Lower Aperiodic Activity is Associated with Reduced Verbal Fluency Performance Across Adulthood

Abbreviated title: Aperiodic EEG activity and cognition

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ABSTRACT

Age-related cognitive decline associations with human electroencephalography (EEG) have previously focused on periodic activity. However, EEG is primarily made up of non-oscillatory aperiodic activity, which can be characterised with an exponent and offset value. In a secondary analysis of a cohort of 111 healthy participants aged 17 – 71 years, we examined the associations of the aperiodic exponent and offset with a battery of cognitive tests assessing processing speed and response inhibition, working memory, verbal learning and memory, psychomotor speed, and verbal fluency. Using Principal Component Analysis and K-Means Clustering, we identified clusters of electrodes that exhibited similar aperiodic exponent and offset activity during resting-state eyes-closed EEG. Robust linear models were then used to model how aperiodic activity interacted with age and their associations with performance during each cognitive test. Exponent by age and offset by age interactions were identified for the verbal fluency model where flatter exponents and smaller offsets were associated with poorer performance in adults as early as 30 years of age. Steeper exponents and greater offsets become increasingly related to verbal fluency performance and executive functioning in adulthood.

SIGNIFICANCE STATEMENT

This study investigates aperiodic components of EEG activity and their association with cognitive function. Using data from 111 participants aged 17 to 71 years, we uncover that variations in aperiodic activity, specifically flatter exponents and smaller offsets, are significantly associated with poorer verbal fluency in adults as early as 30 years of age. Our findings highlight the importance of aperiodic activity and its association with lifespan models. Understanding how aperiodic EEG activity influences cognitive decline could inform future cognitive assessments and interventions for aging populations.

INTRODUCTION

Investigations into the encephalogram (EEG) have historically focused on oscillatory activity across the power spectrum (i.e., periodic activity). However, EEG predominately consists of non-oscillatory (i.e., aperiodic) 1/*f*-like patterns of activity (He, 2014). Once considered artifactual noise, aperiodic activity is of neurophysiological significance and functionally important (Brake et al., 2024; Donoghue et al., 2020). The exponent and offset provide an indication of excitation: inhibition (E:I) balance and neural spiking rate, respectively (Donoghue et al., 2020; Gao et al., 2017). Variation in the exponent and offset predictors of task performance (Hohn et al., 2024; Immink et al., 2021; Pathania et al., 2021) and age-related cognitive decline (Finley et al., 2024; Tran et al., 2020; Voytek et al., 2015), and can be considered biomarkers of brain disorders (Arnett et al., 2022; McKeown et al., 2023).

Previous research has found aging is associated with wide-scale changes in both periodic and aperiodic activity reflecting non-pathological changes in neuronal networks (Finley et al., 2024; Voytek et al., 2015). For example, individual alpha peak frequency (IAPF) reduces with age (Cesnaite et al., 2023; Klimesch, 1997) and the exponent flattens (Voytek et al., 2015), suggesting an increase in E:I balance. The offset decreases with age, reflecting a reduction in neural firing rate (Merkin et al., 2023). IAPF is negatively correlated with cognitive performance. That is, faster a IAPF better the performance during working memory and attention tasks (Angelakis et al., 2004). Aperiodic activity may also play a role in maintaining cognitive function throughout life (Pathania et al., 2022). Here, previous research has uncovered that the exponent and offset are negatively correlated with reaction time (Euler et al., 2024), perceptual sensitivity (Immink et al., 2021), processing speed (Ouyang et al.,

2020), and selective attention (Waschke et al., 2021). However, this association is inconsistent, suggesting that the relationship between aperiodic activity and cognition may vary with age and task (Cesnaite et al., 2023; Pei et al., 2023; Waschke et al., 2021).

Recently, Euler et al. (2024) found no association between exponents and constructs of working memory, perceptual reasoning, processing speed, and verbal comprehension. However, combining the eight Wechsler Adult Intelligence Scale subtests onto a single latent factor revealed that steeper exponents were associated with higher overall general ability. Although Cesnaite et al. (2023) found no associations between aperiodic activity and cognitive performance in a large older cohort (n = 1703, 60 – 80 years old), Smith et al. (2023) demonstrated associations between the exponent and general cognitive function but not with age (n = 86, 50 – 80 years old). While these effects may vary with age and task most studies focus on a narrow snapshot of the lifespan focusing on either midlife (Finley et al., 2024) or older (Cesnaite et al., 2023; Euler et al., 2024; Smith et al., 2023)adults. To date, no studies have examined associations between aperiodic activity, and cognitive ability across adulthood.

We present a secondary analysis of resting-state EEG from the Stimulus-Selective Response Modulation (SRM) project. This dataset consists of resting-state EEG and performance measures during a battery of neuropsychological tests from 111 healthy participants aged 17 – 71 years. Aperiodic activity was derived from the resting EEG and cognitive performance was derived from performance measures of each cognitive test. We hypothesise that reductions in aperiodic activity will be associated with worse performance in each cognitive test. We also hypothesise that these associations will strengthen as age increases.

MATERIALS AND METHODS

Code Availability

The processes and properties of the original data are described in full by Rygvold et al. (2021) and Hatlestad-Hall et al. (2022), with relevant details for the current study described below. Processed data and scripts for the current study are available at https://github.com/MindSpaceLab/Aperiodic_SRM_Cognition.

Participants

The original sample of 111 participants is available at OpenNeuro ("OpenNeuro Dataset ds003775 (SRM Resting-state EEG)"; https://openneuro.org/datasets/ds003775/versions/1.2.1; Hatlestand-Hall et al., 2022). Participants were aged between 17 and 71 (mean age = 37.5, SD = 13.99) and consisted of 68 females. The Bond University Human Research Ethics Committee approved our secondary analysis of this data (approval number: DA202221102).

EEG Acquisition

Full details on the experimental procedure can be found at Hatlestad-Hall et al. (2022) but are summarised here. Four minutes of resting-state eyes-closed EEG data was collected towards the end of the experimental protocol, approximately 45 minutes into the session after the battery of neurophysiological tests using a 64-channel (Ag-AgCl electrodes) BioSemi ActiveTwo system (BioSemi B.V., Amsterdam) arranged according to the extended 10-20 system (10-10). EEG data was initially acquired with a sampling rate of 1024 Hz without online filtering.

EEG Preprocessing

The current study utilised the cleaned raw EEG data files provided by Hatlestad-Hall et al. (2022). The initial preprocessing procedure consisted of re-referencing to the average reference and with the off-line anti-aliasing filter being applied, detecting bad segments and channels then removing them from the data, applying a high-pass filter of 1 Hz, using ZapLine to remove power line noise, calculating independent components with the SOBI algorithm, implementing ICLabel to subtract from the data the components that were considered eye or muscle artifact with 85% certainty, and applying a low-pass filter of 45 Hz. As a result, 64.1% of the EEG data files retained > 90% of their channels, while 23.5% retained 75-90% of their channels. Channels considered to be of poor quality were interpolated.

In our secondary analysis, remaining epochs were then averaged to generate a single 2000 ms segment for calculation of power spectral densities (PSD). We used a Fast Fourier Transformation (FTT; 2000 ms Hamming window, 50% overlap) to transform the data into the PSD from 1 Hz to the Nyquist max. The aperiodic exponent and offset were quantified from the PSD using the *SpecParam* package (https://github.com/fooof-tools/fooof; Donoghue et al., 2020). For each PSD we fit the *SpecParam* model between 1 and 40 Hz (peak width limits: 1.6 – 6; max number of peaks: 8; minimum peak height: .05; peak threshold: 1.5 SD, aperiodic mode: fixed) with a .25 Hz frequency resolution. Aperiodic exponent and offset, as well as the parameterised periodic activity in the alpha band (8 – 13 Hz) were extracted. Fitting of the *SpecParam* model performed excellently (mean R^2 across the scalp and across all participants = .98 ± .005). No participants had fits < .9 R^2 in more than 50% of their channels nor extreme exponent or offset values (> 3 SD). Retainment of alpha was also excellent with 94.95% retained. The analysis of IAPF is reported in Supplementary Material 1.

