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Degree of multilingual engagement modulates resting state oscillatory activity across the lifespan

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ABSTRACT

Multilingualism has been demonstrated to lead to a more favorable trajectory of neurocognitive aging, yet our understanding of its effect on neurocognition across the lifespan remains limited. We collected resting state EEG recordings from a sample of multilingual individuals across a wide age range. Additionally, we obtained data on participant multilingual language use patterns alongside other known lifestyle enrichment factors. Language experience was operationalized via a modified multilingual diversity (MLD) score. Generalized additive modeling was employed to examine the effects and interactions of age and MLD on resting state oscillatory power and coherence. The data suggest an independent modulatory effect of individualized multilingual engagement on age-related differences in whole brain resting state power across alpha and theta bands, and an interaction between age and MLD on resting state coherence in alpha, theta, and low beta. These results provide evidence of multilingual engagement as an independent correlational factor related to differences in resting state EEG power, consistent with the claim that multilingualism can serve as a protective factor in neurocognitive aging.

1. Introduction

Throughout the human lifespan, neurocognition follows a developmental trajectory of dynamic physiological changes as the brain develops, matures, and eventually declines (Hedman et al., 2012). Following rapid development throughout infancy and childhood comes a relatively asymptotic plateau throughout the early and middle adulthood, with an accelerated downturn in late adulthood - measurable as both structural and functional changes of the brain and decline across multiple domains of cognition (Bethlehem et al., 2022; Craik and Bialystok, 2006). Crucially, the trajectory of these changes is not predicted solely by chronological age. Instead, amassing research shows that relative brain functioning is characterized by inter-individual variability in the trajectory of pathological and non-pathological decline across both cognitive and neural domains (Reuter-Lorenz and Park, 2014). Some individuals maintain high levels of cognition even in very advanced age, while others exhibit cognitive decline at an expected, or even accelerated, rate (Hoogendijk et al., 2016; Raz and Rodrigue, 2006).

Although not universally accepted[1] (e.g., Nilsson and Lövdén, 2018), an influential approach to explaining this heterogeneity in aging trajectories is the concept framework of reserve and resilience (Stern et al., 2020). According to this framework genetic factors and lifetime experiences contribute to increased longevity and lower rate of age- or

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[1] Notwithstanding discussion/debate, herein we adopt a reserve framework for two reasons. Firstly, within the neurocognition of aging and multilingualism literature such an approach is (essentially) universally adopted. Secondly, and not unrelated to the first point, this approach provides a solid basis for hypothesizing and interpretation that aligns well with the proposed mechanisms and general discussion of how and why multilingual engagement can, under specific conditions, result in neurocognitive adaptations. As such, it provides, in our view, the best approach presently available for framing the present study.

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disease-related neurocognitive decline in some individuals. The mechanisms underlying neurocognitive resilience are hypothesized to include 'cognitive reserve' (a property of the brain that allows for better-than-expected cognitive performance when brain injury or disease is present), 'brain maintenance' (relative absence of changes in neural resources over time, resulting in a maintained neurocognition in the older age) and 'brain reserve' (the status of neural resources at any given point of time) (Stern et al., 2023). Herein, we will not distinguish between different mechanisms of reserve and resilience and, henceforth, refer to this concept as 'reserves' - referring to the general capacity of the brain to maintain function with increasing chronological age.

Indeed, research has shown that lifestyle enrichment factors such as high educational and occupational attainment (Darwish et al., 2018), healthy dietary patterns (Clare et al., 2017), sustained physical exercise (Eckstrom et al., 2020), and good social health (i.e., participation in an active social life) (Maddock et al., 2023; Vernooij-Dassen et al., 2022) contribute to neurocognitive outcomes that lend themselves to an interpretation of increased reserves in the older age (see Supplementary material "1. The effects of lifestyle on neurocognitive aging" for an overview of environmental factors and lifestyle choices/experiences other than multilingualism contributing to increased neurocognitive longevity, focusing on those considered in the present study). There is now a critical mass of research suggesting that multilingualism is also a factor that can lead to such neurocognitive adaptations (Anderson et al., 2020; Gallo et al., 2022). For example, studies have claimed multilingualism to be associated with maintenance of brain structure (Abutalebi et al., 2014; Anderson et al., 2018; DeLuca and Voits, 2022), increased functional efficiency (Anderson et al., 2021; Calvo et al., 2023; Gold et al., 2013), delayed onset of cognitive decline (Berkes et al., 2021) and a comparatively later manifestation of dementia symptoms (Alladi et al., 2013; Craik et al., 2010; Perani et al., 2017).

Previous investigations in the field of multilingualism and aging have mostly relied on structural neuroimaging methods. However, in complement, spontaneous neural activity has also been highlighted as a crucial part of estimating brain function and a powerful tool to examine reserve and resilience in healthy and pathological aging (Jauny et al., 2022). One way to tap into this estimation of neurocognition is by investigating resting state functional brain rhythms with electroencephalography (EEG), a method well-suited for the investigation of macroscopic function of neural networks. At rest, the brain generates spontaneous electrical activity that can be divided into bands, based on oscillatory frequency (delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), gamma (30–45 Hz) (Buzsaki, 2006). Resting state oscillatory activity fluctuates over longer periods of time (e.g., with increasing age), but is remarkably stable over shorter ones (Anderson and Perone, 2018; Meghdadi et al., 2021). As spectral power – synchronization within the brain – and coherence – interactions between distinct brain regions (or electrodes) – have been associated with multiple aspects of cognitive ability, one can view resting state oscillatory activity as a proxy biomarker for overall (neuro)cognitive status (Ferrari-Díaz et al., 2022; Fleck et al., 2017).

