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Effects of Multilingual Engagement and Physical Activity on Episodic Memory Performance

Exploring the relationship between episodic memory, multilingual engagement, and physical activity in 172 L1 Norwegian healthy bilinguals across the adult lifespan

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Abstract

This study investigates the effects of bilingualism and physical activity on episodic memory performance across the lifespan. Drawing on a sample of 172 bi-multilingual Norwegian L1 English L2 speakers, data were collected using the Language History Questionnaire (LHQ3.0) and the International Physical Activity Questionnaire Short Form (IPAQ-SF), along with an episodic memory task inspired by Babiloni et al. (2004). Generalized linear mixed models were employed to analyze the relationship between bilingual engagement, physical activity, and episodic memory performance. Results indicate a significant association in accuracy for successfully rejecting not seen stimuli. However, no significant effects were observed for physical activity, multilingual engagement, age, or sex on episodic memory performance. These null findings suggest a need for further investigation into the nuanced relationship between bilingualism, physical activity, and episodic memory, considering factors such as sample variability, study design, and task specificity. By addressing these complexities, future research can advance our understanding of cognitive function and inform interventions aimed at promoting healthy cognitive aging.

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1 Introduction

In recent decades, the field of language research has expanded significantly, with increasing attention devoted to exploring the effects of bilingualism on cognition across the lifespan. Bilingualism, defined as the ability to speak and use two or more languages, has emerged as a topic of particular interest due to its potential impact on various cognitive functions. While numerous studies have investigated the behavioral and neurological effects of bilingualism, the link between bilingualism and cognition remains complex and not fully understood (Bialystok, 2021; De Frutos-Lucas et al., 2020). Moreover, parallel research has shed light on the cognitive benefits of physical activity, with evidence suggesting that regular physical exercise can enhance cognitive function and contribute to healthy aging (Klimova et al., 2017b; Fernandes et al., 2021). Understanding the interplay between bilingualism and physical activity in shaping cognitive outcomes across the lifespan is essential for developing comprehensive interventions aimed at promoting cognitive health and overall well-being.

One area of cognition that has not received considerable attention in bilingualism research is episodic memory. Episodic memory plays a crucial role in recalling specific events and experiences from one's past, and it is known to undergo changes with age (Craik & Salthouse, 2000). As individuals age, they often experience declines in episodic memory performance, which can have significant implications for daily functioning and overall quality of life (Park et al., 2002; Salthouse, 2004). Understanding how bilingualism influences episodic memory throughout the lifespan is therefore of great importance, particularly as the global population continues to age (WHO, 2022).

Previous research has suggested that bilingualism may confer cognitive benefits and contribute to cognitive reserve, which refers to the brain's ability to maintain cognitive function despite age-related changes or pathology (Stern, 2009; Craik et al., 2010; Gallo et al. 2022; Voits et al. 2024). By engaging in the continuous management of two languages, bilingual individuals may develop enhanced executive control processes, which are thought to play a role in episodic memory performance (Abutalebi & Green, 2007). However, the extent to which bilingualism influences episodic memory across different age groups and linguistic contexts remains a contentious issue (Schroeder & Marian, 2012).

While much of the existing research has focused on comparing bilingual and monolingual individuals, recent studies have highlighted the importance of considering bilingualism as a dynamic spectrum rather than a categorical variable (DeLuca et al., 2019; Luk and Bialystok, 2013; Gullifer and Titone, 2020). Factors such as multilingual engagement, language experience, and linguistic context may contribute to variations in cognitive effects observed among bilingual individuals (Lehtonen et al., 2018). Therefore, it is essential to explore how differences in bilingual engagement impact episodic memory and cognitive aging while controlling for other demographic and lifestyle factors.

In addition to bilingualism, it is essential to recognize that delaying cognitive decline in aging is influenced by a multitude of factors, including education, socio-economic status, diet, physical activity, social engagement, and more. Among these factors, physical activity stands out as particularly noteworthy due to its well-documented effects on brain health and cognitive function. Research has consistently demonstrated that engaging in regular physical activity can have profound benefits for cognitive health, including improvements in memory, attention, and executive function (Klimova et al., 2017b). Physical activity has been associated with changes in brain structure and function, such as increased hippocampal volume and enhanced neural plasticity, which are thought to underlie its cognitive benefits (Erickson et al., 2011). Moreover, physical activity has been shown to reduce the risk of age-related cognitive decline and neurodegenerative diseases such as Alzheimer's disease (Fernandes et al., 2021). Importantly, physical activity is a modifiable lifestyle factor that individuals can incorporate into their daily routines to promote cognitive health and overall well-being. Therefore, while bilingualism may play a role in delaying cognitive decline, it is essential to consider the broader context of lifestyle factors such as physical activity, which can potentially synergistically contribute to healthy cognitive aging. By investigating the potential interplay between bilingualism and physical activity, researchers and healthcare professionals can develop comprehensive interventions aimed at optimizing cognitive function and promoting successful aging across diverse populations. However, it would be worth noting that there is a lack of literature examining the combined effect of bilingualism and physical activity, indicating a critical gap in our understanding of how these factors interact to influence cognitive outcomes. Future research exploring this intersection could provide valuable insights into the development of tailored interventions for cognitive health maintenance.

This thesis aims to investigate the effects of bilingualism on episodic memory throughout the lifespan. By adopting a comprehensive approach that considers individual differences in bilingual engagement, linguistic context and language use, this study seeks to provide a more nuanced understanding of the relationship between bilingualism and episodic memory. Additionally, self-reported physical activity will be used as a variable to look for potential additive effects on episodic memory. By doing so, the study aims to contribute to the broader discourse on bilingualism, cognitive aging, and physical activity, ultimately informing interventions aimed at promoting healthy cognitive aging and enhancing quality of life for individuals across a diverse lifespan.

2 Theoretical Background

2.1 Aging

With a global trend towards an aging population, there arises a pressing need to understand the challenges associated with this demographic shift. Aging brings about a multitude of physiological, neurological, and cognitive changes that significantly impact individuals' quality of life. As people age, they may experience a decline in muscle mass, strength, vision, and hearing, among other physiological changes (Amarya et al., 2018). However, perhaps one of the most profound effects of aging is its impact on cognitive function. Cognitive decline, characterized by reductions in memory, attention, processing speed, and executive function, can significantly impair daily functioning and independence (Murman, 2015). Understanding the mechanisms underlying cognitive decline in aging individuals is crucial for developing interventions that can improve the overall quality of life for this population.

Ageing exerts profound effects on the brain and cognition, manifesting across multiple domains and involving various underlying mechanisms. One prominent aspect of brain ageing is the decline in brain volume, particularly noticeable in the frontal cortex, with studies indicating a reduction rate of approximately 5% per decade after the age of 40, potentially accelerating beyond the age of 70 (Scahill et al., 2003). While neuronal cell death has been suggested as a contributor to grey matter shrinkage, the exact mechanisms remain subject to ongoing investigation. Importantly, brain changes associated with ageing do not occur uniformly across all regions, with the prefrontal cortex often exhibiting the most pronounced effects, followed by the striatum and temporal lobe, while the occipital cortex tends to be less affected (Peters, 2006). Gender differences have also been noted, with variations in the regions most affected in men versus women (Peters, 2006). These structural alterations in the brain underscore the complexity of age-related cognitive changes.

Cognitive decline refers to the deterioration of cognitive abilities that occurs as individuals age. This decline is not uniform across all cognitive domains but tends to affect certain cognitive processes more severely than others. For instance, cognitive processes involved in higher-level processing and on-the-fly decision-making, such as executive functioning, are particularly vulnerable to the effects of aging (Murman, 2015). Murman also highlights the distinction between crystallized and fluid abilities in aging. Crystallized abilities, which encompass skills and knowledge accumulated over a lifetime, such as reading comprehension and vocabulary, tend to remain relatively stable with age. In contrast, fluid abilities, which involve processing new information quickly and applying it to tasks, such as executive functioning and working memory, are more susceptible to decline (Murman, 2015).

As individuals age, they may experience challenges in various cognitive domains, including memory, attention, and problem-solving. Memory decline, characterized by difficulties in recalling past events or retaining new information, is a common manifestation of cognitive aging (Murman, 2015). Additionally, aging individuals may experience declines in attention and processing speed, making it harder to focus on tasks and respond quickly to stimuli. Problem-solving abilities may also be affected, impacting individuals' ability to navigate complex situations and make decisions effectively. Overall, cognitive decline in aging can significantly impact individuals' ability to maintain their independence and quality of life.

2.2 Episodic Memory

Episodic memory, a fundamental component of human memory, plays a crucial role in remembering personal experiences and events that one has encountered throughout life (Tulving, 1983). It encompasses the ability to recall specific details about past events, such as what one ate for breakfast a few days ago or a conversation held a few minutes ago. However, aging is often accompanied by a decline in episodic memory, where older adults may exhibit decreased performance in tasks requiring the recall of recent events (Craik & Salthouse, 2000; Park et al., 2002; Salthouse, 2004). This decline can have significant implications for an individual's daily life, affecting not only personal functioning but also social interactions and overall well-being (Comijs et al., 2005). The impact of this decline can extend beyond the individual, potentially straining familial relationships and societal engagement, highlighting the far-reaching consequences of compromised episodic memory in aging populations.

Neuroscientific investigations have shed light on the neural underpinnings of episodic memory, highlighting the involvement of key brain regions in its encoding, consolidation, and retrieval processes (Eichenbaum, 2000; Squire, 1992). Among these regions, the hippocampus, situated within the medial temporal lobes, occupies a central role in forming and retaining episodic memories (Eichenbaum et al., 2007). During memory formation, the hippocampus integrates various event details, such as spatial and temporal context, into cohesive episodic representations (Squire & Zola-Morgan, 1991). This process involves binding disparate elements of an experience into a unified memory trace, facilitating later retrieval.

Moreover, the hippocampus contributes to pattern separation, a mechanism that enables the discrimination of similar memories, thus preventing interference between overlapping experiences (McClelland et al., 1995). While the hippocampus plays a pivotal role in episodic memory, other medial temporal regions, such as the perirhinal and parahippocampal cortex, also contribute to encoding item and contextual information, respectively (Davachi et al., 2003). Together, these brain regions form a network supporting the formation and retrieval of episodic memories, underscoring their intricate neural architecture and functional interactions (Komorowski et al., 2009; Ranganath, 2010).

Aging is associated with significant changes in episodic memory, manifesting as declines in both behavioral performance and neural activity (Park et al., 2002; Rönnlund et al., 2005). Episodic memory function typically begins to decline around the age of 60, with older adults exhibiting greater vulnerability to memory impairments compared to other forms of long-term memory (Nyberg et al., 2003). Despite the well-documented nature of age-related episodic memory decline, the specific neurocognitive mechanisms underlying these changes remain elusive (Cansino et al., 2018).

Neuroimaging studies have provided insights into the neural correlates of age-related episodic memory decline, revealing alterations in brain activity patterns during both encoding and retrieval processes (Cabeza et al., 2004). Older adults often exhibit reduced activity in posterior brain regions involved in perceptual processing, coupled with increased activity in the prefrontal cortex during memory tasks (Maillet & Rajah, 2014a). These changes may reflect compensatory mechanisms aimed at maintaining cognitive performance in the face of age-related neural decline.

