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

Abbreviated title: Aperiodic EEG activity and cognition

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Abbreviations: CWIT, Colour-Word Interference Test; DKEFS, Delis-Kaplan Executive Function System score; E:I, Excitation: inhibition; FTT, Fast Fourier Transformation; IAPF, Individual alpha peak frequency; SRM, Stimulus-Selective Response Modulation; OLS, Ordinary least squares; PCA, Principal components analysis; PSD, Power spectral density; RAVLT, Reys Adult Verbal Learning Test; SOBI, Second order blind identification; WAIS-IV DST, Wechsler Adult Intelligence Scale IV Digit Span Test; VFT, Verbal Fluency Test.

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 consisting of the Colour-Word Interference Test, Wechsler Adult Intelligence Scale IV Digit Span Test, Rey Auditory Learning Test, Delis-Kaplan Executive Function System Trial Making Test, and the Verbal Fluency Test. 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. Offset by age interactions were identified for the Verbal Fluency Test, where smaller offsets were associated with poorer performance in adults as early as 33 years of age. Greater aperiodic activity is increasingly related to better verbal fluency performance with age in adulthood.

KEYWORDS

Cognitive decline, Neural biomarkers, Executive function, Neurocognitive aging, Brain oscillations, Resting-state neural dynamics

INTRODUCTION

Investigations into the encephalogram (EEG) have historically focused on oscillatory activity across the power spectrum. 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 (the slope of the EEG broadband) and offset (*y*-intercept of the EEG broadband) 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 are 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; D. McKeown et al., 2023).

Aging is associated with wide-scale changes in aperiodic activity reflecting non-pathological changes in neuronal networks (Finley et al., 2024; Voytek et al., 2015). The exponent reduces with age, suggesting increases in E:I balance, while the offset declines, likely reflecting reduced neural firing (Clark et al., 2024; Finley et al., 2024; Merkin et al., 2023; Voytek et al., 2015). Aperiodic activity also plays a role in maintaining cognitive function throughout life (Pathania et al., 2022). Previous research shows 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 performance (Waschke et al., 2021). However, these associations do not appear across all ages or tasks, suggesting that the relationship between aperiodic activity and cognition varies 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 aperiodic exponent and individual constructs of working memory, perceptual reasoning, processing speed, and verbal comprehension in 166 participants (18 – 52 years). However, combining the eight Wechsler Adult Intelligence Scale subtests revealed that higher exponents were associated with greater general ability. While Cesnaite et al. (2023) found no associations between aperiodic activity and cognitive performance in an older cohort (n = 1703, 60 – 80 years), Smith et al. (2023) linked higher exponents with better general cognitive function but not age (n = 86, 50 – 80 years). While these effects may vary by age and task, most studies focus on limited age ranges, excluding early-life (*M*age = 54.86, 36 - 83 years; Finley et al., 2024), and including exclusively older cohorts (50 - 80 years; Cesnaite et al., 2023; Smith et al., 2023). To date, no studies have examined associations between aperiodic activity, and cognitive ability inclusively across early, mid, and late life.

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 resting EEG and cognitive performance was derived from performance measures of a cognitive test battery consisting of a Colour-Word Interference Test, Wechsler Adult Intelligence Scale IV Digit Span Test, Rey Auditory Learning Test, Delis-Kaplan Executive Function System Trial Making Test, and a Verbal Fluency Test. We hypothesise that reductions in aperiodic activity will be associated with worse performance in each cognitive test and 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; Figure 1) and consisted of 68 females. The Bond University Human Research Ethics Committee approved our secondary analysis of this data (approval number: DA202221102).

Figure 1 here

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 an off-line anti-aliasing filter applied, algorithmically 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 second order blind identification (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. After preprocessing, continuous data was segmented into 4-second epochs with no overlap.

In our secondary analysis, 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 power was also excellent with 94.95% of channels having retained a peak in the alpha band.

Cognitive Test Battery

Participants in the study completed a battery of neurophysiological tests consisting 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). Outcomes measures for the tests consisted of time in seconds to complete the tasks for the Colour-Word Interference Test and the Trail Making Test, and total score for the Digit Span Test, Rey Auditory Learning Test and Verbal Learning 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). Correlations between each electrode cluster and the battery of cognitive tests were corrected for multiple comparisons using the Benjamini and Hochberg method ($_{BH}$; Benjamini & Hochberg, 1995). Following this, we fit the data using iteratively reweighted least-squares robust regression models (statsmodels v0.14.0; Holland & Welsch, 1977) to mitigate the heteroscedasticity of the data. A base formula was constructed that accounted for the impact of age:

Equation 1:

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

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

EEG Data Reduction

We performed a data reduction protocol using PCA and K-Means clustering 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 2A). Correlation matrices were then constructed to identify groups of electrodes that had exhibited similar relationships of aperiodic activity (Figure 2B). In general, exponent,

and offset values were greater and correlated at frontal (exponent r = .60, offset r = .69) and parietal (exponent r = .58, offset r = .67) 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.