Similar to other aspects of neurocognition, neural activation patterns at rest captured with resting state EEG (rs-EEG) are also subject to age-related differences. Physiological aging is typically associated with general slowing of rs-EEG activity, marked power decreases across lower frequency bands – delta, theta, and alpha – (Anderson and Perone, 2018; Ishii et al., 2017), and also slowing of individual alpha peak frequency (IAPF) (Cesnaite et al., 2023; Stacey et al., 2021). Oscillations are most susceptible to slowing with increased age in the alpha frequency band, especially in the upper alpha band frequencies (10–12 Hz) (Scally et al., 2018). Overall, delta and theta oscillations have been reported to decrease in healthy older individuals (Vlahou et al., 2014), where comparatively higher delta and theta power is suggested to be indicative of maintained neurocognitive function (Ishii et al., 2017). With regards to cognition, power within alpha rhythms reflects intelligence, memory, and global cognitive status (Klimesch, 1999). Perhaps more importantly, higher levels of alpha power in the later years are associated with less cognitive decline (Anderson and Perone, 2018). Theta band power is positively associated with performance across domains of verbal recall, perceptual speed, working memory, executive functioning and attention in healthy older individuals and has also been suggested to act as a biomarker for healthy aging (Finnigan and Robertson, 2011; Vlahou et al., 2014)

Despite its informative potential for a series of questions related to the neurocognition of multilingualism at any age, the effect of multilingual language experience on resting state brain activity is as new as it is scant. The existing literature primarily targets healthy young adults and employs fMRI, thus shaping our understanding about the fingerprints multilingual experience can leave on structural and functional connectivity across different brain networks (Berken et al., 2016; Grady et al., 2015; Gullifer et al., 2018). To our knowledge, only two studies have investigated how the bi-/multilingual experience shapes the rs-EEG oscillatory signature. First, a study by Bice et al. (2020) found an association between bi-/multilingualism and greater alpha power in the posterior areas of the scalp in young adults, linking this finding to increased language control demands in the bi-/multilingual participants. The same study found correlations between native language proficiency and bilateral power in the beta frequency band, as well as theta power in the left hemisphere. In terms of coherence, Bice et al. (2020) reported greater coherence in alpha and beta frequency bands, specifically, between posterior regions extending across the head in the alpha band, and from posterior regions with stronger connections to the right hemisphere in the beta frequency band. Second, Pereira Soares et al. (2021) expanded on the above findings by testing the effects of continuous measures of bi-/multilingual experience in a sample of bi-/multilinguals with diverse language experience, and found that age of first significant bi-/multilingual exposure negatively predicted power in the high beta and gamma frequency bands. That is, the earlier the onset of bi-/multilingualism, the higher the resting state power in high beta and gamma. As for coherence Pereira Soares and colleagues found a main effect of non-societal language use (use of languages other than the societally dominant language of the environment, in their case Italian and/or English in Germany) in the theta band. That is, increased use of the non-societal language positively correlated to global coherence. They also report a main effect of age of acquisition in high beta, suggesting a globally increased coherence with earlier onset of bi-/multilingualism. Moreover, their data showed coherence between individual brain region pairings being modulated by age of bi-/multilingualism onset (in gamma), self-rated proficiency in the societal language (in alpha and theta), non-societal language exposure at home (in alpha), and non-societal language exposure in society/community (in alpha and theta).

It is worth noting that the two above studies do not target older aged adults *per se*, nor do they present coverage of the lifespan. While research combining electrophysiology, multilingualism, and aging, is exceedingly rare and no examples with rs-EEG exist, there is a single study using magnetoencephalography (MEG), which is contextually relevant for the present study. de Frutos-Lucas et al. (2020) found greater functional connectivity in bilingual over monolingual healthy older individuals across occipital regions in theta and beta frequency bands. Promising as the results are, the measurement of and thus qualification of individuals as monolinguals versus bilinguals was essentially categorically based on a small set of questions determining if an individual reported speaking only Spanish or, additionally, a language other than Spanish. Thus, the study did not delve into any continuous measurement of bi-/multilingual experience as a modulating factor.

To summarize, multilingual experience can be considered as a lifestyle enrichment factor leading to neurocognitive adaptations interpreted as increases in reserves in the older age (Gallo et al., 2022; Perani and Abutalebi, 2015). It has also been shown to contribute to shaping neural oscillatory patterns at wakeful rest (Bice et al., 2020; Pereira Soares et al., 2021). However, linking the two remains an open gap in the literature. As noted, there are presently no studies showing multilingual effects on resting state oscillatory signature across a wider age range, despite there being good reasons for linking the literatures spanning bi-/multilingualism, neural oscillations, and aging to advance our understanding about the nature of the reserves that can be attributed to multilingualism and language experience. Moreover, multilingualism research, inclusive of all the studies discussed in this section, has typically not collected nor considered data on other relevant lifestyle factors for reserves (just as studies focusing on other lifestyle factors do not report or collect data on individuals' language status). Given the potential for interactions and/or obscuring effects as a result, this practice reflects an unfortunate state of affairs for understanding the dynamics, relative contributions and interactions of lifestyle experiences in any domain (Rothman, 2024; Voits et al., 2022). By bridging these gaps, the present study embodies a first attempt to fill several gaps simultaneously.

Lastly, multilingualism should not be viewed or operationalized as a dichotomous group-categorizing factor. Rather it should be considered as a "spectrum" of experiences, as has been the establishing trend in the literature (DeLuca et al., 2019; Gullifer and Titone, 2020; Luk and Bialystok, 2013; Titone and Tiv, 2022). The benefit of this, more nuanced, approach is the finding that various exponents of multilingualism (e.g., duration of multilingual experience, intensity and diversity of language use) contribute differentially to neurocognitive adaptations (see DeLuca et al., 2020, for a comprehensive model). Given this, the field is increasingly more focused on multilingual-to-multilingual individual differences. This shift has resulted in much work eschewing the traditional bi-/multilingual-to-monolingual comparison, avoiding comparative fallacy issues, and increasing ecological validity by replacing it with analyses designed to relate meaningful multiple language experience with individual outcomes (De Houwer, 2023; Luk and Rothman, 2022; Rothman et al., 2023).