Age-related declines in episodic memory are often characterized by deficits in recollection-based retrieval, wherein individuals struggle to retrieve detailed contextual information associated with past events (Koen & Yonelinas, 2016). Older adults may experience difficulties in recalling spatial and temporal contexts, speaker identities, and encoding tasks engaged during study phases (Morcom et al., 2007). These deficits may stem from alterations in hippocampal function and reduced neural efficiency, highlighting the multifaceted nature of age-related episodic memory decline (Daselaar et al., 2006).

Moreover, the changes observed in episodic memory with aging are thought to be influenced by alterations in executive functioning, a set of cognitive control abilities that play a crucial role in the encoding and retrieval of memories (Moscovitch & Winocur, 1992). Executive functions, which encompass processes such as inhibitory control, task switching, and working memory, collaborate with the medial temporal lobe memory system to facilitate episodic memory processes (Nolde, Johnson, & Raye, 1998; Wheeler, Stuss, & Tulving, 1995). However, as normal aging negatively affects the frontal lobes responsible for executive functioning, older adults may experience difficulties in strategic encoding and retrieval, leading to poorer episodic memory performance (Baudouin et al., 2009; Troyer, Graves, & Cullum, 1994).

Bilingualism, the ability to speak and use two or more languages, has emerged as a potential protective factor against cognitive decline in older adulthood (Bialystok, Craik, Klein, & Viswanathan, 2004; Salvatierra & Rosselli, 2011). Bilingual older adults have been found to outperform their monolingual peers in tasks requiring executive functions, such as inhibitory control and working memory (Bialystok, Craik, & Luk, 2008). This advantage is attributed to the continual practice of managing two languages, which recruits and strengthens executive control systems in the brain (Abutalebi & Green, 2007). Given the role of executive functioning in episodic memory, bilingualism may also influence episodic memory performance in older adulthood.

However, studies investigating the impact of bilingualism on episodic memory in older adults have yielded mixed findings. While some research suggests that bilingualism may enhance episodic memory by facilitating executive control processes (Wodniecka et al., 2010), others have reported no significant adaptations associated with bilingualism in episodic memory tasks (Fernandes et al., 2007). These discrepancies may be attributed to variations in task demands and linguistic processing requirements. For instance, tasks involving verbal stimuli may place greater demands on lexical processes, which could disadvantage bilinguals due to differences in vocabulary size and lexical access speed (Bialystok et al., 2009).

2.3 Bi- Multilingualism's Effect on Cognition

The relationship between bilingualism and cognitive function has been a subject of considerable interest and investigation in recent years, leading to a surge in research activity in this area. The growing body of literature reflects a lively debate surrounding the potential modifications of cognitive function and brain structure associated with bilingualism. Central to this discourse is the question of whether managing two languages on an ongoing basis is linked to improved performance on nonverbal cognitive tasks, particularly those involving executive functions (Antoniou, 2019; Baum & Titone, 2014; Bialystok, 2017).

Psycholinguistic research suggests that bilingualism enhances inhibitory control mechanisms, given that both languages are continually active in the bilingual brain. This heightened inhibitory control is believed to generalize to various cognitive tasks and situations, contributing to enhanced cognitive control in bilingual individuals (Costa et al., 1999; Kroll et al., 2014).

Theoretical models, such as the Inhibitory Control model and the Adaptive Control Model, propose that the demand for inhibition varies depending on the linguistic environment shared by speakers and listeners. Bilinguals typically find themselves primarily in one of three interactional contexts: single language, dual language, and dense code-switching. These contexts shape the underlying processes specific to that context, leading to different outcomes for bilinguals whose interactional experiences differ (Green & Abutalebi, 2013).

Bilingualism has been associated with domain-general cognitive functions, as suggested by the Inhibitory Control model. This model proposes that continual practice with language control extends to nonlinguistic cognitive domains, potentially leading to bilingual advantages in various aspects of domain-general cognitive functioning (Abutalebi and Green, 2007; Bialystok et al., 2009; Kroll et al., 2012). Extensive research across diverse bilingual populations, spanning different age groups and assessing various domain-general cognitive tasks, consistently supports the presence of bilingual advantages, particularly in inhibitory control and task switching (Antoniou and Wright, 2017; Bialystok, 2017; Bialystok et al., 2009; Kroll and Dussias, 2017). These advantages have been observed across the lifespan, suggesting that proficiency in multiple languages may contribute to increased cognitive reserve and slow cognitive decline, particularly in aging populations (Antoniou and Wright, 2017).

Moreover, children and infants raised in bilingual environments have demonstrated advantages over monolingual peers in various cognitive, social, scholastic, and language learning abilities (Kroll and Dussias, 2017). Hilchey and Klein (2011) proposed two hypotheses to explain the bilingual cognitive advantage. The Bilingual Inhibitory Control Advantage hypothesis suggests that bilinguals exhibit cognitive adaptations primarily in conditions requiring conflict resolution, such as incongruent trials in Stroop or flanker tasks. Conversely, the Bilingual Executive Processing Advantage hypothesis suggests a global response time advantage in cognitive control tasks, including both congruent and incongruent trials. These hypotheses provide theoretical frameworks for understanding the mechanisms underlying the bilingual cognitive advantage and highlight the intricate interplay between language control and domain-general cognitive processes.

Meta-analyses and reviews of research on bilingualism reveal both positive and null results regarding its effects on cognitive function. While some studies suggest a positive association between bilingualism and cognitive performance, others find no significant differences between bilingual and monolingual groups. The presence of a small but significant effect size in many studies, typically around 0.20, raises cautious optimism about the potential benefits of bilingualism on cognitive function (Adesope et al., 2010; Grundy, 2020; van den Noort et al., 2019).

Debates surrounding the validity of research findings continue, with conflicting evidence emerging regularly. However, the preponderance of evidence suggests that bilingualism positively affects cognitive performance despite some studies reporting null results (Donnelly et al., 2019; Hartanto et al., 2019; Lehtonen et al., 2018). The controversy surrounding these findings underscores the complexity of the relationship between bilingualism and cognitive function and cautions against oversimplified interpretations (Bak, 2016; Bialystok, 2016; Valian, 2015).

One well-established difference between bilingual and monolingual individuals is the superiority of monolinguals in verbal knowledge, which often translates into better performance on verbal tasks. However, bilinguals may outperform monolinguals on tasks involving nonverbal materials, indicating a potential trade-off between verbal knowledge and attentional control (Luo et al., 2013).

Factors such as early versus late bilingualism, age of bilingual acquisition, frequency of language switching, and the complexity of bilingual experiences have been shown to modulate the relationship between bilingualism and cognitive outcomes. Recent studies have emphasized the importance of considering bilingualism as a continuum along the spectrum of language experience rather than a dichotomy, further refining our understanding of the complex interplay between bilingualism and cognition (Pelham & Abrams, 2014; Vega-Mendoza et al., 2015; DeLuca et al., 2019)

2.3.1 Schroeder, S. R., & Marian, V. (2012)

The study by Schroeder and Marian (2012) explores the impact of bilingualism on episodic memory performance in older adults. The study employs two distinct tasks to assess episodic memory and executive functioning. For episodic memory, participants engage in a picture recall task, where they view a series of pictures and are later asked to recall them. In the encoding phase, participants simply view the pictures without being explicitly instructed to remember them, while in the retrieval phase, they recall as many pictures as possible. Results indicate that bilingual older adults exhibit superior episodic memory compared to their monolingual counterparts, particularly for pictures with higher levels of valence and emotional arousal. Additionally, earlier acquisition of a second language and greater bilingual experience are associated with better memory performance among bilingual individuals.

In assessing executive functioning, participants complete the Simon task, which measures inhibitory control. Bilinguals demonstrate more efficient inhibitory control compared to monolinguals, as evidenced by a smaller Simon effect. Moreover, correlation analyses suggest a relationship between inhibitory control ability and episodic memory performance, particularly among bilinguals. Bilinguals exhibit stronger correlations between inhibitory control and memory performance compared to monolinguals, indicating a potential reliance on executive functions during episodic retrieval.

The study suggests that bilingualism may confer cognitive benefits, including enhanced episodic memory and executive functioning. Bilingual individuals may excel in episodic memory tasks due to superior executive functioning, particularly in the recruitment of inhibitory control during retrieval processes. Furthermore, the study proposes that increased reliance on the medial temporal lobe memory system in bilinguals may contribute to improved memory performance. Overall, the findings highlight the complex interplay between bilingualism, cognitive processes, and memory performance in older adults, offering insights into potential mechanisms underlying the bilingual advantage in cognitive aging.

2.4 Physical Activity's Effect on Cognition

Physical activity plays a crucial role in cognitive function across the lifespan, with its effects becoming increasingly evident as individuals age. While the relationship between physical activity and cognition has been extensively studied, it is essential to consider various factors that may influence this relationship. Cross-sectional and cohort studies have provided valuable insights into the association between physical activity and cognitive performance, particularly in middle-aged and older adults. These studies have highlighted that individuals who engage in regular physical activity tend to exhibit better cognitive performance and a reduced risk of age-related cognitive decline and dementia (Etgen et al., 2010; van Gelder et al., 2004; Yaffe et al., 2001). However, it is crucial to note that while these studies demonstrate an association between physical activity and cognitive health, they cannot establish causality.

Longitudinal cohort studies have further emphasized the importance of physical activity in preserving cognitive abilities over time. For example, research has shown that engaging in physical exercise during midlife is associated with larger gray matter volume in later life, particularly in frontal brain regions implicated in cognitive function (Rovio et al., 2010; Erickson et al., 2010). Moreover, midlife physical activity has been linked to a reduced risk of dementia in older age (Andel et al., 2008; Rovio et al., 2005). These findings suggest that maintaining an active lifestyle, particularly during midlife, may contribute to better brain health and cognitive function in later years.

The effects of physical activity on cognition are thought to be mediated by various mechanisms. One proposed mechanism is the promotion of neuroplasticity, including increased neurogenesis and synaptogenesis, particularly in brain regions crucial for cognitive function such as the prefrontal cortex and hippocampus (van Praag et al., 2000; Erickson et al., 2011; Hötting & Röder, 2013). Additionally, physical activity has been associated with improvements in cardiovascular fitness, which may enhance cerebral blood flow, oxygenation, and nutrient delivery to the brain, thereby supporting cognitive function (Thomas et al., 2012).

Furthermore, intervention studies have provided valuable insights into the cognitive benefits of regular physical activity. Chronic exercise programs, such as aerobic training, have been shown to improve various cognitive domains, including executive function, attention, memory, and processing speed (Colcombe et al., 2004; Kramer et al., 1999; Smiley-Oyen et al., 2008; Voelcker-Rehage et al., 2011). Importantly, these effects have been observed not only in older adults but also in middle-aged and younger individuals (Stroth et al., 2009; Hötting et al., 2012b). However, the specific types and intensities of exercise that yield optimal cognitive benefits remain areas of ongoing research.

