed to the studies conducted by Soares et al. (2021) and Bice et al. (2020) the present thesis did not reveal any correlations between multilingual engagement and theta coherence, and it is therefore not in line with the proposed prediction that theta coherence would be modulated by MLD. However, there was a strong and widespread correlation with age, where the coherence generally decreased with older age. This is not particularly surprising, given that coherence tend to decrease with higher age (Vysata et al., 2014). Interestingly, there also seems to be a trend that the coherence between frontal and posterior regions struggle to maintain communication, but no significant correlation of an age-related decrease was found between the posterior regions (i.e., LP and RP). As the BAPSS model highlights (Grundy et al., 2017), the connectivity between posterior regions tend to also decrease with older age and they rely more on the anterior regions. It is therefore also interesting that the connectivity between the frontal regions, specifically between LFT and MF and between RFT and MF, also significantly decreased with older age.

The results also revealed a two negatively significant correlations with the lifestyle scores between LFT and LP, and between LP and RFT. The lifestyle score was an aggregate score of various questionnaires and demographic data which was then averaged together on a scale between 0 to 1 (see section 3.6.1). The range of these scores were between 0.467 and 0.791 for this group of participants. The proposed prediction was that the lifestyle score would positively modulate coherence in the alpha band, regardless of age or ROIs, in line with Fleck and colleagues' (2017) findings. The results did not show this interaction in the alpha band, and it decreases coherence in the theta band. Their work and the present thesis cannot be directly compared because of major differences in the aggigate scores. However, it is surprising that it negatively affects coherence patterns, and also with the limited research on the matter increases the difficulty in interpreting the results. Nevertheless, the connectivity between frontal and anterior regions are known to be diminish in older age, and the younger participants with a higher CR might also drag the coherence values down, since they also found a similar relationship between younger and older participants and CR scores. Recall that there was also found widespread age-related effects in the theta band, and it might be that those with a higher lifestyle score cannot significantly reverse these main age-related effects between these regions, and therefore these effects remain negative.

In sum, the proposed predictions for the theta band could not be confirmed in the present thesis, since there was no correlation between coherence and multilingual engagement, but some surprising negative interactions were found with lifestyle scores.

5.1.3 Lifestyle affects low beta rhythms

Together with the alpha frequency band, beta has been tied to domain-general top-down processes and preservation of the cognitive state (Engel & Fries, 2010). This frequency band, in terms of power distributions at rest, has also been found to affect L2 learning rate and also engagement to learn a L2 (Prat et al., 2016; Prat et al., 2019). In line with the other frequency bands, the beta band has also not been investigated at rest to the same degree as to on-task investigations. As for coherence measures, Soares et al. (2021) found a negative correlation with socioeconomic status in the low beta band, and a positive correlation between age of acquisition of a L2/2L1 and high beta coherence. Additionally, Bice et al. (2020) found compelling evidence that bilinguals had overall greater and broader coherence in the beta band than monolinguals at rest, where the strongest connections were found in the right hemisphere which they argued to be a mechanism for L2 learning advantages. However, the results here did not reveal any interactions between beta coherence as a whole (low or high) and MLD, and hence does not confirm the prediction. There were only some that were close to significance, both in low beta and high beta. This can also be because of the limited range in the MLD score, or other potential problematics with the MLD score itself (further discussed in section 5.4).

Recall that Fleck et al. (2017) investigated CR in relation to age and hemispheres and found effects for CR depending on the age groups which was mainly driven in the right hemisphere, however no main effect of CR was found in the eyes-closed condition in beta. The results here revealed that one region pair exhibited a main effect of greater coherence for those with a higher lifestyle score regardless of age in the low beta band, which was between RP and MF. This is interesting regarding the opposite effect that was found in the theta band, which was also between the posterior and frontal regions. The results therefore suggests that those with a higher lifestyle score can therefore exhibit greater coherence, and thus not in line with Fleck et al. (2017) since they did not find this effect in beta. However, what actually drives this increase in coherence is difficult to pinpoint because of the various factors included in the lifestyle score, socioeconomic status, which was also included in their study, might be a contributing factor. On the other hand, Soares et al. (2021) revealed a negative effect, which therefore leaves the question standing. An alternative is that there were not widespread negative age-related effects on coherence in low beta, and thus the ‘high lifestyle score’ participants did not need to revert the strong age-related effects, and hence they exhibited overall greater coherence. Additionally, there was also only one general negative age-related effect in the low beta band between the MF and LFT, which further supplements the findings in the alpha and theta bands but interestingly not between the posterior regions.