Cognitive Test Battery

Participants in the study completed a battery of neurophysiological tests. This consisted of the Colour-Word Interference Test, the Digit Span test from the Wechsler Adult Intelligence Scale-IV, the Rey Auditory Verbal Learning Test, the Trail Making Test from the Delis-Kaplan Executive Function System, and the Verbal Fluency Test. Details of the variables and the participant performance of each test can be found in Hatlestad-Hall et al. (2022).

Cognitive functions were inferred from the above test battery. These consisted of response inhibition (time in seconds to complete the naming, reading, interference, and switching tasks of the Colour-Word Interference Test), working memory (total score of the Digit Span Test), verbal learning (total score across the 5 trials of the Rey Auditory Learning Test), verbal memory (total number of correct words recalled immediately and 30 mins later during the Rey Auditory Learning Test), psychomotor speed (time in seconds to complete the numbers, letters, and switching tasks of the Trial Making Test), and executive functioning (total score of the phonemic, semantic, and switching tasks of the Verbal Fluency Test).

Experimental Design and Statistical Analysis

A statistical approach to reduce the complexity of the EEG data was performed using Python (v3.11.5) following the method proposed by Euler et al. (2024). Firstly, the average exponent and offset values across the scalp were plotted topographically using MNE (v1.5.1), and correlation matrices were performed to identify regions of electrodes that exhibited similar aperiodic activity (numpy v1.26.3). Following this, principal components analysis (PCA) was performed to identify dominant components within the EEG data. Lastly, K-Means clustering was

performed to identify electrode clusters that exhibited distinct exponent and offset activity. From this, regions of interests were constructed (skLearn v1.3.2).

Bivariate Pearson correlations were performed to identify how the demographic, EEG, and cognitive variables associated with each other. As age has significant associations with aperiodic activity and cognitive function, partial Pearson correlations were also performed accounting for the age variance in the cohort (pingouin v0.5.3). Bivariate and partial Pearson correlations including IAPF are reported in Supplementary Material 1. Following this, ordinary least squares (OLS) regression models were constructed separately for the exponent and offset to determine how aperiodic activity predicts performance in each cognitive test (statsmodels v0.14.0). A base formula was constructed that accounted for the impact of age:

Equation 1:

Cognitive Test ~ Aperiodic Exponent + Age + Aperiodic Exponent Age*

An extended formula accounting for the impact of IAPF was also conducted but there were no strong patterns of associations detected. The bivariate correlations including IAPF, and the result of these models are reported in the supplementary material.

As some of the residuals of the OLS models demonstrated heteroscedasticity, we opted to fit the data using an iteratively reweighted least-squares robust regression models (statsmodels v0.14.0; Holland & Welsch, 1977). The original OLS models are reported in Supplementary Material 2. Lastly, we used the “interactions” package (v1.1.5) in R (v4.3.1) to calculate simple slopes and Johnson-Neyman intervals to determine at which age aperiodic activity interactions were associated

with performance of each cognitive test (-1 SD = 23.5 years, 0 SD = 37.5 years, +1 SD = 51.5 years).

RESULTS

Data Reduction

We performed a data reduction protocol to aid in the interpretation of the aperiodic findings and their relationship to cognitive function. Firstly, topographic plots of the mean exponent and offset values were plotted to distinguish the pattern of aperiodic activity across the scalp (Figure 1A). Correlation matrices were then constructed to identify groups of electrodes that had exhibited similar relationships of aperiodic activity (Figure 1B). In general, exponent, and offset values were greater and correlated at frontal and parietal locations. Prior to identifying distinct cluster groups of electrodes, we constructed scalp-wide averages of the exponent and offset to represent general cognitive performance, and to see how this compares to electrode cluster regions of interest.

PCA and K-Means clustering were then performed on the exponent (Figure 2) and offset (Figure 3) data. The PCA identified a dominant component that all electrodes loaded consistently, which accounted for 57% and 69% of the variance for the exponent and offset, respectively. The second largest component accounted for 14% and 7% of variance for the exponent and offset, respectively. This is consistent with previous PCA assessments of aperiodic activity (Euler et al., 2024). Lastly, we performed K-Means clustering to identify if there are any electrode clusters with distinct aperiodic activity. It was determined that 4 and 3-4 cluster centroids would be suitable for grouping the exponent (Figure 2B) and offset (Figure 3B) data in the PCA dimension space, respectively. For the exponent, a frontoparietal, central, occipital,

and midline cluster was identified (Figure 2C and 2D). For the offset, a frontoparietal, central, and occipital offset cluster was identified (Figure 3C and 3D).

Correlations

Results of the zero-order correlations are available in the top right quadrant of Table 1. Results of the partial correlations accounting for age are available in the bottom left quadrant of Table 1 and significant correlations are reported below.

The exponent at each electrode cluster correlated with each other (r = .39 – .86, p < .001), as well as with the scalp-wide average exponent (r = .75 – .96, p < .001). The scalp-wide average exponent (r = -.22, CI = -.4 – -.04, p = .018), frontoparietal exponent (r = -23, CI = -.41 – -.05, p = .013), occipital exponent (r = -21, CI = -.38 – -.02, p = .027), and midline exponent (r = -20, CI = -.38 – -.01, p = .035) negatively correlated with the Colour-Word Interference Test . The occipital exponent was positively correlated with recall performance during the Rey Auditory Learning Test (r = .24, CI = .06 – .41, p = .011). The scalp-wide average exponent (r = 31, CI = .14 – .48, p < .001), frontoparietal exponent (r = .29, CI = .11 – .45, p = .002), central exponent (r = .20, CI = .01 – .37, p = .036), occipital exponent (r = .28, CI = .1 – .45, p = .002), and midline exponent (r = .33, CI = .16 – .49, p < .001), were all positively correlated with Verbal Fluency Test performance.

The offset at each electrode cluster correlated with each other (r = .68 - .89, p < .001), as well as with the scalp-wide average offset (r = .84 – .98, p < .001). The occipital offset positively correlated with recall performance during the Rey Auditory Learning Test performance (r = .2, CI = .02 – .38, p = .031). The scalp-wide average offset (r = .31, CI = .06 – .41, p = .01), the frontoparietal offset (r = .26, CI = .08 – .43,

p = .005), and the occipital offset (r = .25, CI = .07 – .42, p = .031) positively correlated with Verbal Fluency Test performance.

Aperiodic Activity and Age as Predictors of Cognitive Function

There were only significant associations of the exponent and offset with the Verbal Fluency Test and no other test. Results of the Verbal Fluency Test models are reported below while the results of the models for the other tests, are reported in Table 2 for the exponent models and Table 3 for the offset models.