Physical activity exerts its influence on episodic memory through several mechanisms that contribute to overall brain health and function. As mentioned above, one key mechanism is the promotion of neuroplasticity, which involves the brain's ability to adapt and reorganize itself in response to experiences and stimuli. Studies have shown that physical activity can increase neurogenesis and synaptogenesis, particularly in brain regions crucial for episodic memory, such as the hippocampus (van Praag et al., 2000; Erickson et al., 2011). These structural changes may support the encoding, consolidation, and retrieval of episodic memories, thereby enhancing episodic memory performance.

Furthermore, physical activity is associated with improvements in cardiovascular fitness, which has downstream effects on brain health. Regular exercise enhances cardiovascular function, leading to improved cerebral blood flow, oxygenation, and nutrient delivery to the brain (Thomas et al., 2012). Adequate blood flow and oxygen supply are essential for the optimal functioning of brain cells involved in memory processes. By promoting vascular health, physical activity indirectly helps maintain the integrity of brain structures involved in episodic memory, thereby potentially preserving memory function.

Intervention studies, such as the one conducted by Hayes et al. (2015), provide empirical evidence supporting the beneficial effects of physical activity on episodic memory. Through structured exercise programs, such as aerobic training, individuals can improve various cognitive domains, including memory. Hayes et al. (2015) found that greater physical activity, as objectively measured by accelerometers, was associated with better performance on measures of episodic memory in older adults. This suggests that incorporating regular physical activity into daily routines can positively impact episodic memory function, potentially reducing age-related declines in memory performance.

2.4.1 Linking Physical Activity and Bilingualism

In exploring the relationship between physical activity and bilingualism within the context of cognitive function, particularly episodic memory, it's essential to recognize the potential interplay between these two factors. While they may appear distinct on the surface, there are underlying mechanisms that suggest a link between them.

Physical activity, influences brain health through mechanisms such as promoting neuroplasticity and enhancing cardiovascular function (Thomas et al., 2012). These effects extend to cognitive domains, including memory, where regular physical activity has been associated with improvements in memory performance (Colcombe et al., 2004). Similarly, bilingualism has been linked to cognitive advantages, particularly in executive functions (Bialystok et al., 2008). The continual practice of managing two languages is thought to strengthen executive control systems in the brain, leading to enhanced cognitive control and potentially influencing memory processes (Abutalebi & Green, 2007).

While physical activity and bilingualism may exert independent effects on cognitive function, there is also the possibility of synergistic or complementary influences. For instance, bilingual individuals who engage in regular physical activity may experience compounded cognitive benefits due to the combined effects of both factors. Conversely, the cognitive advantages conferred by bilingualism may augment the impact of physical activity on memory function.

Moreover, controlling for the effects of one factor while studying the other may reveal more reliable effects and shed light on the specific contributions of each. By disentangling the influences of physical activity and bilingualism on episodic memory, we might better understand their unique roles and potential interactions on cognition.

2.5 The Present Study

The aim of the present study is to investigate the effects of bilingualism on episodic memory throughout the lifespan, while also considering the potential influence of physical activity. This study is motivated by the growing interest in understanding how bilingualism and physical activity, both individually and in combination, contribute to cognitive health and aging.

The present study is a part of the larger ongoing *MindMap* study from the Polar Lab at UiT.

Research Question 1: Does bilingual language engagement modify episodic memory performance on a visuo-spatial task across different age groups?

Research Question 2: Does self-reported physical activity influence episodic memory performance on a visuo-spatial task.

Research Question 3: If self-reported physical activity influence episodic memory performance, are the effects additive when considered alongside bilingual engagement?

2.5.1 Predictions

Research Question 1: Based on previous literature, I predict that there will be a significant effect of bilingual language engagement on episodic memory performance on the visuo-spatial task across different age groups. Specifically, I anticipate that participants with high levels of bilingual engagement will demonstrate superior performance on the task compared to those with lower levels of bilingual engagement. This prediction is grounded in the concept of cognitive reserve, which posits that engaging in mentally stimulating activities, such as bilingualism, may bolster cognitive resilience and mitigate age-related cognitive decline (Stern, 2009).

Furthermore, I expect this effect to be more pronounced among older participants. As individuals age, they typically experience declines in fluid cognitive abilities, including executive functioning and working memory, which are closely linked to episodic memory performance (Murman, 2015). However, bilingualism has been shown to confer cognitive adaptations, particularly in tasks requiring executive control and cognitive flexibility (Bialystok, Craik, Klein, & Viswanathan, 2004). Therefore, older adults with high levels of bilingual engagement may rely on these enhanced executive control processes to compensate for age-related declines in cognitive function, resulting in better episodic memory performance on the visuo-spatial task.

Conversely, I anticipate that the effect of bilingual engagement on episodic memory performance may be attenuated among younger participants. As younger individuals typically exhibit higher levels of cognitive functioning and may already operate near their cognitive ceiling, where additional cognitive stimulation from bilingualism may not yield significant improvements (Bialystok, 2017). Additionally, younger participants may have less accumulated experience with bilingualism compared to older adults, potentially limiting the cognitive benefits associated with bilingual language engagement (Bialystok et al., 2009).

In summary, I predict that bilingual language engagement will modify episodic memory performance on the visuo-spatial task, with a stronger effect observed among older participants. However, I hypothesize that the influence of bilingual engagement on episodic memory performance may be less pronounced among younger participants due to ceiling effects.

Research Question 2: I predict that physical activity will independently modulate episodic memory performance on the visuo-spatial task, with age being a dominant factor in this relationship. As individuals age, the effects of physical activity on cognitive function become increasingly evident, with regular physical activity associated with better cognitive performance and a reduced risk of age-related cognitive decline and dementia (Etgen et al., 2010; van Gelder et al., 2004; Yaffe et al., 2001).

Based on the literature linking physical activity to cognitive function, I anticipate that physical activity will positively influence episodic memory performance on the visuo-spatial task across different age groups. However, the extent of this influence may vary depending on age, potentially leading older adults to derive more significant benefits as their cognitive abilities decline with age.

Research Question 3: Regarding the potential interplay of bilingual engagement and physical activity on episodic memory performance, I hold the view that these factors may act as distinct yet complementary pathways to enhancing cognitive function. While bilingual engagement is known to bolster executive control processes and cognitive flexibility, physical activity fosters neuroplasticity and cardiovascular health. Consequently, I do not anticipate observing a direct additive effect of bilingual engagement and physical activity on episodic memory performance. Instead, I posit that each factor independently contributes to cognitive resilience and may mitigate age-related cognitive decline. Nevertheless, it is conceivable that among older participants, who may confront more pronounced cognitive changes with age, we might discern a synergistic effect of bilingual engagement and physical activity on episodic memory performance.

3 Methodology

3.1 Participants

Data was collected from 228 bi-multilingual Norwegian L1 English L2 speakers. Some participants also had additional languages beyond the required L1 and L2. 56 participants were removed from the dataset during data cleaning which will be discussed in the data cleaning procedure. The final participant pool consisted of 172 participants, 55 male, 115 female, 1 non-binary, and 1 non-relevant participants aged from 18-82 (mean=44.8, SD=17.38). Recruitment strategies varied from advertising the study on social media platforms, newspapers, bus stops, and public transport to approaching sports teams and recreational groups. The overarching goal of the study is to investigate healthy adult bilinguals. Screening questions were used to exclude participants without normal or corrected-to-normal vision, participants with learning disorders, depression, psychiatric or neurological disorders, use of psychotropic medication, or traumatic brain injury. The experiment was divided into two parts: a one-hour interview and a two-to-three-hour lab session. Upon completion, participants were compensated with a 500 NOK gift card, which was later increased to 750 NOK as more tests were added to the test battery.

The entire experimental procedure received prior approval from the Norwegian Centre for Research Data (NSD), ensuring compliance with established standards for research involving human subjects.

3.2 Procedure

In this study, data collection comprised two distinct sessions, each meticulously designed to address specific research objectives and adhere to ethical guidelines. As this study is a part of the larger ongoing MindMap study, only parts of the of the two sessions will be relevant for this study.

3.2.1 Interview

The interview process is methodically structured, employing a series of selected questionnaires to glean insights into participants' language backgrounds and lifestyle profiles. Conducted online via Zoom and exclusively in English. To minimize fatigue and linguistic interference, the interview and lab session are spaced across different days, this approach ensures consistency while mitigating the potential for code-switching.

At the core of the interview are several validated questionnaires, including the Language History Questionnaire 3.0 (LHQ3.0), which delves into participants' multilingual experiences and proficiencies. The International Physical Activity Questionnaire Short Form (IPAQ-SF) offers a glimpse into participants' physical activity levels, while the Short Form Food Questionnaire (SFFQ) provides dietary insights. The Social Network Index explores participants' social connections, while additional brief questionnaires probe emotional control and well-being. Supplementing these assessments is a verbal fluency task, which serves as a cognitive benchmark. Through this structured approach, the study aims to build a comprehensive understanding of participants' backgrounds and behaviors, laying the groundwork for subsequent analysis.

The Language History Questionnaire (LHQ3.0) and the International Physical Activity Questionnaire Short Form (IPAQ-SF) serve as pivotal components of the data collection process in this study.

3.2.1.1 LHQ3.0

The Language History Questionnaire version 3 (LHQ3), developed by Li et al. in 2020, serves as a pivotal tool for evaluating the linguistic background and proficiency of multilingual individuals or second language learners. LHQ3 employs an automatic scoring system to calculate aggregated scores for language proficiency, dominance, immersion, and multilingual language diversity levels. It introduces new functionalities, including the ability for researchers to assign different weights to modules when computing aggregated scores, thereby accommodating diverse research interests and approaches.

By leveraging the LHQ3 calculator, researchers can derive the Multilingual Language Diversity (MLD) score, which delves into the nuanced aspects of bilingualism. This score, computed using Shannon Entropy based on the Proportion of Dominance, provides a refined understanding of bilingual language usage in various contexts and levels of diversity.

3.2.1.2 IPAQ-SF

The International Physical Activity Questionnaire Short Form (IPAQ-SF) is a tool designed for population surveillance of physical activity among adults aged 15-69. It assesses activity across various domains including leisure time, work-related, domestic, gardening, and transport-related activities. The questionnaire specifically evaluates three types of activities: walking, moderate-intensity activities, and vigorous-intensity activities, recording both frequency (days per week) and duration (time per day) for each type. The total score is calculated by summing the duration and frequency of these activities. Additionally, the questionnaire provides a measure of volume of activity in MET-minutes, computed by weighting each activity type by its energy requirements. IPAQ-SF offers both categorical scores, categorizing individuals into inactive, minimally active, or HEPA active (health-enhancing physical activity), and continuous scores expressed as median MET-minutes per week. Data processing rules are established to ensure standardized computation and cleaning of IPAQ datasets, facilitating accurate comparison across studies (International Physical Activity Questionnaire, 2004).