Herein, we propose the first investigation of the effects of multilingual experience on resting state brain function across a wide age range in active multilinguals with varying language use patterns. We employ multilingual engagement (diversity of context-based language use – see section 'Quantification of multilingual language engagement' below) as the independent variable, based on an entropy measure of multilingualism (Gullifer and Titone, 2020; Li et al., 2020). While the effects of multilingualism remain our primary interest, we also control for other lifestyle factors known to contribute to reserves in order to disentangle the individual contributions of multilingual experience. Building upon insights from previous literature, our overarching research question can broadly be defined as such: Does multilingual experience modulate cross-sectional age-related differences in resting state brain activity when other reserve contributor factors are controlled for? More specifically we are interested in answering the following research questions (1) Does multilingual engagement modulate cross-sectional age-related differences of individual alpha peak frequency (IAPF)?; (2) Does multilingual engagement modulate cross-sectional age-related differences in EEG spectral power in alpha and theta frequency bands?; and (3) Does multilingual engagement modulate resting state coherence across the lifespan? We put forward the following hypotheses: (1) We expect multilingual experience to modulate any potential correlation between age and whole head IAPF; (2) We expect multilingual experience to modulate any potential correlations between age and whole-head alpha and theta power; and (3) we predict that multilingual engagement will non-linearly interact with age for resting state coherence outcomes across theta, alpha, beta, and gamma bands.

2. Material and methods

2.1. Participants

Data was collected from 137 bi-/multilingual individuals across a wide age range (Age range = 18–82; $\text{Age}_{\text{Mean}} = 46.49$; SD = 18.27; 99 female; for density plot showing the distribution of participant age see Supplementary material) who converged on Norwegian as either their first or one of their first languages. All participants were also proficient users of English. Most participants reported having had experience and exposure to more than 2 languages (N = 108). Prior to inclusion in the study, participants were screened for any history of traumatic brain injury, neurological disorders, and current use of any psychotropic medication. All participants included in the study were cognitively healthy individuals resident in Norway at the time of testing.

2.2. Study procedure

Data collection took place over two sessions. In the first session, administered either over the phone or as a video call, the participants provided informed consent and were screened for eligibility for the study. Then, a semi-structured interview was carried out in English to collect data on participants' language background and patterns of language use, social health and extent of social networks, physical activity, and dietary patterns based on the Language History Questionnaire 3.0 (Li et al., 2020), Social Network Index (Cohen, 1997), Short Form International Physical Activity Questionnaire (Craig et al., 2003), and Short Form Food Frequency Questionnaire (Cleghorn et al., 2016), respectively.

The second session was conducted in-person in a designated laboratory, with Norwegian as the language of communication. During this session, participants completed the Cognitive Reserve Scale (Leoń et al., 2014) capturing lifetime engagement in a cognitively active lifestyle and the Norwegian version of the Mini-Mental State Examination (MMSE; Folstein et al., 1975; Strobel and Engedal, 2008) as an estimation of general cognition and a screening tool for any cognitive impediment. All participants scored above the cut-off of 24 in MMSE, indicating no suspected cognitive impairment. The MMSE scores were not included in any further data analysis as most participants performed at ceiling. Participants also took part in a resting state EEG recording. Five minutes of task-free eyes-closed EEG data was recorded while the participants were sitting in a sound-attenuated room.

As noted above, the language of communication in the first session was English, while the second session was conducted exclusively in Norwegian. Conducting each session in separate languages allowed us to ensure participants were highly proficient in both languages. The rich dataset collected over two separate sessions allows for forming of a comprehensive language, lifestyle, and demographic profile for each participant. All procedures were approved by UiT the Arctic University of Norway Psychology ethics board and the Norwegian Center for Research Data (NSD).

2.3. Quantification of multilingual engagement

The Language History Questionnaire (LHQ3; Li et al., 2020) was administered to all participants to elicit information about their use of different languages. The Multilingual Language Diversity (MLD) score provided by the LHQ3 calculator, as proposed by the LHQ3 team, allows researchers to better describe multilingualism through language usage in terms of context and diversity. It is calculated in the form of Shannon Entropy (see formula (1), based on Proportion of Dominance (PD; see formula (2) calculated as the proportion of the Dominance score (see formula 3) of one language over the sum of Dominance scores of all languages.

$$MLD = \sum_{i=1}^{n} PD_i \log_2(PD_i) \tag{1}$$

$$PDi = \frac{Dominance_i}{\sum_{i=1}^{n} Dominance_i} \tag{2}$$

$$Dominance = \sum_{j=\{Reading,Writing,Speaking,Listening\}} \omega_j \left(\frac{1}{2}\left(\frac{P_{ij}}{7}\right) + \left(\frac{1}{2}\left(\frac{H_{ij}}{K}\right)\right)\right. \tag{5}$$

Note. H_{ij} stands for the total estimated hours *per day one spent on the j^{th} linguistic aspect of the i^{th} language, K is set to be 16 as a constant scaling factor and ω to 0.25 as a weight assigned to each component.*

However, as can be appreciated from the above formulations, the MLD score in its current format does not reflect the social reality of the current sample nor the research interest of the current study. To start, given formula (1), participants speaking more than two languages would have a larger MLD score even if their engagement with (to the extreme) all languages they speak is minimal than participants speaking two languages who routinely engage with both languages. Secondly, our research questions concern how engaging (the actual use of) with more than one language affects neurocognition—the equal weighting of proficiency relative to usage would mask the actual variation in usage across participants. As adjusting calculations based on specific research interests is encouraged by the LHQ3 team, we decided to designate our own weighting and transform usage data such that all participants share the same range of MLD score (0−1) regardless of how many languages they use. Following previous research (e.g., Pereira Soares et al., 2021), we added up usage data from L2, L3 and L4 for each component per participant to reflect usage of non-societal language(s), languages other than Norwegian. The denominator for PD scores is now the sum of societal language (L1) Dominance score and non-societal language(s) (Ln) Dominance score. Additionally, as schematized in formula (4) below, when calculating the dominance scores, we set the weighting for proficiency to 0 not only because we are interested in the effect of usage but also because all participants were extremely proficient in the common non-societal language they speak, e.g., English—the social reality in Norway where the current study was conducted. The final MLD score across all participants has a mean of 0.58 (SD = 0.28).

$$Dominance = \sum_{j=\{Reading,Writing,Speaking,Listening\}} \omega_j \left(\frac{H_{ij}}{K}\right) \tag{4}$$

2.4. Resting state EEG data acquisition and processing

Neuroimaging data were collected with a 32-Channel Wet-Sponge R-Net cap, connected to a LiveAmp 32 channel amplifier (Brain Products). The electrode placement was in accordance with the 10–10 system where the FpZ (Ground) and FCz (Ref) were used as reference. The impedance threshold was set at 100 kΩs with no electrodes exceeding this threshold in the beginning of data acquisition. Data was continuously digitized using a LiveAmp amplifier (Brain Products, Inc) at a 2000 Hz sampling interval with a sampling rate of 512 Hz.