Verbal Fluency Test. In the exponent models, there was a main effect of age for the scalp-wide average (β = -.86, CI = -1.65 – .07, p = .032), at the occipital (β = -.44, CI = -.88 – 0.01, p = .047) and midline (β = -1.10, CI = -2.06 – -.15, p = .024) clusters. Furthermore, there was scalp-wide average exponent and age interaction (β = .70, CI = .12 – 1.28, p = .019) as well as an exponent and age interaction at the frontoparietal (β = .59, CI = .002 – 1.18, p = .049), occipital (β = .41, CI = .04 – .78, p = .031), and midline (β = .80, CI = .16 – 1.46, p = .015) clusters. Simple slopes revealed that the association at the scalp-wide average was not significant at -1 SD of age (β = 5.86, p = .35) while significant at 0 SD of age (β = 15.66, p <.001) and +1 SD of age (β = 25.47, p < .001; Figure4 and 4B). The association at the frontoparietal cluster was not significant at -1 SD of age (β = 5.85, p = .35) while significant at 0SD of age (β = 15.66, p < .001) and +1 SD of age (β = 25.46, p < .001; Figure 5A and 5B). The association at the occipital cluster was not significant at -1 SD of age (β = 2.64, p = .44) while significant at 0 SD of age (β = 8.35, p = .001) and +1 SD of age (β = 14.01, p < .001; Figure 5C and 5D). The midline cluster was not significant at -1 SD of age (β = 7.00, p = .33) while significant at 0 SD of age (β = 18.27, p < .001) and +1 SD of age (β = 29.53, p <.001; Figure 5E and 5F).

In the offset models, there was a main effect of age for the scalp-wide average (β = 6.38, CI = 1.98 – 10.78, p = .004), at frontoparietal (β = 5.59, CI = 1.44 – 9.73, p = .008), central (β = 6.49, CI = 1.74 – 11.26, p = .008), and occipital (β = 5.58, CI = 1.91 – 9.26, p = .003) clusters. Furthermore, there was an age and offset interaction for the scalp-wide average (β = .48, CI = .15 – .83, p = .005), at frontoparietal (β = .43, CI = .11 – .75, p = .009), central (β = .5, CI = .13 – .86, p = .008), and occipital (β = 5.58, CI = 1.91 – 9.26, p = .003) clusters. Simple slopes revealed that the scalp-wide association was not significant at -1 SD of age (β = 1.29, p = .74) while significant at 0 SD of age (β = 8.14, p = .01) and +1 SD of age (β = 15.00, p < .001; Figure 4C and 4D). The frontoparietal cluster association was not significant at -1 SD of age (β = .39, p = .92) while significant at 0 SD of age (β = 6.55, p = .04) and +1 SD of age (β = 13.49, p < .001; Figure 5G and 5H). The central cluster association was not significant at -1 SD of age (β = 1.65, p = .665) while significant at 0 SD of age (β = 7.79, p = .007) and +1 SD of age (β = 13.93, p < .001; Figure 5I and 5J). The occipital cluster association was not significant at -1 SD of age (β = .60, p = .85) while significant at 0 SD of age (β = 6.62, p = .01) and +1 SD of age (β = 12.64, p < .001; Figure 5K and 5L).

DISCUSSION

This study identified how resting aperiodic activity is associated with cognitive function across adulthood. Poorer performance during the Verbal Fluency Test was associated with flatter exponents scalp-wide and in the frontoparietal, occipital, and midline electrode clusters, in adults from 30 years of age. This was also associated with smaller offsets scalp-wide and in the frontoparietal, central, and occipital electrode clusters. We provide evidence that the aperiodic exponent and offset are associated with verbal fluency ability. Furthermore, these associations appear to be

happening earlier in the lifespan than expected, with better verbal fluency being associated with steeper exponents and greater offsets in adults from 30 years of age.

Increasing age was associated, to a varying degree, with poorer performance in the battery of cognitive tests (Salthouse, 2009). Age was also associated with flatter exponents and smaller offsets, indicating greater E:I balance and neural spiking rates in younger adults. Previous research has demonstrated that cognitive decline throughout the lifespan occurs concurrently with changes in aperiodic activity (Finley et al., 2024; Merkin et al., 2023; Thuwal et al., 2021; Tran et al., 2020; Voytek et al., 2015). Although age predicts both cognitive decline and aperiodic activity, partial correlations reveal that changes in aperiodic activity contribute to variation in verbal fluency performance and executive functioning. Furthermore, this association strengthens with age, suggesting that the influence of aperiodic activity on cognitive performance becomes more pronounced across adulthood (Voytek et al., 2015). Previous research suggests that changes in cognitive function with aging may be attributable to a generalised factor that is shared across many domains of cognition (Salthouse, 2017). Our robust regressions suggest that an intricate relationship between age, aperiodic activity, and cognitive performance exists. However, as only the models for the Verbal Fluency Test remained, changes in aperiodic activity confer domain-specific declines.

Associations between aperiodic activity and verbal fluency

Many cognitive tasks require higher-order executive functioning that integrate lower-order cognitive processes (Berg et al., 2016; Kaplan, 1990). Aging progressively impairs executive functioning due to anatomical changes to neural

circuits and depletion of neurotransmitters. Of note, the frontal-striatal network of the prefrontal cortex, integral for verbal fluency (Ghanavati et al., 2019), is particularly susceptible to pathological consequences associated with aging (Buckner, 2004). This can result in difficulty performing cognitively demanding tasks as aging progresses, that is the Verbal Fluency Test (McDowd et al., 2011).

The Verbal Fluency Test discriminates between healthy aging and mild cognitive impairment (McDonnell et al., 2020; Sebaldt et al., 2009). Previously, verbal fluency has been demonstrated to remain stable or increase from early to mid-adulthood, decline around 60 years of age (Whitley et al., 2016), then is relatively consistent in later life (50 - 75 years; Clark et al., 2009; Price et al., 2012). Younger adults outperform older adults in verbal performance consistently, which may be due to changes in the prefrontal cortex (Kim et al., 2021). Indeed, under-recruitment of the prefrontal cortex has been seen in older adults compared to their younger counterparts which coincide with reductions in verbal memory and retrieval performance (Kapur et al., 1996; Logan et al., 2002). This has been suggested to be due to a reduction in neural plasticity with age and an inability to reorganise neurocognitive networks (Cabeza et al., 2002).

Early investigations into EEG and verbal fluency across the lifespan have demonstrated that theta activity is important for verbal fluency performance (Brickman et al., 2005; Mousavi et al., 2020). However, since aperiodic activity conflates resting-state theta activity (Finley et al., 2022), it may in fact be aperiodic activity and not theta activity that is associated with the preservation of verbal fluency with aging. Contention regarding the presence of theta activity and to what extent changes in theta activity can be accounted to underlying changes in aperiodic activity exists. Indeed, changes in theta activity are likely due to aperiodic activity

(Cesnaite et al., 2023; Finley et al., 2022; McKeown et al., 2023). However, if aperiodic activity conflates task-related theta activity is still a point of debate. As the current study assessed aperiodic activity during resting EEG recordings, if the associations of aperiodic activity and cognitive performance remains during task-related recordings warrants further investigation.

We identified that flatter exponents and smaller offsets at frontoparietal, occipital, and scalp-wide averages, were associated with poorer performance during the Verbal Fluency Test. What we did not initially expect was that these associations were present in adults as early as 30 years of age. As flatter exponents indicate an increase in E:I balance either due to increased excitation or decreased inhibition (Donoghue et al., 2020; Gao et al., 2017), the presence of poorer performance during the Verbal Fluency Test indicates that the exponent may be crucial for higher-order cognitive processing, such as executive functioning, in adults as early as 30 years of age. Furthermore, as this association was also present in the offset models, the rate of neural spiking may also be crucial for higher-order cognitive processing. These findings suggest that the maintenance of greater relative inhibition and neural spiking from early adulthood onwards may be beneficial for maintaining higher-order cognitive processing throughout the lifespan.