3.2.2 Lab Session

The lab session unfolds with a multifaceted test battery targeting various cognitive domains crucial to the study's goals. Participants commence with self-assessments utilizing the Cognitive Reserve Scale (CRS) and the MacArthur Scale of Subjective Social Status (MSSSS), gauging cognitive engagement over the lifespan and subjective social status, respectively. Subsequently, participants engage in a series of cognitive tasks, including episodic memory assessments (Encoding and Retrieval), the Flanker task, Corsi block-tapping task, Mini Mental Status Evaluation (MMSE), Verbal fluency task, AX-CPT, and Stroop task. Notably, EEG data collection accompanies most cognitive tasks, enriching the depth of cognitive assessments.

However, for the present study, emphasis is placed solely on behavioral data derived from the Episodic memory (Encoding and Retrieval) task. This deliberate selection streamlines data analysis, focusing on behavioral outcomes while circumventing complexities associated with EEG data interpretation that are beyond the scope of this thesis. Through this streamlined approach, the study aims to elucidate specific cognitive processes pertinent to its objectives, facilitating nuanced insights and conclusions.

3.2.2.1 Encoding Retrieval

The episodic memory task utilized in our experiment draws inspiration from the experimental design proposed by Babiloni et al. (2004). Participants were situated comfortably in a reclining armchair within a dimly lit, sound-damped, and electrically shielded room, with their forearms resting on the armchairs and their right index finger positioned between two buttons spaced 6 cm apart. A computer monitor placed approximately 60 cm away presented stimuli throughout the task.

Following the structure outlined by Babiloni et al. (2004), our experimental paradigm comprised an encoding (ENC) phase followed by a retrieval (RET) phase. During the ENC phase, participants were presented with 50 complex colored magazine pictures displayed sequentially after a red central target acted as a visual warning stimulus for 1 second.

In the ENC phase, participants were instructed to identify whether the picture depicted an interior (indoor) or landscape (outdoor) scene by pressing one of two buttons corresponding to their choice (left = "indoor"; right = "outdoor") as quickly as possible after a green central target appeared at the center of the image, with a presentation time of 5 seconds.

Notably, no explicit mention of a 'retrieval' phase was provided before the encoding phase, adhering to the standard paradigm of 'incidental memory'. Approximately 1 hour later, the RET condition commenced. In this phase, participants were presented with 25 previously viewed outdoor pictures (termed "tests") randomly intermixed with 25 novel outdoor pictures (termed "distractors"). Participants were tasked with distinguishing between "tests" and "distractors" by pressing one of the two buttons with either their right or left index fingers (left = "tests"; right = "distractors") immediately after the appearance of the go stimulus, maintaining the same timing as in the encoding phase. Our task differs from for the original task by Babiloni et al. (2004), as they used interior (indoor) pictures for their retrieval phase.

Prior to the ENC phase, participants underwent a brief training session lasting about 10 minutes, involving a different set of figures to acquaint them with the experimental apparatus and the general procedure employed for the ENC-RET tasks. This training aimed to ensure participants' readiness to respond promptly to visual stimuli by pressing the designated buttons with their right index finger.

3.3 Data Analysis

The initial step in the data analysis process involved the meticulous cleaning of interview data obtained from the language and physical activity questionnaires. Employing an R-Studio script facilitated the identification and rectification of inaccurately entered data. Subsequently, the language data underwent processing to generate Multilingual Diversity (MLD) scores for each participant. The computation of MLD scores drew inspiration from the Language History Questionnaire 3 (LHQ3) proposed by Li et al. (2020). LHQ3 captures comprehensive language background information, including overall language usage and self-reported proficiency across languages. The Language History Questionnaire (Li et al., 2020) was utilized to gather information regarding participants' language usage. To better capture bilingualism in terms of context and diversity, the MLD score provided by the LHQ3 calculator was employed. This score, calculated using Shannon Entropy based on the Proportion of Dominance (PD), offers a nuanced understanding of bilingualism.

However, as outlined by Voits et al. (2024), the MLD score in its current form may not fully align with the social reality of the sample or the specific research interests of the study. For instance, the equal weighting of proficiency relative to usage may obscure variations in language engagement among participants. To address this limitation and tailor the calculations to the research focus, adjustments were made to the weighting and transformation of usage data. Following prior methodologies (Pereira Soares et al., 2021), usage data from additional languages beyond the societal language (L1) were aggregated for each participant. The denominator for PD scores was adjusted to include both societal and non-societal language dominance scores. Additionally, proficiency weighting was set to zero, considering participants' high proficiency in the common non-societal language spoken, such as English, in the Norwegian context where the study was conducted.

The final MLD score calculation provides a score ranging from 0-1, where 0 represents the most extreme cases where a bilingual may be considered functionally monolingual and a score of 1 represents a scenario where a speaker is a balanced bi-multilingual. As a result of these adjustments all participants exhibited a mean of 0.62 (SD = 0.27), providing a more tailored representation of bilingual engagement and facilitating the investigation of its effects on neurocognition.

Following the determination of MLD scores, the International Physical Activity Questionnaire - Short Form (IPAQ-SF) was utilized to compute participants' Physical Activity scores. Adhering to guidelines outlined by the International Physical Activity Questionnaire (2004), activity volume was measured in MET-minutes, factoring in the energy requirements of various activities. IPAQ-SF yields both categorical scores (inactive, minimally active, or HEPA active) and continuous scores expressed as median MET-minutes per week. Standardized data processing rules ensure consistency and accuracy across studies (International Physical Activity Questionnaire, 2004), categorizing participants into Low, Moderate, or High activity levels based on their calculated scores.

Integration of behavioral data from the retrieval task conducted during lab sessions further enriched our dataset. This dataset encompassed responses to each of the 50 tasks, including whether the picture presented during the retrieval task was previously seen or not seen during the encoding task, participant responses, correct answers, and reaction times. Cleaning procedures were applied to this dataset, eliminating participants with missing input answers, indicative of potential user error. Additionally, participants exhibiting over 70% incorrect responses were excluded from the analysis, presumed to have misconstrued the task. Consequently, six participants were excluded from the dataset. Retrieval task statistics after cleaning: mean = 0.72 (SD=0.09)

Utilizing an R-Studio script, the compiled dataset from interview data was merged with task data from the retrieval task. Participants who had completed the interview but not the lab session were identified and excluded, resulting in the removal of 50 participants from the dataset. Ultimately, a comprehensive dataset comprising 172 participants was obtained, primed for in-depth analysis and interpretation.

After data cleaning and merging, participant age was stratified into distinct age groups to facilitate analyses that account for potential age-related effects on cognitive outcomes. This stratification aimed to capture variations in cognitive performance across different life stages. Age ranges were predefined, with participants categorized as "Young (18-35)," "Middle (36-51)," or "Older (52-99)" based on their ages.

Moreover, several data preprocessing steps were undertaken to ensure compatibility with the chosen statistical analyses. Categorical variables, including *Correct, id, sex,* and *ipaq_category,* were coerced into factors to enable appropriate modeling of categorical relationships. This conversion allows for the interpretation of these variables as distinct groups rather than continuous numerical values. Additionally, the *Trial* variable, was also converted to a factor.

Furthermore, continuous variables such as *age*, *mld*, and *ipaq_met_minutes* underwent standardization using the *scale()* function. Standardization rescales variables to have a mean of zero and a standard deviation of one, which facilitates comparisons between variables with different units and magnitudes.

To establish a reference level for categorical variables, the *relevel()* function was employed. For instance, *ipaq_category* and *sex* were re-leveled to have "Low" and "Male" as the reference levels, respectively, allowing for meaningful interpretation of the subsequent model outputs.

Finally, the *Correct* variable, representing participants' responses in the retrieval task, was re-leveled to have "seen" as the reference level. This re-leveling facilitates the interpretation of subsequent model outputs in terms of differences between correctly and incorrectly identified stimuli during the task.

4 Results

The results of the generalized logistic mixed models (GLMMs) are presented below. All analyses were conducted using R Statistical Software (v4.1.2; R Core Team 2021) within the RStudio environment (v2023.12.1+402; Posit team 2024). The GLMM was fitted using the lme4 package (Bates et al., 2015).

4.1 Simple Model with Age Group

We initiated our investigation by employing a generalized logistic mixed-effects model (GLMM) to explore the relationship between cognitive performance, as measured by accuracy (Go.ACC), and age group. The model formulation is represented as follows:

*model_with_age <- glmer(Go.ACC ~ Correct * age_group + (1 | id), family = binomial, data = eegcap_mld)*

In this GLMM, the dependent variable Go.ACC signifies participants' accuracy in the cognitive task, exhibiting a binomial distribution with values of 0 for an incorrect response and 1 for a correct response. The predictors encompass Correct, denoting the correctness of responses, and age_group, which classifies participants into distinct age categories, namely "Young (18-35)," "Middle (36-51)," or "Older (52-99)," based on their ages.

To account for individual-level variability in cognitive performance, random intercepts for subjects (id) were integrated into the model formulation. The GLMM was tailored using the binomial family, aligning with the nature of binary outcome data, and utilized the logit link function to model the relationship between predictors and the probability of a correct response.

Estimation of the model parameters was facilitated through maximum likelihood estimation with Laplace Approximation, a method suited for handling complex models like GLMMs. This approach enabled the extraction of robust estimates for the fixed effects, capturing the associations between predictors and cognitive performance, while considering the inherent variability between subjects.

effect	group	term	estimate	std.error	statistic	p.value
fixed		(Intercept)	0,608	0,087	6,957	0
fixed		Correctnot_seen	1,229	0,116	10,591	0
fixed		age_groupOlder	-0,129	0,11	-1,176	0,24
fixed		age_groupYoung	-0,313	0,107	-2,917	0,004
fixed		Correctnot_seen:age_groupOlder	-0,213	0,143	-1,492	0,136
fixed		Correctnot_seen:age_groupYoung	0,409	0,144	2,837	0,005
ran_pars	id	sd__(Intercept)	0,331			

Table 1

In Table 1, we present the results of the generalized logistic mixed-effects model (GLMM) examining the relationship between performance on the retrieval task accuracy (Go.ACC) and Correct response, as well as age group, while accounting for individual variability (random effects).

The fixed effects estimates reveal significant associations between Go.ACC and Correct response (Estimate = 1.229, z = 10.591, $p < 0.001$), indicating that participants were more likely to correctly respond to the retrieval task when they had previously not seen the stimuli, i.e. correctly rejecting not seen pictures. Additionally, age group showed a significant effect on Go.ACC, with older participants exhibiting lower performance compared to younger participants (Estimate = -0.129, z = -1.176, p = 0.240). However, younger participants showed significantly lower performance compared to the reference group "middle age" (Estimate = -0.313, z = -2.917, p = 0.004).

The inclusion of interaction terms between Correct response and age group further elucidates the relationship. Younger participants demonstrated a significantly higher performance in rejecting not seen stimuli (Estimate = 0.409, z = 2.837, p = 0.005), while there was a non-significant trend towards lower performance for older participants who had not seen the stimuli (Estimate = -0.213, z = -1.492, p = 0.136).

The confidence limits (95% CI) for the fixed effects suggest that the effect of Correct response on Go.ACC is robust and highly significant, with narrow confidence intervals indicating precision in estimation. However, the effect of age group appears to be weaker, with wider confidence intervals suggesting some uncertainty in the estimate.