For preprocessing we used the Brain Vision Analyzer 2.0 software (Brain Products, Inc). The data were first downsampled to 128 Hz from the original 512 Hz. The data were then segmented to a total of 270 s starting after the first 15 s into the recording. A new reference was then applied to the data which was a common average reference of all electrodes. Then, the data passed through a band-pass filter from 1 to 45 Hz with a slope of 48 dB/oct. Given that the caps were unshielded, we opted to account for any remaining 50 Hz noise not captured with this lowpass filter via a 50 Hz notch filter. Dead or otherwise overtly noisy channels were interpolated via a spherical spline interpolation algorithm (average of 0.16 channels per participant). Furthermore, in order to remove potential blinks, eye movement, or other biological artifacts (e.g., heartbeat), an independent component analysis (ICA) was performed on the whole data with a total of 512 steps and using the infomax restricted algorithm. Components were identified as noise with a semi-automatic artifact detection algorithm within the ICA function. The ICA output was manually checked and any components identifiable as noise were manually removed. An average of 2.17 components were removed per participant. Finally, the pre-processed data was exported to R-studio for further analysis where the data followed a publicly available R-script (available online on https://github.com/UWCCDL/QEEG), originally developed by Prat et al., 2016) and adapted by Pereira Soares et al. (2021) further customized to make it compatible with the R-Net system used in the present study.

The study implemented an individualized approach to delineate frequency bands. Rather than using fixed frequency band ranges (such as delta: 2–4 Hz, theta: 4–8 Hz, alpha: 8–12 Hz, beta: 12–30 Hz, and gamma: 30+ Hz), this approach adjusted the bands according to each participant's IAPF following (Klimesch, 1997). For instance, delta band was defined as anything under 6 Hz below the IAPF, while gamma encompassed frequencies equal to or greater than 20 Hz above the IAPF.

The final analysis dataset was reduced from 137 to 122 participants as follows: IAPF failed to calculate for 12 participants, 1 participant was removed due to unsatisfactory data quality (recording missing from 3 electrodes), 1 participant was removed due to suspected childhood epilepsy and 1 additional participant was excluded due to exhibiting atypical power in a critical threshold of channels. Following the procedure done in Pereira Soares et al., (2021), channels exhibiting atypical levels of activity within the frequency spectrum ('bad channels') were identified via calculating the average log power in the frequency range of 1–40 Hz for each channel across all subjects. Subsequently, any channel whose average log power deviated by more than ±2.5 standard deviations from the overall channel average was deemed an outlier and thus omitted from further consideration. This one additional excluded participant had less than 80% of their channels remaining, 21 of 32. For the remaining participants, an average of 1.04 bad channels were removed per participant (3.3% of the total).

Data acquired from individual channels for alpha power, theta power, and IAPF were averaged across the whole brain to yield a whole brain resting state power value. For coherence, we followed the procedure in Pereira Soares et al. (2021). Coherence was calculated as the correlation of activity across each frequency band between electrodes in different regions of the scalp. We grouped and averaged electrodes into 5 regions of interest (ROI), namely medial frontal (Fp1, Fp2, F3, Fz, F4, FC1, FC2), left fronto-temporal (F7, F9, FC5, C3, T7), right fronto-temporal (F8, F10, FC6, C4, T8), left posterior (CP1, CP5, P3, P7, P9, O1) and right posterior (CP2, CP6, P4, P8, P10, O2).

2.5. Statistical procedures

Changes in power and coherence as a function of age may occur non-linearly. Adopting linear models, thus, can create autocorrelation patterns in the residuals (Sóskuthy, 2017). Although including (orthogonal) polynomials can estimate non-linear relationships in some cases, Generalized Additive Models (GAMs) can identify non-linear patterns automatically without overfitting and are more flexible (Coupé, 2018; Wieling, 2018; Winter and Wieling, 2016; Wood, 2017). Meanwhile, GAMs not only allow the presence of smoothing functions (smoothers) for non-linear predictors but also "unsmoothed" covariates. Thus, the present study adopts GAMs for statistical modeling for the analyses of both power and coherence, unless the smoothers are penalized to have less than 1 effective degree of freedom (edf) suggesting underfitting for the smoothed effects of interest. For all analyses, all numeric variables are scaled, and categorical variables are sum-coded. To avoid over-fitting, gamma value for all models was set to 1.4 (see Wood, 2017).

For the analyses of Power, given our theoretically motivated research questions and predictions, an appropriate confirmatory statistical approach was adopted (see Winter, 2019, for its advantages). This means that all models included *Age* as a fixed effect with *Age* being smoothed via thin plate regression spline (s() function in mgcv). The tensor product interaction term between *Age* and *MLD* (ti() function in mgcv) was also included as a fixed effect. Tensor product interaction was selected over full tensor product smooth (te() function in mgcv) because it produces a tensor product interaction appropriate when the main effects are also present. K(not) value for the smooth term for Age was set to 24 as there are 50 unique values. Additionally, *Sex, Education Level, Social Network Diversity* (a measure from Social Network Index)*, IPAQ category* (a group index of high, medium, and low physical activity), *Dietary Quality Score* (a proxy for healthy diet)*,* and *Cognitive Reserve Scale Score* (overall engagement in cognitively healthy activities throughout one's life) were included as covariates.