Considerations

Due to the nature of the dataset, we are unable to determine if maintaining steeper exponents and greater offsets is associated with maintained cognitive function longitudinally. However, Finley et al. (2024) recently demonstrated in a cohort aged 36 – 83 at the time of EEG assessment that steeper exponents were associated with better cognitive function across 10 years which was primarily driven

by an executive function factor. This association was dependent on IAPF, with those individuals with “matching” IAPF and exponent activity having preserved cognitive function compared to those with “mismatched” IAPF and exponent activity. Our exponent models support the work of Finley et al. (2024) by demonstrating that flatter exponents are associated with poorer verbal fluency not only in older adults but also younger adults.

Although investigations into aperiodic EEG activity associations with cognition are in their infancy, this is not the first study to adopt a similar methodology. Euler et al. (2024) recently investigated how electrode clusters of activity associate with “domains” of cognition (i.e., working memory, perceptual reasoning, processing speed, and verbal comprehension). However, there were no associations of the exponent with any specific cognitive process, but rather the scalp-wide average was associated with a general intelligence *g* factor in a cohort of 165 adults (18 – 52 years). These findings support the notion of a common influencing factor to differences in cognitive performance with age (Salthouse, 2017). However, as age impacts aperiodic activity and cognition substantially in the later years of life, the inclusion of a cohort in the current study across a larger age range may explain why aperiodic and age interactions were found for specific cognitive tests and not others.

Other factors beyond aging can impact an individual’s cognitive performance that were not investigated in the current study. One such factor is education which has been shown to be a significant predictor of cognitive performance throughout the lifespan (Lövdén et al., 2020). Although not reported in the demographic information for the current dataset, it is possible there are differences in education level between the younger and older adults in the cohort. Considering this, the potential for educational effects in our findings could not be controlled.

Conclusion

Our study examined variations in aperiodic EEG activity and how they relate to cognitive performance. This comprehensive approach expands our understanding of the cognitive implications of aperiodic activity. Aperiodic activity was associated with cognitive performance in some but not all tests. Aperiodic activity and age interactions were observed for the VFT, where flatter exponents and smaller offsets were associated with worse VFT performance in adults as early as 30 years of age. The presence of early life alterations in aperiodic activity and cognitive performance suggests that aperiodic activity may be an increasingly significant factor for preserving an individual's cognitive function earlier than previously thought, despite age-associated declines in cognition throughout the lifespan.

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TABLES

	Mean SD	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	13
i. Age	37.5 13.99	**-.38**	**-.41**	**-.40**	**-.38**	-.16	**-.37**	**-.41**	**-.39**	**-.36**	**.25**	-.15	**-.23**	**-.22**	**.38**	.00
ii. Exponent scalp-wide average	1.36 .17		**.80**	**.96**	**.88**	**.74**	**.94**	**.79**	**.74**	**.740**	**-.30**	.08	.13	**.25**	**-.25**	**.29**
iii. Offset scalp-wide average	-12.84 .27	**.78**		**.79**	**.72**	**.53**	**.79**	**.98**	**.95**	**.86**	**-.23**	.11	**.20**	**.25**	**-.22**	**.22**
Exponent clusters																
1. Frontoparietal	1.35 .18	**.96**	**.76**		**.87**	**.63**	**.88**	**.79**	**.77**	**.67**	**-.31**	.09	.13	**.24**	**-.26**	**.27**
2. Central	1.26 .22	**.86**	**.67**	**.85**		**.42**	**.74**	**.71**	**.74**	**.52**	**-.23**	.08	.09	.17	**-.19**	**.19**
3. Occipital	1.17 .30	**.75**	**.52**	**.61**	**.39**		**.7**	**.49**	**.39**	**.77**	**-.24**	.14	.15	**.27**	**-.20**	**.28**
4. Midline	1.48 .15	**.93**	**.75**	**.86**	**.68**	**.68**		**.79**	**.69**	**.77**	**-.27**	.04	.12	**.22**	**-.25**	**.31**
Offset clusters																
5. Frontoparietal	-12.76 .28	**.76**	**.98**	**.75**	**.64**	**.44**	**.75**		**.91**	**.82**	**-.23**	.11	.19	**.25**	**-.23**	**.24**
6. Central	-12.95 .26	**.7**	**.94**	**.72**	**.69**	**.32**	**.62**	**.89**		**.72**	**-.21**	.09	.19	**.23**	**-.19**	.16
7. Occipital	-12.95 .26	**.72**	**.84**	**.61**	**.42**	**.74**	**.72**	**.8**	**.68**		**-.19**	.14	**.21**	**.27**	**-.22**	**.24**
Cognitive Test Battery																
8. CWIT	39.06 7.81	**-.22**	-.14	**-.23**	-.15	**-.21**	**-.20**	-.14	-.13	-.11		**-.41**	**-.43**	**-.43**	**.66**	**-.62**
9. WAIS-IV DST	28.16 5.02	.04	.06	.00	.00	.11	.00	.00	.00	.10	**-.39**		**.32**	**.19**	**-.46**	**.37**
10. RAVLT_tot	60.41 7.67	.06	.12	.05	.00	.11	.00	.10	.10	.14	**-.39**	**.29**		**.78**	**-.47**	**.3**
11. RAVLT_del	12.79 2.41	.18	.20	.16	.09	**.24**	.15	.17	.15	**.20**	**-.40**	.16	**.76**		**-.47**	**.36**
12. DKEFS	41.42 16.31	-.14	-.08	-.12	.00	-.15	-.12	-.08	.00	-.09	**.63**	**-.44**	**-.42**	**-.42**		**-.39**

13. VFT	38.12 8.10	**.31**	**.31**	**.29**	**.20**	**.28**	**.33**	**.26**	.17	**.25**	**-.64**	**.37**	**.31**	**.36**	**-.42**	

Table 1: Descriptive statistics, bivariate correlation (upper right quadrant), and partial correlations controlling for age (lower left quadrant).

Correlations in bold and shaded indicate those that are significant (p <.05). Aperiodic exponent and offset correlations, and with cognitive domains are in red boxes. CWIT, Colour-Word Interference Test; WAIS-IV DST, Wechsler Adult Intelligence Scale IV Digit Span Test; RAVLT_tot, Reys Adult Verbal Learning Test total score; RAVLT_del, Reys Adult Verbal Learning Test immediate and delay recall score; DKEFS, Delis-Kaplan Executive Function System score; VFT, Verbal Fluency Test score.

Table 2: Exponent by age robust regression models.