Furthermore, the random effects standard deviation for the intercept indicates variability between individuals, suggesting that while there is an average effect of Correct response and age group on Go.ACC, there is considerable variability between participants.

The results from Table 1 are visualized below in Figure 1, where the predicted probabilities of accuracy for seen and not seen stimuli are depicted for each age group. In the figure, red represents middle age, blue denotes old, and green signifies young participants. As visualized, participants were significantly more likely to correctly reject not seen stimuli than correctly accept seen stimuli. There is also a slight age effect; however, the confidence levels are low due to individual variability.

In the "not seen" condition, the young group slightly outperformed the middle group in correctly rejecting the not seen stimuli, while the older group performed slightly worse than the other groups. For the "seen" condition, accuracy was highest for the middle group, worst for the young group, while the old group was in the middle of the two. This observation suggests an inverted U-shape effect on episodic memory in aging, wherein performance peaks in middle age and declines slightly in both younger and older age groups.

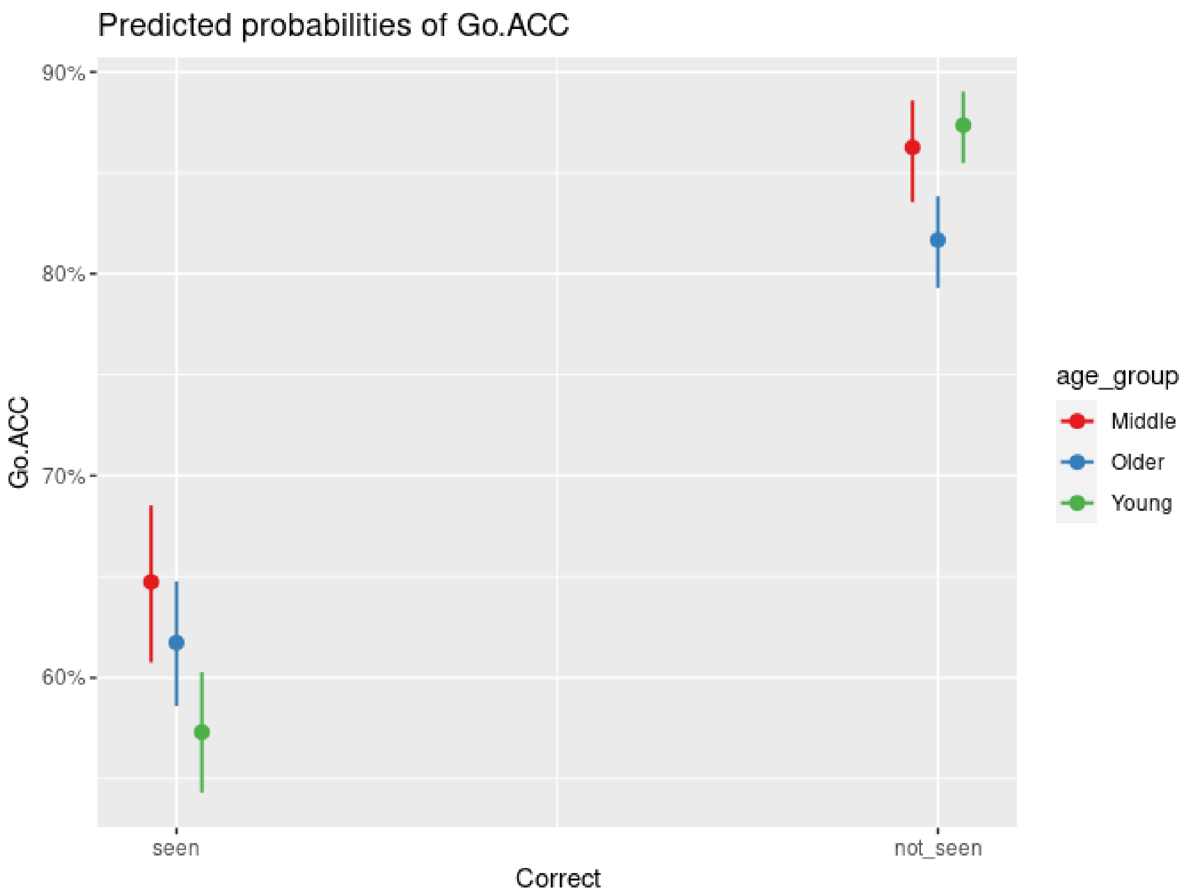

Figure 1

4.2 Model with Interactions

We initiated our exploration of the relationship between physical activity level, multilingual diversity, age, and cognitive performance by fitting a generalized binomial logistic mixed-effects model (GLMM). This model, designated as *model_with_interaction_ipaqmin*, was constructed with the following formulation:

ctrl <- glmerControl(optimizer = "bobyqa")

*model_with_interaction_ipaqmin <- glmer(Go.ACC ~ ipaq_met_minutes * c_mld * c_age * Correct + sex + (1 | id), family = binomial, data = eegcap_mld, control = ctrl)*

In this model, the dependent variable Go.ACC represented the accuracy of participants' responses in the cognitive task. The predictors included ipaq_met_minutes, reflecting participants' physical activity level measured in MET-minutes, c_mld, indicating multilingual engagement, and c_age, representing age. To enhance model convergence, all variables were scaled appropriately. Additionally, the model accounted for the interaction terms between these predictors to discern potential combined effects. Covariates such as Correct and sex were also incorporated to mitigate potential confounding effects. Random intercepts for subjects were included to accommodate individual variability in cognitive performance. The GLMM was fitted using the binomial family and the logit link function. The optimization control parameter ctrl was set to "bobyqa" to facilitate model convergence during estimation.

effect	group	term	estimate	std.error	statistic	p.value
fixed		(Intercept)	0,617	0,105	5,9	0
fixed		ipaq_met_minutes	0,142	0,101	1,413	0,158
fixed		c_mld	0,029	0,088	0,331	0,74
fixed		age_groupOlder	-0,213	0,116	-1,835	0,067
fixed		age_groupYoung	-0,333	0,111	-2,994	0,003
fixed		Correctnot_seen	1,241	0,124	10,016	0
fixed		sexFemale	0,032	0,08	0,395	0,693
fixed		sexNon-binary	0,944	0,542	1,742	0,081
fixed		sexNon-relevant	-0,63	0,456	-1,382	0,167
fixed		ipaq_met_minutes:c_mld	0,027	0,097	0,278	0,781
fixed		ipaq_met_minutes:age_groupOlder	-0,192	0,126	-1,53	0,126
fixed		ipaq_met_minutes:age_groupYoung	-0,157	0,123	-1,275	0,202
fixed		c_mld:age_groupOlder	-0,133	0,114	-1,166	0,244
fixed		c_mld:age_groupYoung	-0,046	0,112	-0,413	0,68
fixed		ipaq_met_minutes:Correctnot_seen	-0,07	0,139	-0,502	0,616
fixed		c_mld:Correctnot_seen	0,136	0,12	1,133	0,257
fixed		age_groupOlder:Correctnot_seen	-0,04	0,158	-0,255	0,799
fixed		age_groupYoung:Correctnot_seen	0,365	0,153	2,376	0,017
fixed		ipaq_met_minutes:c_mld:age_groupOlder	-0,134	0,13	-1,033	0,302
fixed		ipaq_met_minutes:c_mld:age_groupYoung	-0,061	0,12	-0,512	0,608
fixed		ipaq_met_minutes:c_mld:Correctnot_seen	0,068	0,134	0,51	0,61
fixed		ipaq_met_minutes:age_groupOlder:Correctnot_seen	0,228	0,172	1,32	0,187
fixed		ipaq_met_minutes:age_groupYoung:Correctnot_seen	0,188	0,172	1,093	0,275
fixed		c_mld:age_groupOlder:Correctnot_seen	0,173	0,152	1,137	0,256
fixed		c_mld:age_groupYoung:Correctnot_seen	-0,054	0,153	-0,355	0,722
fixed		ipaq_met_minutes:c_mld:age_groupOlder:Correctnot_seen	0,294	0,172	1,703	0,089
fixed		ipaq_met_minutes:c_mld:age_groupYoung:Correctnot_seen	-0,128	0,166	-0,771	0,441
ran_pars	id	sd__(Intercept)	0,316			

Table 2: Results from the interaction between MLD, Physical Activity, Age, and Performance on the Episodic Memory Task.

In Table 2, we present the results of the generalized logistic mixed model (GLMM) examining the relationship between performance on the retrieval task accuracy (Go.ACC) and several predictors. The fixed effects estimates indicate that participants were significantly more likely to respond correctly when they had previously not seen the stimuli (Estimate = 1.241, z = 10.016, $p < 0.001$). However, none of the other predictors, including physical activity (ipaq_met_minutes), multilingualism (c_mld), age (age_groupOlder, age_groupYoung), and sex (sexFemale, sexNon-binary, sexNon-relevant), showed significant effects on Go.ACC. Notably, the predictors (sexNon-binary) and (sexNon-relevant) each consisted of only one participant, limiting the interpretability of their effects.

The confidence limits (95% CI) for the fixed effects suggest that the effect of Correct responses on Go.ACC is robust and highly significant, with narrow confidence intervals indicating precision in estimation. However, for the other predictors, the confidence intervals are wider, indicating greater uncertainty in the estimates. Furthermore, the random effects standard deviation for the intercept indicates variability between individuals, suggesting that while there is an average effect of accuracy on seen and not seen stimuli, there is considerable variation between participants.

It is worth noting that there were some trends toward significance for certain predictor interactions, such as age group “Young” interacting with Correctnot_seen (Estimate = 0.365, z = 2.376, p = 0.017), indicating that younger participants performed significantly better than older participants in correctly rejecting not seen stimuli. However, caution is warranted in interpreting these results due to the relatively low confidence levels and the complexity of the model.

Additionally, the predictors ipaq_met_minutes, c_mld, and their interactions with age group and Correct responses did not demonstrate significant effects on Go.ACC, as evidenced by their p-values exceeding the conventional threshold of 0.05.

Overall, the results from this analysis are that the task worked. The expected effects for episodic memory performance was observed, however the modulatory effects of physical activity, multilingualism, age, and sex on Go.ACC were not statistically significant.

Creating a visualization of a 4-way interaction involves a significant level of complexity and interpretation. In Figure 2, we aim to visualize the interaction effects between age, multilingual diversity (MLD), physical activity (measured in IPAQ Met Minutes), and accuracy in the retrieval task. To achieve this, we first divided the MLD scores into groups using quantiles, allowing us to categorize participants based on their MLD levels.

Upon analysis of the figure, several trends and observations emerge. For middle-aged participants, there is a subtle trend towards higher accuracy with high MLD and high physical activity levels in both conditions. However, for older adults, a more pronounced negative effect of the variables is observed for the "seen" condition, while a positive effect for the "not seen" condition. It's essential to note that all confidence intervals overlap, suggesting that the observed trends should be interpreted with caution, and definitive conclusions should not be drawn solely based on the depicted lines.

Analyzing a 4-way interaction introduces significant complexities. It involves understanding how multiple variables interact simultaneously to influence the outcome, making interpretation challenging. The visualization attempts to capture these complex interactions, but it's essential to recognize that the effects of each variable may vary depending on the levels of other interacting variables. Additionally, the interpretation of such interactions may require further statistical techniques and considerations to fully understand their implications.