For the analyses of Coherence, we adopted Generalized Additive Mixed Models (GAMMs) to account for within-participant data nesting, as coherence values were extracted for the same participants across ROI pairs. Different from the analyses of Power, the analyses for Coherence were exploratory. Nevertheless, we started with a theoretically-driven "base" model in which the thin plate regression spline smoothed *Age* effect was included as the fixed effect (k = 24), along with all covariates, i.e., *Sex, Education Level, Social Network Diversity, IPAQ category, Dietary Quality Score,* and *Cognitive Reserve Scale Score*. The "base" model also included the theoretically motivated interaction, i.e., the by-ROI tensor product interaction term between *Age* and *MLD*, and the by-participant random intercept (by setting the value for bs in s() function in mgcv to "re"). A forward stepwise approach using maximal likelihood ratio tests was adopted to explore if (1) ROI has a main effect; (2) MLD when not smoothed has a main effect; and (3) if MLD when smoothed via thin plate regression spline (k = 59) has a main effect on Coherence. Below, we report the optimal model (and its R syntax) and refer readers to the associated R scripts (DOI: 10.17605/OSF.IO/HS7ZX) for the results of the maximal likelihood ratio tests.

3. Results

3.1. Bi-/multilingual engagement and alpha power

The R syntax is in the format of gam.alpha = gam(Power_alpha~ s (age_scaled, *k* = 24) + ti(age_scaled, MLD_scaled) + sni_network_diversity_scaled + Ipaq_category_sum + dqs_score_scaled + Sex_sum + Edu_sum + crs_total_scaled, data =, gamma = 1.4). A significant smoothed effect of *Age* was identified (Figure 1a), such that with the increase of age, alpha power decreases (F(1.89) = 3.33, p =.04). The effective degree of freedom (edf) is 1.89, suggesting the effect is, indeed, non-linear. The interaction between *Age* and *MLD* (Figure 1b) is also significant (F(1.15) = 6.50, p =.01). As visualized in Figure 1, the interaction term suggests that (1) alpha power is the lowest for the oldest participant who has the lowest MLD score; (2) for older participants, with an increase of MLD score, there is an increase in alpha power; 3) for younger participants, with an increase of MLD score, there is a decrease in alpha power and, (4) for younger participants, with an increase of MLD score, there is a small(er) decrease of power relative to the degree of increase for the older participants.

3.2. Bi-/multilingual engagement and theta power

A significant smoothed nonlinear effect of *Age* was identified for theta power as well (Figure 2a)—with the increase of age, theta power decreases (F(1.39) = 7.73, p =.001). The interaction between *Age* and *MLD* (Figure 2b) was also significant (F(1) = 6.38, p =.01). R syntax is gam.theta = gam(Power_theta~ s(age_scaled, *k* = 24) + ti(age_scaled, MLD_scaled) + sni_network_diversity_scaled + Ipaq_category_sum + dqs_score_scaled + Sex_sum + Edu_sum + crs_total_scaled, data =, gamma = 1.4). Note here that although the edf has been penalized to 1, the base function allows the relationship to act as if it were linear, i.e., it can be approximated to be linear. As it is not theoretically relevant, whether the interaction is truly linear or not is out of the scope of the study. As visualized in Figure 2, similar to the results for Alpha power, the interaction term suggests that (1) theta power is the lowest for the oldest participant who has the lowest MLD score; (2) for older participants, with an increase of MLD score, there is an increase in theta power; and (3) for younger participants, with an increase of MLD score, there is a decrease in theta power and, (4) for younger participants, with an increase of MLD score, there is a small(er) decrease of power relative to the degree of increase for the older participants.

3.3. Bi-/multilingual engagement and whole head IAPF

A significant smoothed effect of *Age* was identified (Figure 3a)—with the increase of age, IAPF decreases (F(1) = 13.56, p <. 001). Here, the effect was penalized to be linear (edf = 1). The interaction between *Age* and *MLD* (Figure 3b) was not significant (p =.14). R syntax is gam.IAF = gam(WholeHeadIAF~s(age_scaled, *k* = 24) + ti(age_scaled, MLD_scaled) + sni_network_diversity_scaled + Ipaq_category_sum + dqs_score_scaled + Sex_sum + Edu_sum + crs_total_scaled, data =, gamma=1.4)

3.4. Bi-/multilingual engagement and resting state coherence

Starting with model specifications of the optimal models, the optimal models for each frequency band included the main effect of ROI (BrainRegion in syntax). However, a main effect of MLD (being smoothed or not) was not selected in any optimal models. Therefore, optimal models for all frequency bands have the R syntax of gam(Frequency_Alpha/LowBeta/HighBeta/Theta/Gamma ~ s(age_scaled, *k* = 24) + BrainRegion + ti(age_scaled, mld_Scaled, by = BrainRegion) + s (Subject, bs="re") + sni_network_diversity_scaled + Ipaq_category_sum + dqs_score_scaled + Sex_sum + Edu_sum + crs_total_scaled, data = Data_WH_Scale, gamma = 1.4).

An effect of *Age* was significantly attested for Alpha (F(1.93) = 6.05,

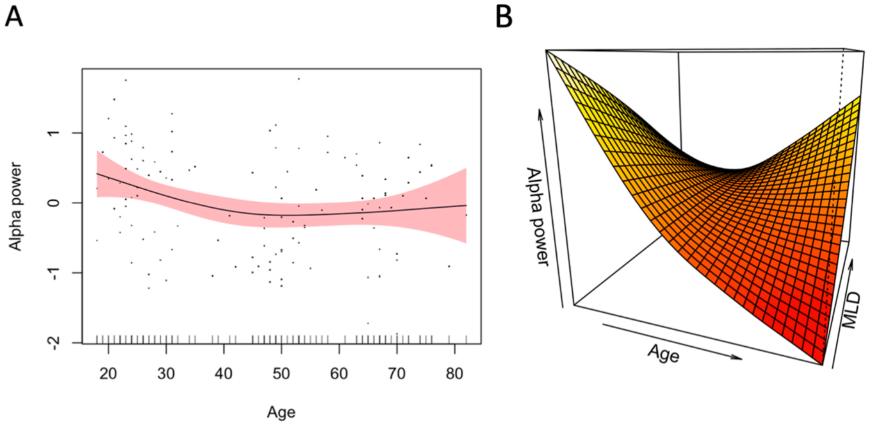

Fig. 1. The effect of age (a; left) and the effect of Age and MLD interaction (b; right) on alpha power. All variables are scaled. Age represented numerically for illustration purposes.