		CWIT			WAIS-IV DST			RAVLT_tot			RAVLT_del			DKEFS			VFT		
	Predictor	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*
Scalp-wide average	*Intercept*	27.70	-4.81 60.22	.09	21.99	-.12 44.11	.05	**60.75**	**27.44 94.06**	**<.01**	**12.55**	**2.45 22.87**	**.01**	31.29	-35.41 98.01	.36	**49.73**	**16.28 83.18**	**<.01**
	Exponent	5.81	-17.46 29.07	.62	5.88	-9.94 21.76	.46	2.87	-20.96 26.71	.81	.88	-6.49 8.26	.81	-3.22	-50.95 44.52	.89	-10.60	-34.54 13.33	.38
	Age	.67	-.09 1.43	.08	.12	-.39 .64	.64	-.09	-.88 .68	.81	-.08	-0.33 .15	.48	.70	-.87 2.27	.38	**-.86**	**-1.65 -.07**	**.03**
	Exponent X Age	-.43	-1.00 .13	.13	-.13	-.51 .25	.51	.01	-.59 .57	.96	.05	-.13 .23	.62	-.23	-1.39 .93	.69	**.70**	**.12 1.28**	**.02**
Frontoparietal	*Intercept*	30.21	-1.52 61.93	.06	**24.99**	**3.37 46.63**	**.02**	**60.38**	**27.86 92.89**	**<.01**	**13.17**	**3.08 23.27**	**.01**	26.38	-38.75 91.52	.43	**46.51**	**13.32 79.69**	**<.01**
	Exponent	4.06	-18.64 26.76	.44	3.66	-11.82 19.14	.64	3.15	-20.12 26.42	.79	.44	-6.77 7.67	.904	.36	-46.25 46.97	.99	-8.1	-31.85 15.65	.50
	Age	.61	.14 1.36	.11	.05	-.47 .56	.86	-.08	-.86 .69	.84	-.09	-0.33 .15	.45	.79	-.75 2.34	.32	-.71	-1.5 .07	.08
	Exponent X Age	-.39	-.95 .17	.17	-.07	-.45 .31	.72	-.02	-.59 .55	.94	.05	-.13 .23	.58	-.30	-1.45 .84	.60	**.59**	**.00 1.18**	**<.05**
Central	*Intercept*	**25.33**	**1.71 48.96**	**.03**	**24.63**	**8.76 40.49**	**<.01**	**67.93**	**44.02 91.83**	**<.01**	**14.34**	**6.86 21.82**	**<.01**	17.99	-30.1 66.1	.46	**47.78**	**22.79 72.77**	**<.01**
	Exponent	7.57	-10.33 25.48	.41	4.31	-7.71 16.34	.48	-2.22	-20.34 15.89	.81	-.28	-5.95 5.39	.92	6.08	-30.37 42.54	.74	-8.94	-27.89 9.99	.36
	Age	.53	-.01 1.07	.05	.07	-.29 .44	.69	-.19	-.74 .35	.49	-.07	-.25 .09	.38	.75	-.34 1.85	.18	-.49	-1.06 .07	.09
	Exponent X Age	-.34	-.76 -.08	.12	-.10	-.39 .19	.49	.06	-.38 .49	.80	.04	-.09 .17	.60	-.27	-1.14 .6	.54	.43	-.02 .89	.06
Occipital	*Intercept*	**31.14**	**14.57 47.72**	**<.01**	**26.04**	**14.89 37.19**	**<.01**	**56.25**	**39.52 72.99**	**<.01**	**10.87**	**5.73 16.03**	**<.01**	**33.66**	**-.01 67.33**	**.05**	**45.11**	**27.93 62.28**	**<.01**
	Exponent	2.86	-10.82 16.56	.68	3.32	-5.89 12.53	.48	7.27	-6.56 21.09	.30	2.65	-1.6 6.9	.22	-6.72	-34.54 21.1	.64	-6.95	-21.14 7.24	.34
	Age	.38	-.03 .80	.07	.00	-.28 .28	.99	.02	-.40 .45	.91	-.01	-.14 .12	.90	.45	-.4 1.3	.30	**-.44**	**-.88 -.01**	**<.05**
	Exponent X Age	-.22	-.58 .13	.21	-.04	-.28 .20	.75	-.12	-.48 .24	.51	-.02	-.13 .09	.72	-.02	-.76 .70	.94	**.41**	**.04 .78**	**.03**
Midline	*Intercept*	28.16	-12.36 68.69	.17	22.17	-5.15 49.5	.11	**64.32**	**23.15 105.49**	**<.01**	**15.12**	**2.35 27.89**	**.02**	39.71	-42.77 122.18	.35	**52.89**	**11.94 93.85**	**.01**
	Exponent	4.83	-21.98 31.65	.72	5.49	-12.59 23.57	.55	.32	-26.93 27.56	.98	-.86	-9.35 7.59	.84	-8.69	-63.27 45.88	.76	-11.91	-39.01 15.18	.39
	Age	.68	-.25 1.63	.15	.18	-.46 .82	.57	-.18	-1.14 .78	.71	-.15	-.45 .14	.31	.58	-1.35 2.5	.56	**-1.10**	**-2.06 -.15**	**.02**
	Exponent X Age	-.40	-1.04 .24	.22	-.17	-.6 .27	.46	.04	-.61 .7	.90	.08	-.12 .29	.40	-.13	-1.44 1.18	.85	**.80**	**.16 1.46**	**.02**

Cells in bold indicate those that are significant (p <.05). Shaded cells indicate main effects of age and exponent by age interaction effects. CWIT, Colour-Word Interference Test; WAIS-IV DST, Wechsler Adult Intelligence Scale IV Digit Span Test; RAVLT_tot, Reys Adult Verbal Learning Test total score; RAVLT_del, Reys Adult Verbal Learning Test immediate and delay recall score; DKEFS, Delis-Kaplan Executive Function System score; VFT, Verbal Fluency Test score.

Table 3: Offset by age robust regression models

		CWIT			WAIS-IV DST			RAVLT_tot			RAVLT_del			DKEFS			VF		
	Predictor	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*	*β*	*CI*	*p*
Scalp-wide average	*Intercept*	52.61	-123.64 228.86	.56	36.89	-80.49 154.28	.54	97.72	-77.84 273.28	.27	11.12	-43.41 65.55	.69	126.25	-228.01 480.52	.49	-95.91	-275.26 83.44	.29
	Offset	1.36	-12.38 15.11	.84	.55	-8.61 9.71	.91	2.62	-11.07 16.32	.71	-.19	-4.44 4.05	.93	7.77	-19.86 35.41	.58	-10.22	-24.21 3.77	.15
	Age	-1.89	-6.22 2.42	.39	.14	-2.73 3.03	.92	.22	-4.09 4.53	.92	.65	-.69 1.98	.34	-3.88	-12.57 4.81	.38	**6.38**	**1.98** **10.78**	**<.01**
	Offset X Age	-.15	-.49 .18	.36	.01	-.21 .24	.89	.03	-31 .36	.88	.05	-.05 .16	.32	-.33	-1.01 .34	.33	**.48**	**.15** **.83**	**<.01**
Frontoparietal	*Intercept*	28.56	-141.07 198.19	.74	39.68	-73.18 152.53	.49	102.52	-66.45 271.49	.23	14.91	-37.53 67.34	.58	97.78	-242.86 438.43	.57	-68.51	-240.86 103.83	.44
	Offset	-.51	-13.82 12.79	.94	.76	-8.09 9.82	.86	3.0	-10.25 16.26	.66	.09	-4.02 4.21	.96	5.58	-21.14 32.31	.68	-8.13	-21.64 5.4	.24
	Age	-1.18	-5.26 2.89	.57	.01	-2.71 2.72	.99	-.09	-4.15 3.97	.96	.49	-.77 1.75	.44	-3.1	-11.28 5.09	.46	**5.59**	**1.44** **9.73**	**<.01**
	Offset X Age	-.10	-.42 .22	.53	.01	-.21 .22	.97	.00	-.32 .32	.99	.04	-.06 .14	.42	-.27	-.91 .37	.40	**.43**	**.11** **.75**	**<.01**
Central	*Intercept*	79.65	-101.38 260.69	.39	27.91	-92.81 148.64	.65	59.7	-120.75 240.16	.52	-4.51	-60.49 51.47	.88	172.55	-191.76 536.49	.35	-119.82	-307.58 67.94	.21
	Offset	3.45	-10.55 17.44	.63	-.15	-9.45 9.17	.97	-0.34	-14.29 13.61	.96	-1.41	-5.74 2.92	.52	11.32	-16.84 39.49	.43	-12.04	-26.56 2.48	.10
	Age	-2.57	-7.17 2.01	.27	.23	-2.83 3.29	.81	1.14	-3.43 5.72	.62	.99	-.42 2.42	.17	-4.64	-13.88 4.6	.33	**6.49**	**1.74** **11.26**	**<.01**
	Offset X Age	-.21	-.56 .14	.25	.02	-.21 .26	.86	.09	-.26 .45	.59	.08	-.03 .19	.16	-.39	-1.1 .32	.28	**.5**	**.13** **.86**	**<.01**
Occipital	*Intercept*	70.96	-76.25 218.17	.34	40.15	-57.26 137.56	.42	129.16	-16.52 274.85	.08	25.89	-19.42 71.21	.26	86.76	-208.14 381.68	.56	-85.91	-234.46 62.64	.26
	Offset	2.83	-8.69 14.36	.63	.82	-6.80 8.45	.83	5.09	-6.32 16.5	.38	.95	-2.59 4.49	.60	4.71	-18.37 27.8	.69	-9.51	-21.14 2.12	.11
	Age	-1.83	-5.47 1.81	.32	.25	-2.16 2.66	.84	-.65	-4.26 2.96	.72	.18	-.94 1.31	.75	-2.82	-10.13 4.47	.45	**5.58**	**1.91** **9.26**	**<.01**
	Offset X Age	-0.15	-.43 .13	.29	.02	-.17 .21	.82	-.04	-.32 .24	.76	.02	-.07 .1	.72	-.25	-.82 .32	.39	**.43**	**.14** **.72**	**<.01**