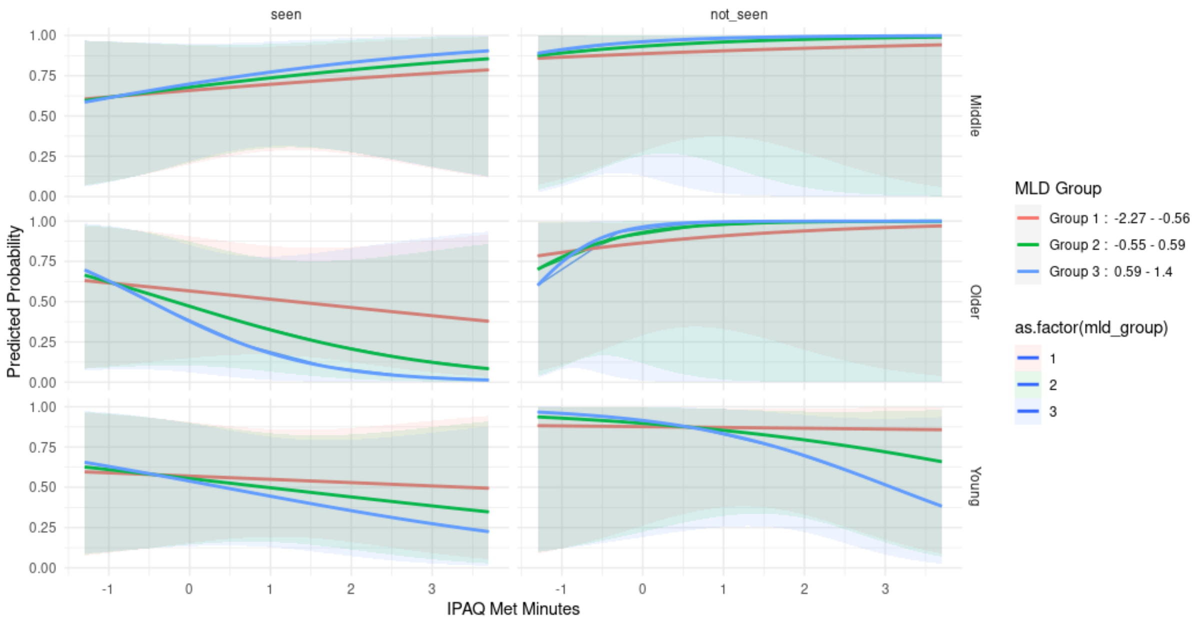

Figure 1: The figure depicts predicted probabilities of accuracy on the y-axis and IPAQ Met Minutes on the x-axis. It is divided into six sections, with three sections on the left representing the "seen" condition for each age group, and three sections on the right representing the "not seen" condition for each age group. Within each section, colored lines represent different MLD groups: orange for low MLD, green for middle MLD, and blue for high MLD. Additionally, confidence intervals are displayed around each line to indicate the uncertainty associated with the estimates.

5 Discussion

In this study, the primary aim was to investigate the effects of bilingualism on episodic memory performance across the lifespan, while also considering the potential influence of physical activity. Motivated by the interest in understanding how bilingualism and physical activity contribute to cognitive health and aging, the study sought to address the following research questions:

Research Question 1: Does bilingual language engagement modify episodic memory performance on a visuo-spatial task across different age groups?

Research Question 2: Does self-reported physical activity influence episodic memory performance on a visuo-spatial task?

Research Question 3: If self-reported physical activity influences episodic memory performance, are the effects additive when considered alongside bilingual engagement?

The predictions formulated for each research question provided a theoretical framework for interpreting the study outcomes. For Research Question 1, it was predicted that bilingual language engagement would significantly affect episodic memory performance, with older participants expected to demonstrate a stronger effect due to cognitive reserve. Conversely, younger participants were anticipated to show less pronounced effects due to potential ceiling effects.

For Research Question 2, it was predicted that physical activity would independently modulate episodic memory performance across different age groups, with older adults deriving greater benefits from regular physical activity due to its established association with cognitive function and reduced risk of age-related cognitive decline.

Regarding Research Question 3, it was predicted that while bilingual engagement and physical activity may act as distinct pathways to enhancing cognitive function, there may not be a direct additive effect on episodic memory performance. Instead, it was posited that each factor independently contributes to cognitive resilience, with the potential for a synergistic effect among older participants experiencing more pronounced cognitive changes with age.

In the subsequent sections, the results of the study will be discussed in light of the research questions and predictions outlined above, considering potential implications for the study, and how it may contribute to understanding cognitive aging and promoting healthy lifestyles.

5.1 Discussion of Results

Taking the results of the study at face value, it becomes evident that the statistically significant finding was that participants were more likely to correctly reject pictures not seen in the encoding phase. There is a slightly significant effect of age on accuracy when participant age is divided into groups. However, none of the variables in the interaction model - age, gender, physical activity, and multilingual engagement - yielded statistically significant results. This discrepancy between the observed results and the predictions made raises important questions about the potential implications of these null findings.

Firstly, the null results suggest that there may be no substantial effect of multilingual engagement, or physical activity on episodic memory, or that any such effects are too small to measure with the current study design and sample size. This challenges the initial hypotheses formulated based on existing literature, which suggested significant relationships between these variables and episodic memory performance.

It is crucial to acknowledge that null results are not indicative of the absence of an effect but rather provide evidence that the effect, if present, may be weaker or more nuanced than initially anticipated. In the context of this study, the null findings underscore the complexity of the relationship between bilingualism, physical activity, and episodic memory, highlighting the need for further investigation using more refined methodologies and or larger sample sizes.

One potential explanation for the null results could be the limited variability in the study sample. The participants in this study were predominantly highly bilingual, with generally high levels of physical activity, reflecting the demographic characteristics of the population from which they were recruited. This lack of variability may have constrained the ability to detect significant effects, particularly if the observed differences in bilingual engagement or physical activity levels were not sufficiently large to influence episodic memory performance.

Furthermore, the study may have been underpowered to detect small or moderate effects, particularly for variables with subtle influences on episodic memory. The sample size and study design may have lacked the sensitivity needed to capture these effects accurately, contributing to the null findings observed.

Another consideration is the specificity of the episodic memory task used in the study. While the task was designed to assess episodic memory performance through a visuo-spatial task, it is possible that the task did not effectively capture the nuances of episodic memory across different age groups. The task may have been insufficiently challenging or lacked ecological validity, limiting its ability to detect meaningful differences in episodic memory performance.

Additionally, methodological limitations, such as measurement error or confounding variables not accounted for in the analysis, could have influenced the study results. Factors such as participant motivation, fatigue, or individual differences in cognitive abilities may have contributed to variability in episodic memory performance, obscuring any underlying effects of bilingualism or physical activity

In the following sections, these implications will be discussed further, exploring the potential factors that might have influenced the null results observed in the study. By scrutinizing limitations, methodological considerations, and theoretical implications, the goal is to develop a comprehensive understanding of the complexities underlying cognitive function and highlighting potential factors that should be considered in further research.

5.2 Age Effect

While there was a slightly significant observed effect of age and accuracy when participants were divided into groups, the absence of a significant relationship between age and episodic memory performance in our study raises important questions about the factors influencing cognitive aging. As highlighted in the theoretical background, aging is commonly associated with declines in cognitive function, particularly in domains such as memory, attention, and executive function (Murman, 2015). Given the robust evidence for age-related cognitive decline, the lack of a significant age effect in our study is noteworthy and warrants careful consideration.

One possible interpretation of our findings is that the effect of age on episodic memory performance may be too subtle to detect within the context of our study. Despite the well-documented nature of age-related cognitive decline, the specific neurocognitive mechanisms underlying these changes remain elusive (Cansino et al., 2018). Age-related alterations in brain structure and function, including reductions in hippocampal volume and changes in neural activity patterns, may contribute to declines in episodic memory function (Park et al., 2002; Rönnlund et al., 2005). However, the extent to which these neurobiological changes translate into observable differences in episodic memory performance may vary across individuals and experimental contexts.

Another possibility is that uncontrolled variables or methodological limitations may have confounded the relationship between age and episodic memory performance in our study. As individuals age, they may experience a myriad of physiological, neurological, and cognitive changes that can influence cognitive function (Amarya et al., 2018). Factors such as health status, education level, cognitive reserve, and genetic predispositions may interact with age to modulate episodic memory performance (Scahill et al., 2003). Moreover, methodological factors such as task sensitivity, sample characteristics, and statistical power may influence the detection of age-related effects in cognitive aging research.

Additionally, it is conceivable that the episodic memory task employed in our study may not have been sufficiently sensitive to detect age-related differences in memory performance. Episodic memory tasks vary in their demands on cognitive processes such as encoding, consolidation, and retrieval, and may differ in their sensitivity to age-related changes (Tulving, 1983). While our task aimed to assess episodic memory using a visuo-spatial paradigm, it is possible that other types of memory tasks or experimental paradigms may be better suited to capture age-related differences in memory performance.

5.3 Task implications

The episodic memory task employed in our study, inspired by the experimental design proposed by Babiloni et al. (2004), aimed to assess memory performance across different age groups. The task consisted of an encoding phase followed by a retrieval phase, wherein participants were presented with complex colored magazine pictures during the encoding phase and subsequently tested on their ability to distinguish between previously viewed and novel pictures during the retrieval phase. Despite its adherence to established paradigms of incidental memory, our task may have exhibited limitations in detecting subtle differences in memory performance, particularly in the context of healthy aging.

The study by Korkki et al. (2020) sheds light on the importance of task difficulty in assessing episodic memory performance, particularly in older adults. They found that declines in memory precision were evident across different types of information retrieved from long-term memory, suggesting that decreases in memory precision may be a consistent feature of age-related memory decline. However, significant age-related decreases in the probability of successful memory retrieval were observed only in conditions with higher task difficulty, highlighting the differential sensitivity of memory processes to age-related cognitive decline.

Our task may have faced challenges related to task specificity and methodological constraints that could have influenced its effectiveness in capturing age-related differences in episodic memory performance. For instance, the task design did not explicitly mention a retrieval phase before the encoding phase, potentially affecting participants' encoding strategies and subsequent memory retrieval processes. Moreover, the task may not have been sufficiently challenging to detect subtle differences in memory performance across age groups, as evidenced by the lack of significant findings for age-related effects.

Furthermore, the task may have lacked sensitivity to detect age-related changes in memory precision, particularly in the absence of explicit manipulations of task difficulty. Previous research has highlighted the importance of incorporating sufficiently challenging tasks to measure episodic memory accurately, especially in older adults, who may exhibit declines in memory precision with healthy aging (Korkki et al., 2020). Therefore, future research endeavors should consider refining task designs to enhance their sensitivity to age-related changes in memory performance and to better capture the nuances of episodic memory processes across the lifespan.