The prediction that greater beta coherence would be manifested through MLD was not confirmed. No significant results were revealed in relation to MLD. Anterior connectivity was reduced with higher age, specifically between MF and LFT, and not between posterior regions as one might anticipate. Lifestyle enrichment factors revealed to have a positive main effect on coherence between posterior and anterior regions but what drives this increase is difficult to pinpoint because of all the different variables in this aggregated score.

5.1.4 Gamma and multilingual engagement and aging

The gamma frequency band has been tied to local processing and motor control (von Stein & Sarnthein, 2000; Ulloa, 2021) even though different studies has also found evidence that long-range communication could occur at rest in relation to age of acquisition of L2/2L1 and that bilinguals could exhibit greater gamma coherence than monolinguals (Soares et al., 2021; Bice et al., 2020). Therefore, it was predicted that greater MLD scores would modulate the coherence measures in the gamma band as well, in terms of greater coherence. As with the previous result in the alpha band, it appears that greater multilingual engagement negatively modulates gamma coherence, but this time between the frontal regions (between LFT and MF and between RFT and MF). This is not in line with what von Stein and Sarnthein (2000) suggested, since these local coherence pairs are significantly out of synchrony with each other, but bear in mind that there is nothing to process here, and that the previous results on rs-EEG and gamma coherence interpretations in relation to language background are limited. This main MLD effect could also be the caused by that the younger participants drives the coherence down since they are too young to have a CR trade-off, as seen in Fleck et al. (2017). These results should therefore be interpreted with caution.

Neither of these coherence pairs were modulated by the interaction between MLD and age, meaning that MLD had no significant effect on the aging process. By reviewing the previously plotted graphs (figure 8 and 9), one can see that they might follow the same trend as the discussed change in coherence for the alpha band. The coherence for the younger participants is marginally higher in the ‘low MLD’ group than in the ‘high MLD’ group, which might explain the negative correlation between MLD and coherence patterns. However, this effect remains the same for the older participants, where the ‘low MLD’ group also have marginally better coherence than those in the ‘high MLD’ group but bear in mind that these results are in fact insignificant and not even close to significance. It is therefore impossible to conclude anything based on these graphs. There was however a trending main effect for MLD and another in the interaction between MLD and age in the MF and RP coherence pair (see appendix B), which seems to be similar to the finding in alpha (between LP and RFT). However, with all these results in mind, it then again problematises the MLD measure as a whole since it does not seem to capture the variance between the participants’ diversity in multilingual engagement.

In regard to aging, there were some main effects of age in the gamma band, where there were found negative correlations between aging and coherence between the RFT and MF and between MF and RP. This only replicates the earlier results that aging modulates coherence, both in terms of short range and long-range communication. Surprisingly, no such effect was found between LFT and MF, which only correlated with MLD. This means that the negative effect of MLD is significantly stronger than the age-related effect, which is not remotely in line with the prediction, and does not correlate with any previous findings.

None of the variables seemed to explain the results in line with the predictions, where those with higher MLD did not exhibit greater gamma coherence, and it had no significant impact on the aging trajectory, only a trending effect between MF and RP which seemed similar to the result found in alpha. Additionally, the lifestyle scores did not predict coherence.

5.2 Behavioural flanker and aging

Previous models and theoretical frameworks on EF have suggested that bilingualism can have an effect on how the brain processes information and whether this proposed increased efficiency can also be seen behaviourally and neurologically. Since bi-multilingualism imposes unique cognitive demands, and they have to inhibit language interference, and control and maintain their languages, Green (1998) proposed the IC model. This model proposes a mechanism that bilinguals evolve in order to inhibit the non-target language through a supervisory attentional system. Generally speaking, it has been shown that congruent trials in cognitive tasks are easier and faster to process than incongruent ones, and hence it has been suggested that bilinguals are faster at inhibiting the distractions in incongruent trials since they are familiar with inhibiting language interference. However, as previous research has shown, there are inconsistent findings regarding whether multilingual engagement can modulate behavioural responses in domain-general cognitive tasks (Lehtonen et al., 2018), especially when considering the fact it can be dependent on the specific task (Kousaie & Phillips, 2017), as well as the difficulty of the task (Costa et al., 2009; Bialystok & Craik, 2022).