Cells in bold indicate those that are significant (p <.05). Shaded cells indicate main effects of age and offset by age interaction effects. CWIT, Colour-Word Interference Test; WAIS-IV DST, Wechsler Adult Intelligence Scale IV Digit Span Test; RAVLT_tot, Reys Adult Verbal Learning Test total score; RAVLT_del, Reys Adult Verbal Learning Test immediate and delay recall score; DKEFS, Delis-Kaplan Executive Function System score; VFT, Verbal Fluency Test score.

FIGURES

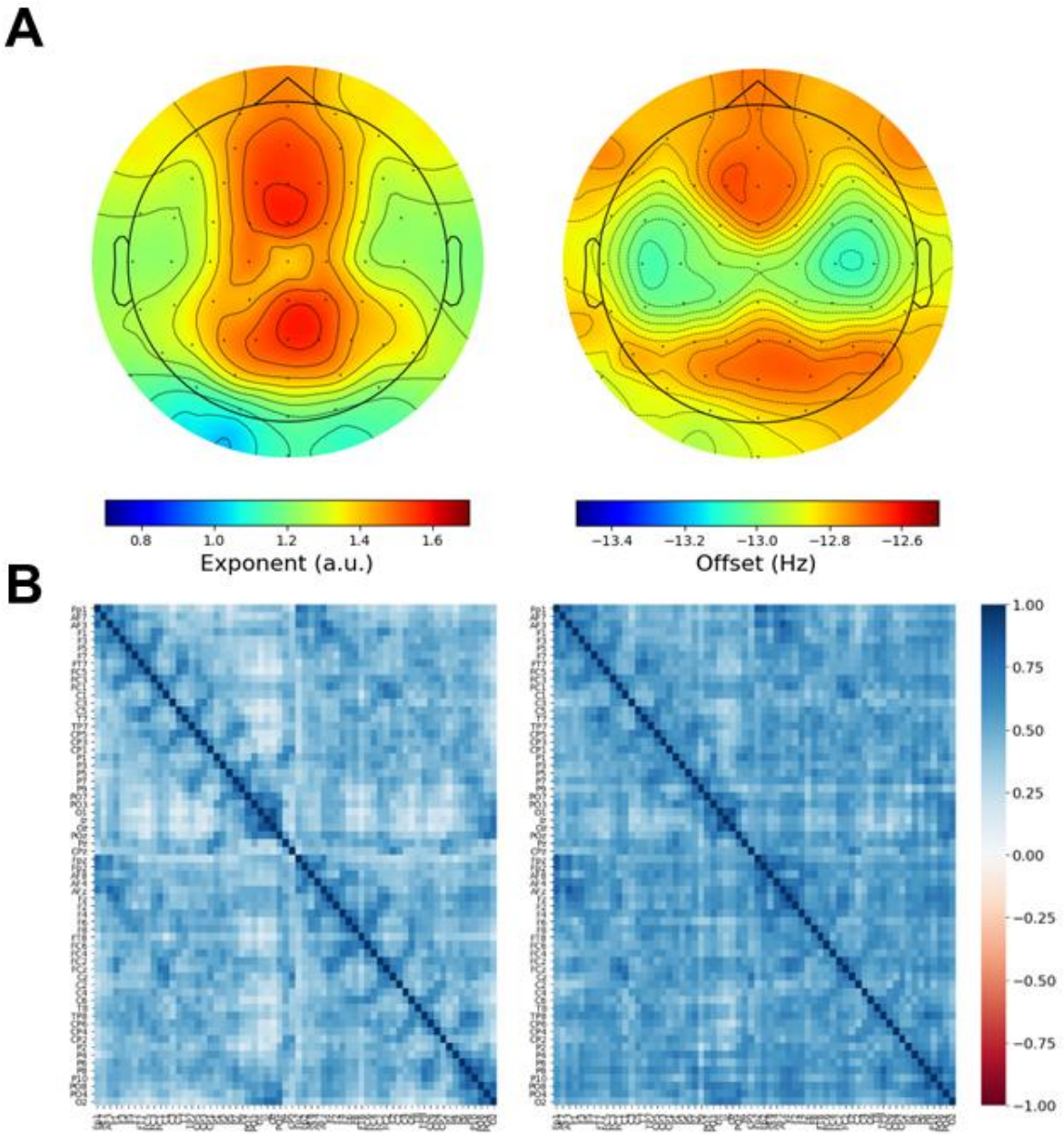

Figure 1. Group average topographies of the exponent and offset during eyes-closed resting EEG (A) and electrode correlation matrices for the exponent and offset (B).