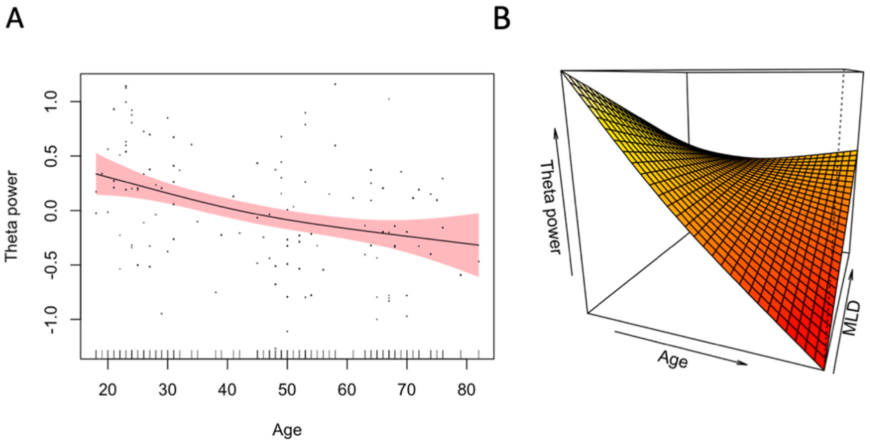

Fig. 2. The effect of age (a; left) and the effect of age and MLD interaction (b; right) on theta power. All variables are scaled. Age represented numerically for illustration purposes.

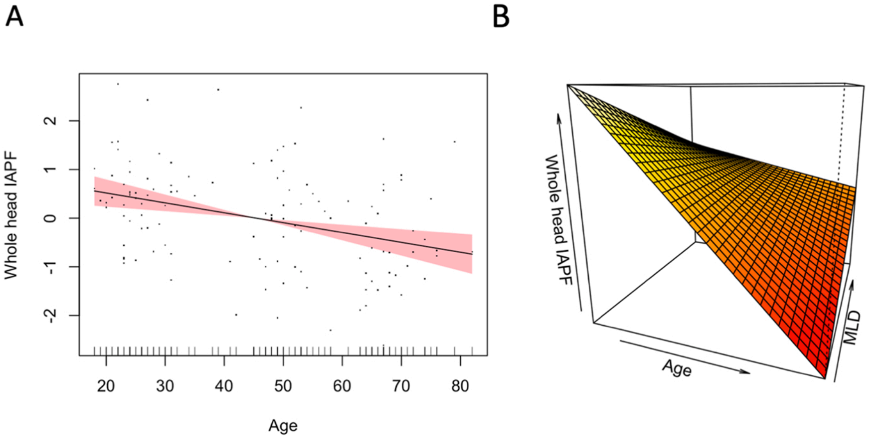

Fig. 3. The effect of age (a; left) and the (non-significant) effect of age and MLD interaction (b; right) on whole head IAF. All variables are scaled. Age represented numerically for illustration purposes.

p =.002), Theta (F(2.08) = 15.45, p <.001) and Gamma (F(1) = 8.69, p =.003), but not for Low Beta (F(1) = 0.29, p =.59) or High Beta (F(1) = 0.16, p =.69). However, as a main effect of Age is not of our interest (especially because it reflects effects across ROI pairs), we will not elaborate on them and refer readers to the R script for visualizations. Rather, we will focus on the three-way interaction terms, i.e. *Age* and *MLD* interaction by ROI pairs. Given space restrictions, Table 1 below summarized the F values and indicated alpha levels for the effect of Age and MLD across all brain region pairings, i.e., the three-way interaction term ti(age, mld, by = brain region), for each frequency band. See the R scripts for more information on edf values from the model outputs.

Table 1
F values for the three-way interaction (ti(age_scaled, mld_scaled, by = BrainRegion). LFT – left fronto-temporal; RFT – right fronto-temporal; LP – left posterior; RP – right posterior; MF – medial frontal.

	Alpha	Low Beta	High Beta	Theta	Gamma
LFT-LP	2.71	0.43	0.11	3.51	0.02
LFT-MF	**2.53***	**3.02***	1.16	2.45	0.37
LFT-RFT	1.94	1.03	1.47	**8.49****	0.15
LFT-RP	2.11	1.45	0.73	2.61.	0.08
LP-MF	**5.10***	0.65	1.53	1.67	0.28
LP-RFT	1.60	1.51	0.02	2.03	1.06
LP-RP	2.09	0.14	0.01	1.50	0.09
MF-RFT	2.67	**4.10***	0.40	0.05	1.01
MF-RP	1.45	1.52	1.15	2.47	0.02
RFT-RP	3.29.	1.30	0.50	**6.15***	0.57

Note.p<.1 *p <.05, **p <.01, ***p<.001

Figure 4 illustrates the significant interaction terms to assist interpretation. Starting from Alpha frequency, for the ROI pair LFT-MF, with an increase of MLD, coherence showed an inverted U-shape development (increased and then decreased) for the younger participants. For the older participants, the opposite occurs: with an increase of MLD, coherence showed a U-shape development (decreased and then increased). For the ROI pair LP-MF, alpha coherence decreased for the younger participants but increased for the older participants as a function of an increasing MLD. Turning to Low Beta frequency, an inverted U-shape change for the younger participants and a U-shape change for the older participants were observed for both the ROI pair LFT-MF and the ROI pair MF-RFT. Lastly for Theta frequency, coherence decreased for the younger participants but increased for the older participants as a function of an increasing MLD for the LFT-RFT and RFT-RP pairs.