The present results did not show any interaction between RT and multilingual engagement, both with MLD and with the MLD and age interaction. Because of the previously inconsistent EEG data with MLD, the MLD score may also be problematic in this scenario and therefore one might not see its effects in the behavioural data. Bialystok and Craik (2022) argued that the cognitive tasks had to be difficult enough in order to consistently find any bilingual effects. Hence, another alternative is that the task in and of itself is not difficult enough for the participants, especially for the younger participants who are at their cognitive peak. However, this version of the flanker task consisted of an equal number of incongruent and congruent trials which was similar to Costa and colleagues' (2009) “high-monitoring” version of the flanker task, where they found differences between bilinguals and monolinguals. Hence, it may be possible that the combination of the flanker task and the MLD score did not sufficiently detect any potential variations. The only significant correlation was that older age significantly increased the RT difference between congruent and incongruent trials, which means they struggled more dealing with the interference. This is not particularly surprising considering that the efficiency in EF decreases with older age.

5.3 Coherence and flanker performance

The post-hoc analysis was conducted as an exploratory investigation as there is very limited previous work on whether neuroimaging dynamics can predict task performance. Only a few studies have attempted to correlate neuroimaging findings at rest with behavioural task performance where neuroimaging methods, subcategories of EF (e.g., working memory, inhibition), and results vary (e.g., Gordon et al., 2018; Xie et al., 2021; Bice et al., 2020). The proposed prediction was that there would be a correlation in the alpha, theta, and beta band between posterior and anterior sites. The results did not demonstrate that coherence in the frequency bands that correlated with MLD could predict task performance, and there was no interaction between them through the correlation matrix. This could partially be because of the low predictability of the MLD score since the only region pairs in their respective frequencies that correlated with MLD were included in this analysis. An alternative though, could be that the age effect on the coherence, as previously seen in the rs-EEG analysis alone, is fairly widespread and can therefore obscure any potential correlations between flanker performance and coherence. This is also true for the age-related effect seen in the flanker task where this effect was highly significant, hence the age-related effect altogether could be the issue in this instance. The final interpretation could also be that there simply is no correlation whatsoever, meaning that coherence measures cannot predict task performance.

5.4 General discussion

The present thesis aimed to investigate whether multilingual engagement could modulate cognition throughout the adult lifespan through measuring rs-EEG coherence, behavioural performance in a flanker task, and whether rs-EEG coherence could predict behavioural flanker performance. Recent research has just begun conducting investigations on whether bilingualism, and also differences in dual-language use and engagement, can modulate rs-EEG oscillations. While previous studies have found evidence for this, none of them have investigated the entire adult lifespan while also controlling for lifestyle enrichment factors. The present thesis attempted to fill this gap where healthy Norwegian-English bi-multilingual adults, in various stages of their adult life, were recruited (see appendix A for age distribution). These speakers had to be native speakers of Norwegian and English as their second language, while any additional languages were also welcome.

Rs-EEG recordings were utilised to capture their coherence and further correlated to age, multilingual diversity, while also controlling for lifestyle enrichment factors. The results revealed a main effect of MLD in the alpha and gamma band in the opposite direction of what was expected. However, this may be the cause of the younger participants driving it down since they are too young to have any CR trade-off, in line with what Fleck et al. (2017) found. Although the gamma band revealed that the older participants with a low MLD had marginally higher coherence than those with a higher MLD (figure 8 and 9), one should still interpret these results with caution because these interactions with age were in fact insignificant interactions and therefore should not be treated as such. Additionally, there is a lack of interpretations from other rs-EEG studies on the gamma band in relation to bilingualism and dual-language engagement. However, trending effects showed that greater multilingual diversity may flatten the age-related effects on cognitive decline, both in the alpha and gamma bands. One can therefore argue that if other measures of multilingual diversity had been used then maybe more significant interactions would have been found, and perhaps the results would have been more in line with Soares et al. (2021).