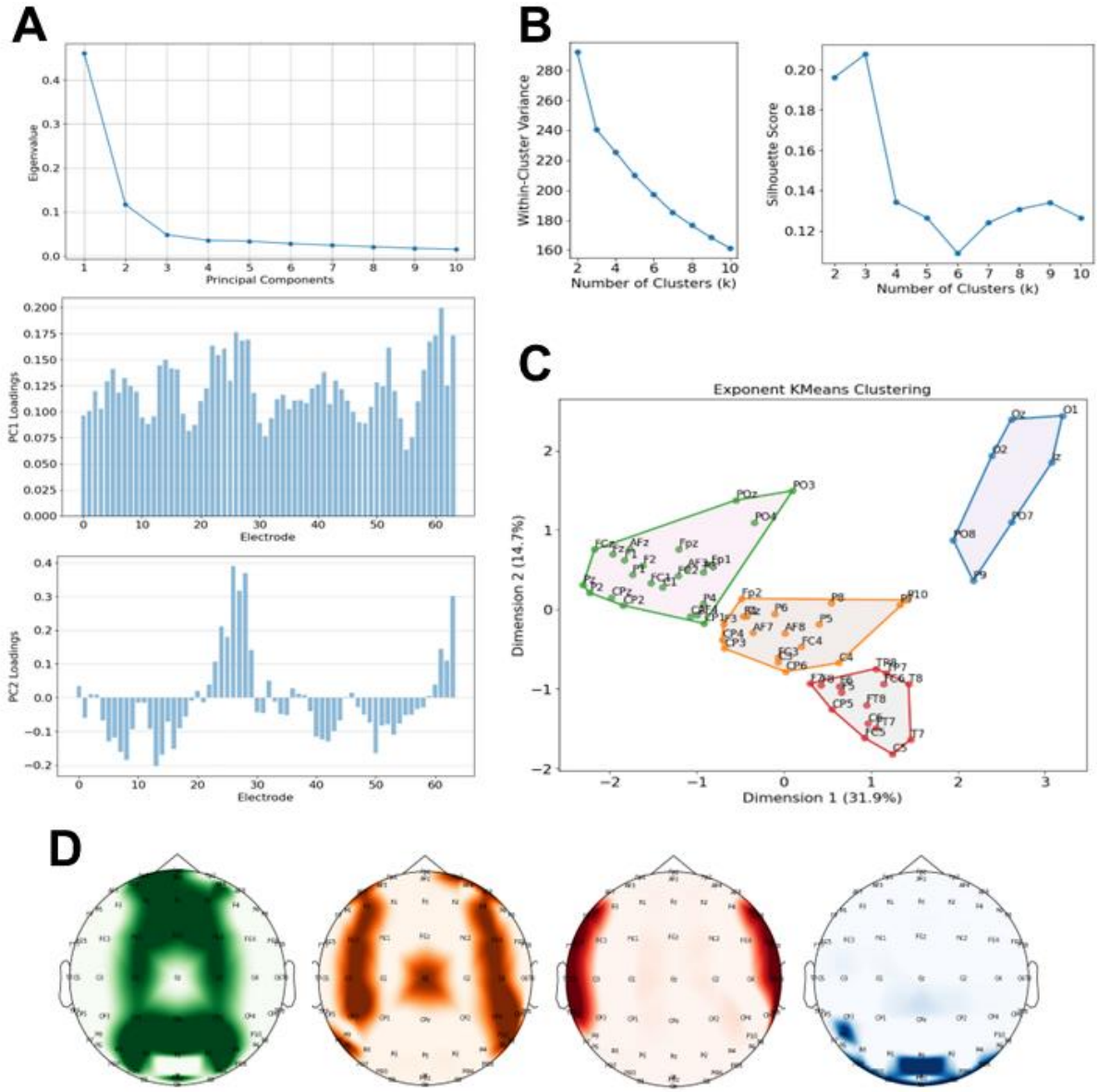

Figure 2. Data reduction protocol for exponent data. First, principal components analysis (PCA) was performed to identify sources of variability in the data (A). The number of clusters used in K-Means clustering was then determined by visualising the elbow plot and silhouette score of the exponent data. Four clusters were deemed suitable for clustering (B). Clustering of the exponent data was performed in the PCA dimensional space (C). Midline (green), frontoparietal (orange), central (red), and occipital (blue) electrode clusters were identified (D).

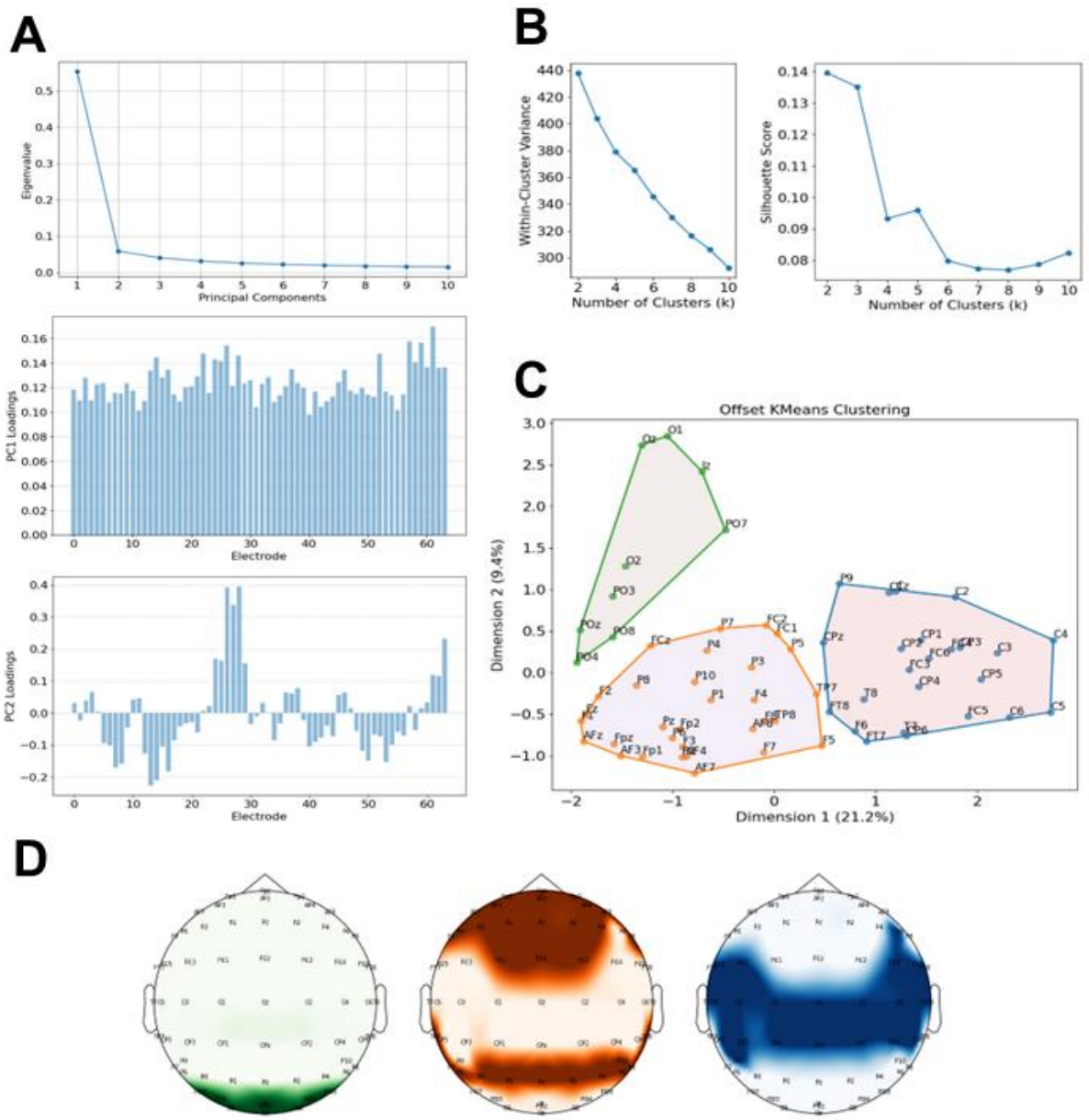

Figure 3. Data reduction protocol for offset data. First, principal components analysis (PCA) was performed to identify sources of variability in the data (A). The number of clusters used in K-Means clustering was then determined by visualising the elbow plot and silhouette score of the offset data. Three to four clusters were deemed suitable for clustering (B). Clustering of the offset data was performed in the PCA dimensional space (C). Occipital (green), frontoparietal (orange), and central (blue) electrode clusters were identified (D).