5.4 Measures from Self-Report Questionnaires

In assessing the reliability of measures, it's crucial to consider the use of self-report questionnaires, which offer both advantages and disadvantages in psychological research. One significant advantage of self-report questionnaires is their practicality and efficiency in gathering data from a large sample of individuals quickly and at minimal cost (Demetriou et al., 2015). By enabling the collection of quantitative data, self-report questionnaires facilitate the generalization of findings, especially when samples are collected randomly. Moreover, because respondents provide information about their own experiences and behaviors, self-report questionnaires often yield more accurate data compared to observations or reports from external sources.

However, despite their utility, self-report questionnaires are not without limitations. One major concern is the potential for respondents to provide invalid answers, either due to social desirability bias or response biases (Demetriou et al., 2015). Respondents may feel compelled to respond in a socially acceptable manner or may exhibit a tendency to respond in a certain way regardless of the content of the question. Additionally, issues related to the clarity of questionnaire items and the lack of flexibility in fixed-choice questions can affect the reliability and validity of self-report measures.

Despite these potential limitations, self-report questionnaires remain a valuable tool for collecting data, providing researchers with insights into individuals' thoughts, feelings, and behaviors. In the following section, we will examine the specific self-report questionnaires utilized in our study, considering their reliability and validity in assessing multilingual engagement and physical activity levels.

5.4.1 MLD

Several potential limitations emerge when considering the reliability of the LHQ3 questionnaire and the calculated MLD score as self-report measurements of multilingual engagement. While these tools offer valuable insights into participants' language background and proficiency, there are notable challenges in accurately capturing multilingual engagement solely through self-report methods.

Relying solely on self-report measures may only partially capture the complexity of multilingual engagement. While the LHQ3 questionnaire and MLD score aim to quantify language diversity, usage patterns and adjust weighting, and transformation of parameters to better align with research interests and sample characteristics (Voits et al., 2024), the measurements may not fully align with the social reality of the sample or the specific research interests of the study.

Moreover, self-report measures may be subject to interpretation biases and response inconsistencies. Participants may interpret questionnaire items differently, leading to variability in their responses and potentially affecting the reliability of the data collected (Demetriou et al., 2015).

While objective measures such as language proficiency tests could provide more accurate assessments of multilingual engagement, they may primarily assess proficiency rather than engagement. Testing participants' language abilities may not fully capture their day-to-day language use and engagement in different linguistic contexts.

Despite these limitations, the MLD score derived from the LHQ3 questionnaire remains a valuable tool for assessing multilingual engagement. While self-report measures have inherent limitations, they still offer a practical and accessible means of assessing multilingual engagement, particularly in large-scale studies where objective measures may be impractical or costly.

5.4.2 IPAQ-SF

When assessing the validity of measures from the International Physical Activity Questionnaire Short Form (IPAQ-SF), particularly regarding the age range and reliability, it is crucial to consider potential limitations and biases inherent in self-report methods. The IPAQ-SF is designed for adults aged 15-69 and aims to capture physical activity across various domains. Notably, our study included participants up to 82 years old. While the questionnaire provides valuable insights into participants' activity levels, there are challenges associated with its validity and reliability.

One potential limitation is the high likelihood of response bias in self-report measures of physical activity. People tend to overestimate their physical activity levels due to social desirability bias or simply because they perceive themselves to be more active than they truly are (Prince et al., 2008). This bias could impact the accuracy of the data obtained from the IPAQ-SF, particularly if participants inaccurately report their activity levels.

Moreover, the reliability of self-reported physical activity measures, such as the IPAQ-SF, may vary depending on the population studied and the methods used for data collection. While the IPAQ-SF offers standardized data processing rules to ensure consistency across studies, there may still be discrepancies in participants' interpretations of questionnaire items and their ability to recall activity levels accurately over time (Prince et al., 2008).

In the systematic review by Prince et al. (2008) examined the relationship between self-report and directly measured estimates of physical activity in adults. The review identified potential biases and inconsistencies in the studies included, highlighting the challenges associated with comparing self-report measures to direct methods of assessing physical activity. While some studies found reasonable agreement between self-report and direct measures, others reported discrepancies, particularly in capturing higher intensity physical activities.

5.5 Physical activity and cognition

The literature on the effect of physical activity on cognition provides substantial evidence supporting the importance of regular exercise for healthy aging. Physical activity has been consistently associated with better cognitive performance and a reduced risk of age-related cognitive decline and dementia. Cross-sectional and cohort studies have demonstrated that individuals who engage in regular physical activity tend to exhibit superior cognitive function, particularly in domains such as memory, attention, and executive function (Colcombe et al., 2004; Kramer et al., 1999; Smiley-Oyen et al., 2008; Voelcker-Rehage et al., 2011). Moreover, longitudinal cohort studies have highlighted the long-term benefits of physical activity, showing that maintaining an active lifestyle, especially during midlife, is associated with larger gray matter volume in later life and a reduced risk of dementia (Rovio et al., 2010).

The theoretical background emphasizes the mechanisms through which physical activity influences cognition, including the promotion of neuroplasticity and improvements in cardiovascular fitness. These mechanisms contribute to the maintenance of brain health and function, supporting processes such as neurogenesis, synaptogenesis, and cerebral blood flow, which are essential for optimal cognitive performance (van Praag et al., 2000; Erickson et al., 2011). Intervention studies have further corroborated these findings, demonstrating that chronic exercise programs, such as aerobic training, can improve various cognitive domains, including memory (Hayes et al. 2015).

However, it is important to consider recent evidence from an umbrella review conducted by Ciria et al. (2022), which reanalyzed 24 meta-analyses of randomized controlled trials (RCTs) examining the effects of physical exercise on cognition. The review found inconclusive evidence supporting the existence of a significant cognitive benefit derived from regular physical exercise in healthy populations. Despite the vast body of literature on this topic, the review suggests that the effect of exercise on cognition reported in previous meta-analytic reviews may have been overestimated, and the available causal evidence from RCTs is far from conclusive.

The umbrella review raises important considerations regarding the quality and reliability of evidence in the exercise-cognition literature. It highlights methodological and theoretical issues, such as the use of underpowered RCTs and potentially biased meta-analyses, which may have contributed to the inconsistent findings observed across studies. Furthermore, the absence of a firm theoretical model explaining the mechanisms underlying exercise-induced cognitive improvements in humans underscores the need for further research in this area.

In light of these findings, it is essential to approach the relationship between physical activity and cognition with caution. While the theoretical rationale and observational evidence support the potential cognitive benefits of regular exercise, the lack of robust evidence from RCTs calls for a critical reevaluation of existing findings. The inconclusive nature of the evidence suggests that null results from studies investigating the relationship between physical activity and episodic memory, such as the one discussed, may not be entirely surprising given the current state of the literature. Further research incorporating rigorous study designs and addressing methodological limitations is needed to elucidate the true nature of the relationship between physical activity and cognition.

5.6 Participants

The lack of diversity in the participant sample may have contributed to the null results observed in the study. The homogeneous nature of the sample population, consisting of Norwegian L1 English L2 speakers, limits the variability in participants' language backgrounds. As all participants completed a 1–2-hour interview in English, indicating a high level of bilingual proficiency, the baseline level of bilingualism may have been too high to detect significant effects related to bilingual engagement.

Furthermore, Norway's sociocultural context as an egalitarian society may have influenced the study outcomes. In such a context, where there are minimal differences in socio-economic factors and general health among individuals, the observed effects of variables such as bilingual engagement and physical activity on cognitive function may have been attenuated. The lack of variation in these factors within the participant sample could have masked potential associations between bilingualism, physical activity, and episodic memory performance.

However, the egalitarian nature of the Norwegian society could also be interpreted as an argument for expecting a more pronounced effect of the variables under investigation. In societies with fewer disparities in socio-economic status, health, and access to education, subtle differences in factors such as bilingual engagement and physical activity may have a greater impact on cognitive outcomes. With fewer confounding variables related to socio-economic disparities, the effects of bilingual engagement and physical activity on cognitive function might be more readily apparent. Therefore, the lack of significant findings in the study despite the homogeneous nature of the sample population suggests that other factors, such as the complexity of the cognitive tasks or individual differences in cognitive reserve, may also play a significant role in shaping cognitive outcomes.

5.7 Future directions

Moving forward, several considerations should be taken into account to advance our understanding of the complex relationships between bilingualism, physical activity, and episodic memory performance across the lifespan.

Multiple Task Paradigms: Incorporating multiple episodic memory tasks with varying levels of complexity and cognitive demands could provide a more comprehensive assessment of memory function across different age groups. By utilizing a battery of tasks that tap into different aspects of episodic memory, such as verbal recall, spatial recognition, and associative memory, researchers can better capture the nuances of memory performance and elucidate age-related differences more effectively.

Enhanced Measurement Tools: Improving the reliability and validity of measurement tools used to assess bilingual engagement and physical activity is essential for obtaining accurate data. While self-report questionnaires offer practical advantages in data collection, supplementing these measures with objective assessments, such as language proficiency tests and accelerometers, can enhance the robustness of findings and provide a more nuanced understanding of participants' language abilities and activity levels.

Longitudinal Designs: Longitudinal studies that track individuals over time can provide valuable insights into the trajectory of cognitive aging and the longitudinal effects of bilingualism and physical activity on cognitive function. By following participants from midlife into older age, researchers can examine how changes in language use and activity patterns influence cognitive outcomes longitudinally, offering a more dynamic perspective on cognitive aging processes.

Intervention Studies: Implementing intervention studies that target bilingual engagement and physical activity interventions can elucidate the causal relationships between these factors and episodic memory performance. Randomized controlled trials that assign participants to bilingual language training programs or exercise regimens and assess their effects on cognitive outcomes can provide stronger evidence for the potential benefits of these interventions in promoting cognitive health and resilience.

Consideration of Cultural and Societal Factors: Recognizing the influence of cultural and societal factors on cognitive aging is crucial for interpreting study findings and generalizing results across diverse populations. Cultural differences in language use, social norms surrounding physical activity, and access to resources may impact the relationships between bilingualism, physical activity, and cognitive function. Therefore, studies should strive to include diverse participant samples that represent a range of cultural backgrounds and socio-economic contexts to ensure the generalizability of findings.

By adopting a multi-faceted approach that integrates diverse methodologies, longitudinal perspectives, and cultural considerations, future research can advance our understanding of the intricate interplay between bilingualism, physical activity, and episodic memory across the lifespan. By addressing methodological limitations, refining measurement tools, and embracing the complexity of cognitive aging processes, researchers can pave the way for more comprehensive insights into cognitive health and aging.

6 Conclusion

This study set out to explore the intricate interplay between bilingualism, physical activity, and episodic memory performance across different age groups. Through the application of generalized linear mixed-effects models (GLMMs) and rigorous statistical analyses, we aimed to address several key research questions concerning the influence of bilingual language engagement and physical activity on cognitive health and aging.

Our findings showed that participants were more likely to correctly reject not seen stimuli in the retrieval task, and older participants exhibited lower performance compared to younger participants when divided into age groups. However, the model incorporating interaction effects between physical activity level, multilingual diversity, age, and cognitive performance did not yield significant results for most predictors, suggesting a more nuanced relationship between these variables.