4. Discussion

The present study investigated the potential association between multilingual experience and resting state oscillatory activity in a sample of proficient multilingual adults spanning a wide age range and with varying degrees of language use. Several notable correlations were found between participants' age, multilingual engagement, and rs-EEG power and coherence. Taken together the data are compatible with an interpretation of multilingual engagement having a modulatory effect on resting-state oscillatory patterns with advancing age. Crucially, these

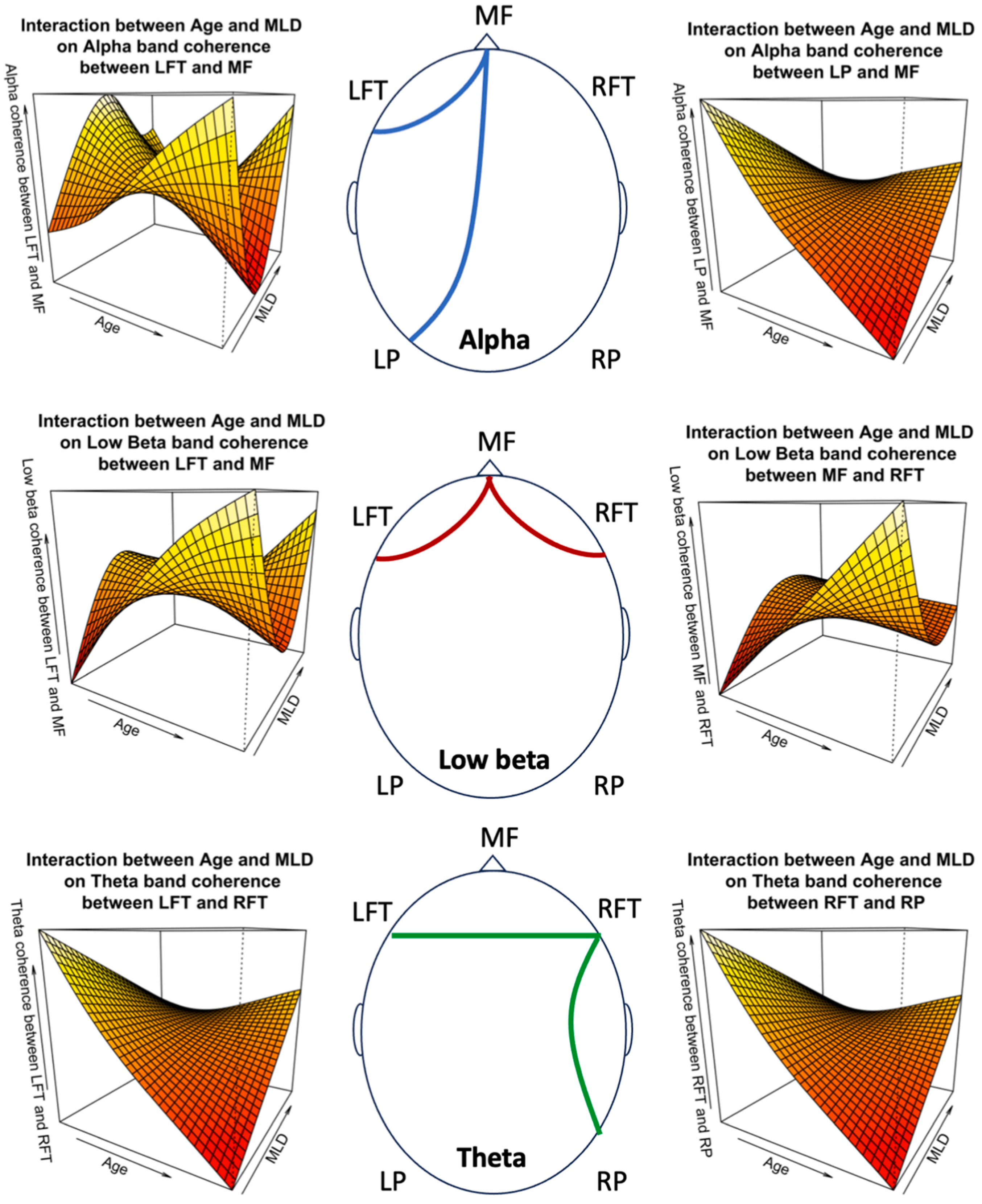

Fig. 4. The significant effect of the interaction between age and MLD interaction by brain region pairs for Alpha (top row), Low Beta (Middle row) and Theta (Bottom row). The middle column contains coherence maps by frequency band visualizing the ROI pairs for which a significant effect of age by MLD interaction was found.

results obtained independently of effects of other known modulating lifestyle factors. In what follows, we will unpack the results with respect to our research questions and the larger study aims.

Recall that we predicted that increased multilingual engagement would correlate with a relative stability of neural state across the whole adult lifespan. Based on measured outcomes, this was expected to have manifested as comparable levels of power, connectivity and/or IAPF between the younger and older participants, as a function of degree of multilingual engagement. The results generally support predictions for power and connectivity, but not for IAPF.

4.1. Multilingual engagement and rs-EEG power in alpha and theta frequency bands across the adult lifespan

In line with our predictions, a key finding within the analyses on rs-EEG power was that increased multilingual engagement modulated the correlation with age across the alpha and theta bands. As expected, rs-EEG power decreased as a function of age in our sample within both alpha and theta bands, but significantly less so for individuals who reported regularly engaging with multiple languages. Couched within previous literature showing a correspondence of rs-EEG power with preserved cognitive ability in aging (for discussion see Anderson and Perone, 2018), these results are compatible with an interpretation of a contribution of higher degree of multilingual engagement towards reserves.

Although relatively little work has been done examining this, mechanistically, we may consider that higher resting state power reflects a greater capacity to deploy available cognitive resources (Raichle and Snyder, 2007). Indeed, rs-EEG power, specifically occipital alpha power, has been tentatively linked to hubs within the default mode network (DMN) in rs-fMRI (Bonnard et al., 2016). The DMN, among other functions, has been argued to coordinate the engagement of cognitive processes (Deco et al., 2011, 2013). Given these connections, the present data are also compatible with the postulation that higher degrees of experience in managing multiple languages confers adaptations towards more efficiently making use of available neural/cognitive resources to handle existing demands, and thus preserve cognitive functions in aging. More research—especially longitudinal studies (see comments further below) — is needed, however, to properly assess these connections.