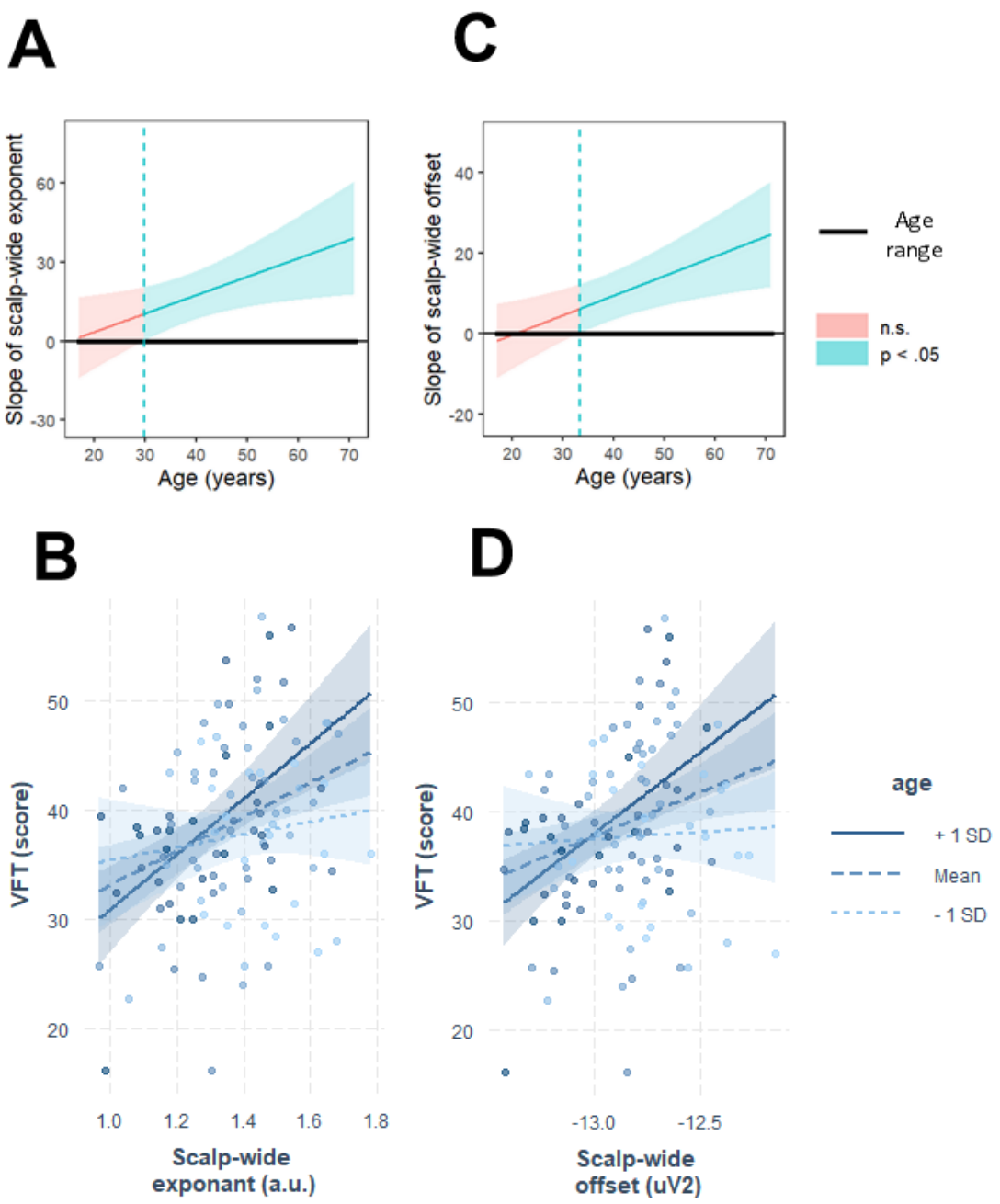

Figure 4. Johnson-Neyman plots (A and C) and interaction plots (B and D) for Verbal Fluency Test (VFT) and scalp-wide averages of the exponent and offset. Reductions in the scalp-wide average exponent and offset were associated with worse performance during the Verbal Fluency tasks for adults greater than 30 years and 33 years of age, respectively. Smaller scores indicate worsening performance during the Verbal Fluency tasks. Mean age = 37.5 years, -1 SD = 23.5 years, +1 SD = 51.5 years. Error bars represent 95% confidence intervals.

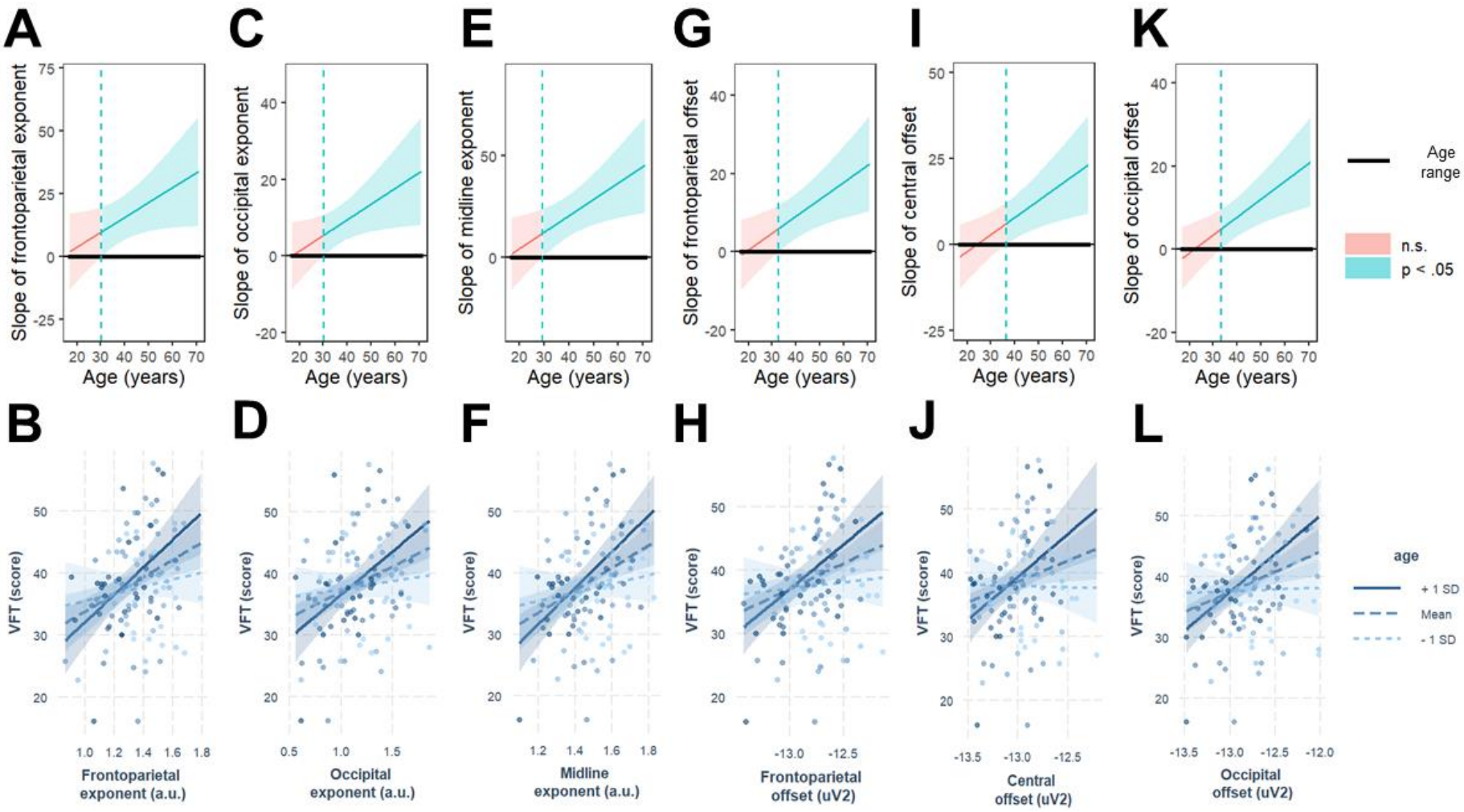

Figure 5. Johnson-Neyman plots (top row) and interaction plots (bottom row) for Verbal Fluency Test (VFT). Reductions in the frontoparietal (A, B), occipital (C, D), and midline (E, F) exponent were associated with worse performance during the VFT for adults over the age of 30 years. Similarly, reductions in the frontoparietal (G,H), occipital (I,J), and central (K,L) offset were

associated with worse performance during the VFT for adults over the age of 33-37 years. Greater score indicates improving performance during the VFT. Mean age = 37.5 years, -1 SD = 23.5 years, +1 SD = 51.5 years. Error bars represent 95% confidence intervals.