Then, what may be the problem with the MLD score? There are several reasons for this. First, the population in Norway, where this experimental study was conducted, is generally proficient in English as opposed to other countries. One reason for this is that in 1969, English became a known subject in all Norwegian schools and further changes in the education plan from 1997 caused English L2 learning to start already in the first grade (Utdanningsdirektoratet, 2023). Additionally, Norwegians are used to English in their daily lives where they are often exposed to English, for instance, through music, TV, social media, to name a few. However, the usage of English varies though, where some do not regularly use English, as opposed to others who have to communicate in English with other people in different contexts, for instance through their work. When the MLD score is heavily reliant on this self-reported proficiency, which in and of itself can be an issue, the score is skewed and limits the variance of the MLD score. This is backed up by the fact that only 37 percent of these participants reported an average English proficiency below the mean of 5.25 out of 1 to 7. This may be the reason for that the overall range in the MLD score is remarkably low (between 0.895 and 1.059 out of 0 to 2). Two of the participants also reported that their L2 English proficiency was higher than their native language proficiency, one might ask questions to if this self-reported proficiency is an appropriate method to measure this. Second, this proficiency issue can also be in unison with conducting the interview session in English. This could be an issue for some of the potential participants, where they were not comfortable enough with speaking English for 1-2 hours straight, hence, more ‘balanced’ bilinguals were recruited[2]. Third, the purpose of this thesis was to correlate the different tasks with multilingual engagement, and proficiency of their languages is not necessarily related to engaging in multilingual language use. These remarks are food for thought for future research when conducting studies on multilingual engagement in a highly bi-multilingual society, where L2 proficiency is generally high.

The first research question asked whether the differences in bi-multilingual engagement, above and beyond other lifestyle enrichment factors, affect RS oscillations across the lifespan. The results make it difficult to answer this question because of the negative main effects of MLD as well as the other insignificant, although trending, effects of MLD on aging. As previously argued, the main MLD effects is likely due to the younger population driving it down, and it is arduous to answer how it affects the aging trajectory because of the insignificance in the age and MLD interaction. The answer to this question would then be based on trending effects, and thus would be affected by researcher bias. An interpretation of why these effects occur might be that the current model may not account for all the explanatory variables well enough since it is a linear model and tries to account for them through plotting a linear line, especially regarding the large age span and the age distribution (see appendix A). In sum, the main effect of MLD is affected by the younger participants and it might seem that MLD can flatten the age-related effect on cognitive decline, but both the modelling method and the MLD score might be problematic in this instance and thus the question still stands.

The second research question asked whether the differences in bilingual engagement, above and beyond other lifestyle enrichment factors, affect cognitive task performance across the

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[2] Supported by anecdotal experience during participant recruitment efforts.

lifespan. The predictions for this question were also hierarchal where MLD would affect the performance, if not, then the lifestyle factors, and if not MLD or lifestyle factors, the age-related effects would show themselves for the older participants. Neither MLD, lifestyle factors, nor the interaction between MLD and age were significant, only a main effect of age was significant. The third prediction was therefore confirmed, but not the research question. I will argue in line with the previous argument that MLD might not account for multilingual engagement enough, or that the task itself is not difficult enough to show any potential advantages of lifelong bi-multilingualism. It is also important to note that the current results cannot provide evidence for or against the IC model (Green, 1998) or the concept of attentional control (Bialystok & Craik, 2022), nor was it the goal of the thesis. Further research on EF and bilingualism, especially when treating it as a dynamic spectrum, should choose their tasks carefully or manipulate the level of difficulty in the task which was suggested by Bialystok and Craik (2022), while also use stronger predictors for multilingual diversity especially when conducting research in countries where the speakers are highly proficient in their L2.

The third research question asked whether there is a correlation between RS oscillations and task performance. As previously discussed, no correlation was found, neither in the models nor with the correlation matrix. This was argued to be because of three main reasons, the predictability of the MLD score and hence other regions and bands could not be included since they were insignificant, or that the effect of age on coherence and the flanker performance was too large to capture coherence predictability, or that there was no correlation whatsoever. Previous studies on cognitive task performance and EF have correlated on-task power outputs with performance and found promising results (e.g., Sauseng et al., 2005; Klimesch et al., 1999), but less is known whether off-task power outputs can predict behavioural performance. Bice et al. (2020) tried to approach this and found a relationship between better Simon performance and higher alpha power in frontal electrode regions, but for monolinguals only. They concluded that they did not find any relationships in the bilingual group because they generally had higher power and broader coherence, thus further illuminates the importance of treating bi-/multilingualism as a dynamic spectrum. Although, it may be a limiting factor for the present thesis that RS power outputs were not included, even though it is a part of the coherence calculation, it would have been interesting to investigate it, clearly because of its ties to EF. Hence, the third research question could not be confirmed, it may be a limiting factor that power outputs were not included in the thesis, especially for this specific issue.