It is interesting to note that below a certain age threshold MLD predicts the opposite trend–namely a decrease in rs-EEG power with greater degrees of engagement in young adults for both frequency bands. However, this effect is not unexpected, if interpreted within the notion of efficiency. As young adults are known to be at the proverbial peak of cognitive abilities, it is likely that the cognitive demands brought on by multilingual experience correspond to reduced neural recruitment during processes involving cognitive control. Indeed, several recent papers examining oscillatory dynamics during cognitive tasks in bi-/multilingual populations indicate precisely this – stimulus-related theta power is negatively correlated to degree of bi-/multilingual engagement (Pereira Soares et al., 2022; Carter et al., 2023). It is logical that, as cognitive capacities reduce with aging, the adaptations brought on by multilingual experience would allow for a shift towards increased readiness to use the existing or remaining cognitive resources.

4.2. Multilingual engagement and resting state coherence across the adult lifespan

Although exploratory in nature, the connectivity analyses showed several notable results: 1) lower degree of multilingual engagement correlated to increased connectivity in frontal ROI pairs, whereas 2) higher degrees of multilingual engagement largely correlated to higher connectivity in fronto-posterior ROI pairs. Given the cross-sectional nature of the present data, our results do not provide direct evidence, but are, nonetheless, compatible with an interpretation of adaptations towards increased reserves in aging. This pattern of results is also in line with our predictions.

It is worth noting that, akin to rs-EEG power, connectivity in the fronto-posterior ROI pairs for alpha power showed a general decline with age, but this effect was modulated by degree of multilingual engagement. Although we cannot make direct links to any underlying brain regions in terms of connectivity, the data herein indirectly speak to the possibility of widespread functional connections as a means to compensate for the effects of cognitive aging (Grant et al., 2014; Grundy et al., 2017). While the spatial resolution of rs-EEG also limits any direct comparisons to results seen in rs-fMRI research, the effects in the alpha band overlap with previous rs-fMRI data examining effects of bi-/multilingualism in aging (Grady et al., 2015). Specifically, the fronto-posterior connections seen for theta and alpha connectivity align with connectivity patterns in the frontoparietal control network for bi-/multilinguals.

The frontal ROI connectivity effects seen in alpha, beta, and theta bands are more difficult to functionally explain, but all show a significant modulatory effect of multilingual engagement. One possible explanation is that the differential patterns of connectivity, in combination with the effects in fronto-posterior ROI connectivity reflect a shifting in reliance within the large-scale functional networks to optimize against decreasing neural resources with increased age (Bialystok, 2021; Grant et al., 2014). Such a claim, however, constitutes its own empirical question that would be best addressed in a longitudinal design.

4.3. Multilingual engagement and age-related differences of IAPF

The data herein suggest a minimal (or at least nonsignificant) effect of multilingual engagement, which does not confirm our predictions. While at first glance, it would be logical to interpret this result as indicating no relationship between multilingual experience and IAPF in aging, there are some considerations to keep in mind.

Recall that our analyses controlled for a number of other lifestyle factors (exercise, diet, education, social engagement, etc.). Given known effects of these factors, particularly physical exercise, on IAPF (Babiloni et al., 2010; Gutmann et al., 2015; Lardon and Polich, 1996), it is conceivable that the variance explained by such factors simply overrides any independent input of multilingualism, statistically. It is worth noting, albeit with caution (given lack of statistical significance) that the visual trends in IAPF do overlap with the results for whole-brain alpha and theta power. Nonetheless, further research is required to assess the relative contributions of each lifestyle factor in order to assess this interpretation. The final consideration is the range of (multilingual) language experience within our cohort. Although there was considerable range of routine multilingual engagement, all participants in this cohort were highly competent, lifelong speakers of at least two languages. It is thus possible that to see effects for IAPF the cohort would require more diverse language experiences.

5. Conclusions

This is the first study to bridge the gap between multilingualism, aging, and resting state oscillatory patterns and pave the way for a more comprehensive understanding of how multilingual engagement –independently and/or its mediated role with other reserve accruing activities – shapes resting state oscillations throughout the human lifespan. With this study, we extend the previous literature by showing an effect that is compatible with an interpretation of multilingualism-related maintenance of alpha and theta power across the lifespan and through healthy aging as well as an interaction between age, multilingualism and (mostly) frontal connectivity across alpha, theta and low beta frequency bands. Taken together, our findings add further support to the interpretation of multilingualism as a potential lifestyle experience that contributes to preservation of brain status in aging as evidenced by its effects on resting state oscillatory patterns across the lifespan.

From the outset, we have attempted to be mindful of what can be directly claimed, inclusive of the way we framed the research questions, hypotheses, presentation of the data and resulting discussions. After all, there are inherent limitations to what one can claim based on cross-sectional data, especially as it relates to change/maintenance over time. Within the present cross-sectional design, one can only observe correlations that are or are not compatible with a particular hypothesis space. Nevertheless, such correlations can be profound, especially when they stack together towards supporting (or not) a predicted set of claims that couple together and lead to a more generalized conclusion. While it is true that a longitudinal study of similar scope to the present one would be in the best position to make claims beyond correlational compatibility (i.e., document or not actual change and/or maintenance), we are reminded that in the beginning of a novel research program the first such studies bear the burden of demonstrating the potential value and need for more resource intensive ones, which come at a considerably higher costs (in capital and human resources at multiple levels). The present study embodies a case in point. It lays the groundwork for future multilingualism and cognitive aging studies that are longitudinal in nature. These will be able to take the discussions of the systematicity in correlations we have revealed as points of departure for more rigorous testing, insofar as they are predicted to bear out in longitudinal data more directly bearing on theoretical claims within multilingualism and aging and in the neuroscience of aging more generally.

Verification

The work described has not been published previously, it is not under consideration for publication elsewhere, its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neurobiolaging.2024.04.009.

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