The discussion section further contextualized these findings, exploring potential explanations for the observed results and discussing implications for future research. We addressed methodological considerations, such as task specificity and participant characteristics, that may have influenced the study outcomes. Additionally, we examined the limitations of self-report measures in capturing multilingual engagement and physical activity levels, emphasizing the need for more refined methodologies in future studies.

Despite the nuanced findings and methodological limitations, this study contributes to the ongoing discourse on cognitive aging and cognitive reserve. By highlighting the complexities of the relationship between bilingualism, physical activity, and episodic memory, our findings underscore the importance of considering individual differences and contextual factors in understanding cognitive function across the lifespan.

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Appendix

effect	group	term	estimate	std.error	statistic	p.value
fixed		(Intercept)	0,608	0,087	6,957	0
fixed		Correctnot_seen	1,229	0,116	10,591	0
fixed		age_groupOlder	-0,129	0,11	-1,176	0,24
fixed		age_groupYoung	-0,313	0,107	-2,917	0,004
fixed		Correctnot_seen:age_groupOlder	-0,213	0,143	-1,492	0,136
fixed		Correctnot_seen:age_groupYoung	0,409	0,144	2,837	0,005
ran_pars	id	sd__(Intercept)	0,331			

Table 1. Generalized logistic mixed-effects model with accuracy and age group.

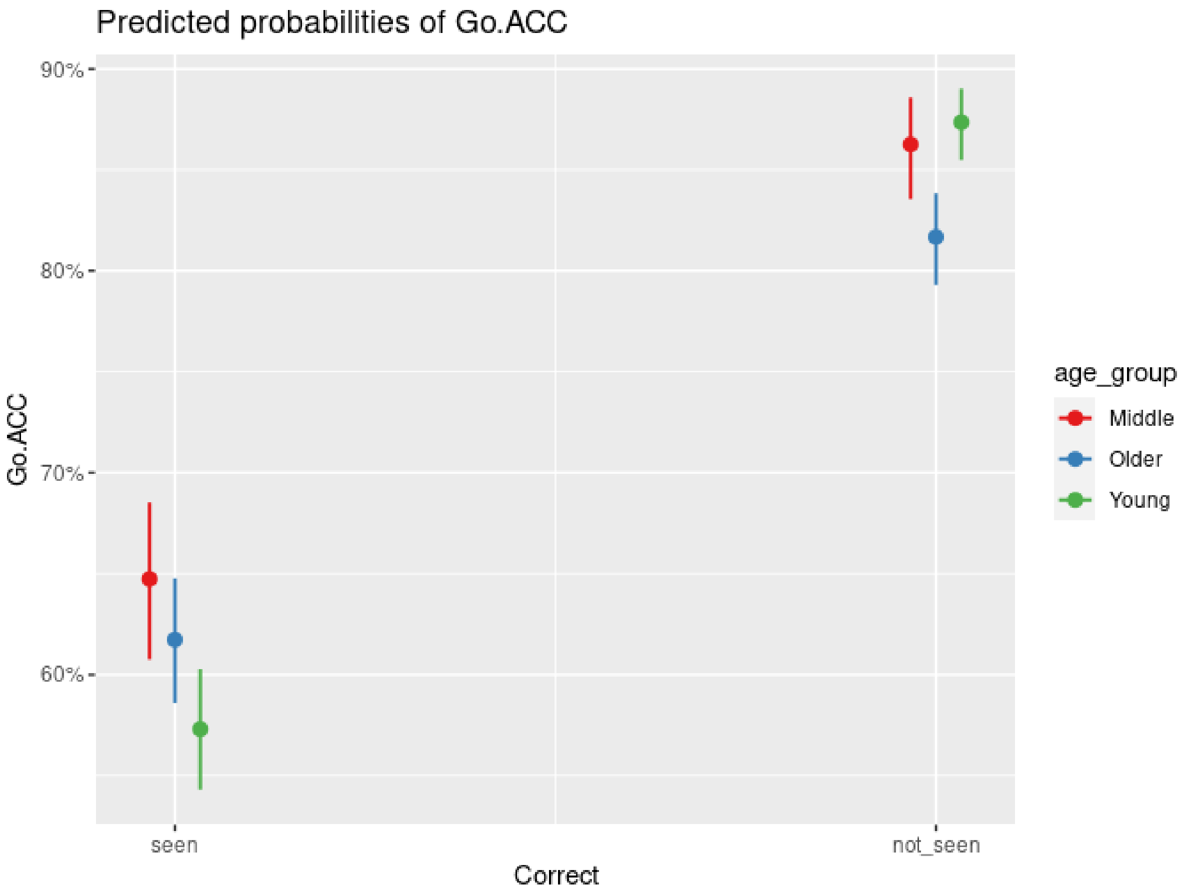

Figure 2. Visualization of the results from Table 1

effect	group	term	estimate	std.error	statistic	p.value
fixed		(Intercept)	0,617	0,105	5,9	0
fixed		ipaq_met_minutes	0,142	0,101	1,413	0,158
fixed		c_mld	0,029	0,088	0,331	0,74
fixed		age_groupOlder	-0,213	0,116	-1,835	0,067
fixed		age_groupYoung	-0,333	0,111	-2,994	0,003
fixed		Correctnot_seen	1,241	0,124	10,016	0
fixed		sexFemale	0,032	0,08	0,395	0,693
fixed		sexNon-binary	0,944	0,542	1,742	0,081
fixed		sexNon-relevant	-0,63	0,456	-1,382	0,167
fixed		ipaq_met_minutes:c_mld	0,027	0,097	0,278	0,781
fixed		ipaq_met_minutes:age_groupOlder	-0,192	0,126	-1,53	0,126
fixed		ipaq_met_minutes:age_groupYoung	-0,157	0,123	-1,275	0,202
fixed		c_mld:age_groupOlder	-0,133	0,114	-1,166	0,244
fixed		c_mld:age_groupYoung	-0,046	0,112	-0,413	0,68
fixed		ipaq_met_minutes:Correctnot_seen	-0,07	0,139	-0,502	0,616
fixed		c_mld:Correctnot_seen	0,136	0,12	1,133	0,257
fixed		age_groupOlder:Correctnot_seen	-0,04	0,158	-0,255	0,799
fixed		age_groupYoung:Correctnot_seen	0,365	0,153	2,376	0,017
fixed		ipaq_met_minutes:c_mld:age_groupOlder	-0,134	0,13	-1,033	0,302
fixed		ipaq_met_minutes:c_mld:age_groupYoung	-0,061	0,12	-0,512	0,608
fixed		ipaq_met_minutes:c_mld:Correctnot_seen	0,068	0,134	0,51	0,61
fixed		ipaq_met_minutes:age_groupOlder:Correctnot_seen	0,228	0,172	1,32	0,187
fixed		ipaq_met_minutes:age_groupYoung:Correctnot_seen	0,188	0,172	1,093	0,275
fixed		c_mld:age_groupOlder:Correctnot_seen	0,173	0,152	1,137	0,256
fixed		c_mld:age_groupYoung:Correctnot_seen	-0,054	0,153	-0,355	0,722
fixed		ipaq_met_minutes:c_mld:age_groupOlder:Correctnot_seen	0,294	0,172	1,703	0,089
fixed		ipaq_met_minutes:c_mld:age_groupYoung:Correctnot_seen	-0,128	0,166	-0,771	0,441
ran_pars	id	sd__(Intercept)	0,316			

Table 2. Generalized logistic mixed-effects model with interaction of variables.

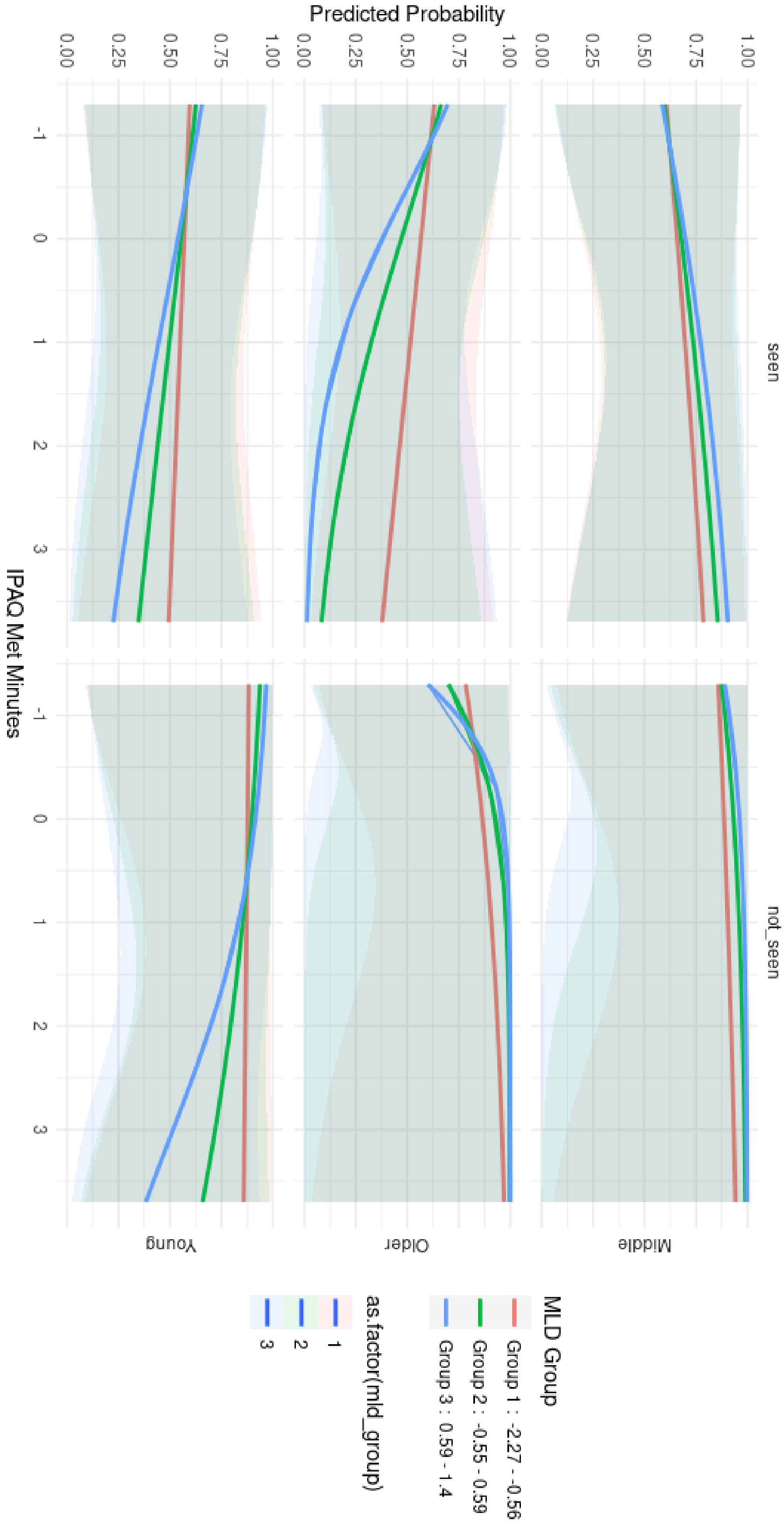

Figure 2 Visualization of the 4-way interaction.