5.5 Future investigations and limitations

As discussed above, the MLD score may not have been the most appropriate proxy for bi-/multilingual experience in the present highly L2-proficient participant sample as the high weighting of L2 proficiency as part of MLD may have obscured the effects of individual variability in L2 use and engagement. In addition to that, the fact that the initial interview was conducted in English may have led to recruitment of a self-selecting sample of highly proficient Norwegian-English bi-/multilinguals thus denying the opportunity to test individuals at the lower end of L2 proficiency spectrum. Future research that are investigating differences in bi-multilingual engagement should then have proficiency on its own and either approach it similar to Soares et al. (2021) where the different language use contexts are investigated, or treat the engagement as an entropy score. This entropy score would then consist of whether the bi-multilingual engages in multilanguage contexts, and does not rely on proficiency, which is especially important in areas where the bi-multilinguals are generally proficient in their additional language(s). The notion of an entropy score can be better explained through an example, for instance with two hypothetical Norwegian-English bilinguals, Jon, and Marianne. If Marianne were to use English daily at work and Norwegian at home and elsewhere in society, this would cause a higher entropy score compared to Jon who is not engaging in dual-language contexts at work (example adapted from Gullifer et al., 2021). Through this, one can capture the indices of language use more clearly and as Gullifer and Titone (2020) notes, it can reduce data complexity. Future research should therefore index multilanguage diversity through language engagement in an entropy score, and maybe include proficiency and L*n* age of acquisition as separate scores in order to explore whether these factors can affect cognition, both neurologically and behaviourally dependent on the task demands. In regard to age of acquisition, this was not included in the present thesis mainly because of the Norwegian school system, where there is very little variation of when the additional language(s) is/are acquired.

A lot of the work on bilingualism and aging have included participants with some form of pathological disease, like dementia, and as previously stated, the world is slowly but surely getting older as birth rates are declining. I would not argue to abandon or reduce the attention to researching these pathological diseases, since it is incredibly important to expand our knowledge on preventative methods against these diseases. However, it is also important to conduct more research on the healthy senior population in order to explore whether bi-multilingualism can facilitate the cognitive aging trajectory. In regard to aging, I also mentioned there might be some issues with the chosen modelling method in the present thesis. The age-range is wide and the age-related effect on coherence is strong and widespread, and a linear regression model might not be the most optimal analytic method to investigate the different variables' explanatory effect on the whole lifespan since a linear model is trying to account for all of the variables in a linear line. Future studies might attempt to incorporate other modelling methods, such as a more complex path analysis, or other structural equation models, which allows the investigator to clarify the relationships between the different variables more directly (Ullman & Bentler, 2012). These approaches are suited for large sample sizes and the sample size presented here is simply too small for such approaches. Perhaps such attempts can also adequately account for whether the RS dynamics can predict performance in EF tasks across the adult lifespan. Those tasks should also be difficult enough where they might also reveal effects of differences in multilingual engagement on behavioural EF task performance.

6. Conclusion

The present thesis is one of the first studies to be conducted on the healthy bi-multilingual adult lifespan where lifestyle enrichment factors known to affect brain health in the older age have been controlled for while investigating the neurocognitive effects of bi-/multilingual experience. The present thesis therefore aimed to answer whether both rs-EEG dynamics and behavioural flanker performance are modulated by multilingual engagement, above and beyond other lifestyle factors, and as well if there is a correlation between RS rhythms and task performance.

I found a main effect of MLD and a trending interaction between MLD and age on rs-EEG dynamics in the alpha and gamma frequency bands. Results also revealed significant age-related effects in all frequency bands, which was most pronounced in the theta band, where older participants exhibited worse coherence. The behavioural flanker analysis revealed no significant effects with MLD, likely to be due to the difficulty of the task, or perhaps the MLD could not account for it properly. Finally, there were no correlations between RS coherence and flanker performance, likely to be due to that the age-related effect on coherence was too strong, or that there simply were no correlation at all. Overall, the present study suggests that higher bi-multilingual engagement can help maintain the functional architecture of the brain in aging, however, further research is wholeheartedly welcome to investigate this further and whether it modulates EF performance, and finally, if RS dynamics can predict task performance.

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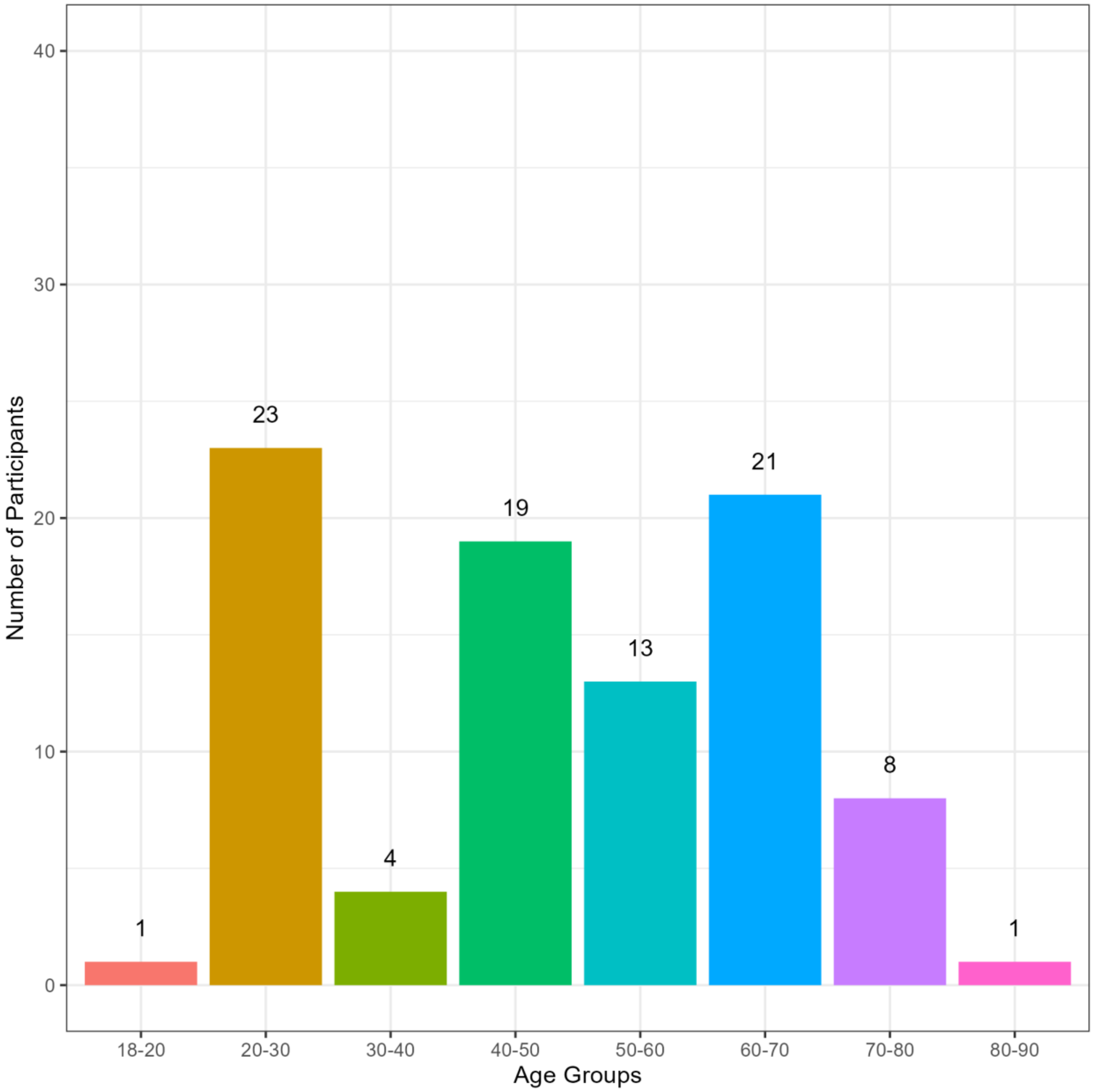
Appendices

A: Age distribution of the 90 participants



B: Gamma coherence by MLD and age between MF & RP