Figure 2 here

PCA and K-Means clustering were then performed on the exponent (Figure 3) and offset (Figure 4) 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 cluster centroids would be suitable for grouping the exponent (Figure 3B) and offset (Figure 4B) data in the PCA dimension space, respectively. For the exponent, frontoparietal, frontotemporal and centrotemporal, occipital, and midline clusters were identified (Figure 3C and 3D). For the offset, frontoparietal, central, and occipital clusters were identified (Figure 4C and 4D). Electrodes contained within each cluster can be found in Table 1.

Figure 3 & 4 here

Table 1 here

Correlations

Results of the zero-order correlations are available in the top right quadrant of Table 2. Results of the partial correlations accounting for age are available in the bottom left quadrant of Table 2 and significant correlations are summarised below.

Table 2 here

Age was negatively correlated with the average exponent (r = -.38, p_{BH} <.001) and the average offset (r = -.41, p_{BH} <.001), and at frontoparietal (r = -.40, p_{BH} <.001), frontotemporal and centrotemporal (r = -.38, p_{BH} <.001), and midline clusters (r = -.37, p_{BH} <.001) for the exponent, and at frontoparietal (r = -.41, p_{BH} <.001), central (r = -.39, p_{BH} <.001), and occipital (r = -.36, p_{BH} <.001) clusters for the offset. That is, the exponent and the offset reduced with age. Age was associated with longer durations to perform the Colour-Word Interference Test (r = .25, p_{BH} = .012) and the Trail Making Test (r = .38, p_{BH} = <.001), while lower scores on the the Ray Adult Verbal Learning Test (r = .24, p_{BH} = <.001).

When accounting for age, the exponent at each electrode cluster correlated with each other (r = .39 – .86, p_{BH} < .001), as well as with the scalp-wide average exponent (r = .73 – .96, p_{BH} < .001). The scalp-wide average exponent (r = -.22, CI = -.41 – -.05, p_{BH} = .034) and frontoparietal exponent (r = -.23, CI = -.41 – -.05, p_{BH} = .026) negatively correlated with the Colour-Word Interference Test. The scalp-wide average exponent (r = .32, CI = .14 – .48, p_{BH} = .001), frontoparietal exponent (r = .29, CI = .11 – .45, p_{BH} = .004), occipital exponent (r = .29, CI = .1 – .45, p_{BH} = .005), and midline exponent (r = .34, CI = .16 – .49, p_{BH} < .001), were all positively correlated with Verbal Fluency Test performance. That is, greater exponents were associated with faster time during the Colour-Word Interference Test and greater score during the Verbal Fluency Test.

The offset at each electrode cluster correlated with each other (r = .68 - .89, p_{BH} < .001), as well as with the scalp-wide average offset (r = .84 – .98, p_{BH} < .001). The frontoparietal offset (r = .26, CI = .08 – .43, p_{BH} = .012), and the occipital offset (r = .25, CI = .07 – .42, p_{BH} = .015) positively correlated with Verbal Fluency Test performance. That is, higher offsets were associated with better performance during the Verbal Fluency Test.

Aperiodic Activity and Age as Predictors of Cognitive Function

There were only significant main effects for the Colour-Word Interference Test and the Verbal Learning Test, and interaction effects for the Verbal Learning Test. Results of these tests are summarised below while the results of the models for the other tests, are reported in Table 3 for the exponent models and Table 4 for the offset models.

Table 3 & 4 here

Colour-Word Interference Test. In the exponent models, there was a main effect of age for the occipital exponent (β = .38, CI = -.03 – .80, p_{BH} = .049). There were no other main effects or interactions for the scalp-wide average exponent nor the exponent clusters.

Verbal Fluency Test. 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_{BH} = .022), and at frontoparietal (β = 5.59, CI = 1.44 – 9.73, p_{BH} = .041), central (β = 6.49, CI = 1.74 – 11.26, p_{BH} = .044), and occipital (β = 5.58, CI = 1.91 – 9.26, p_{BH} = .017) clusters, which were moderated by age interactions for the scalp-wide average (β = .48, CI = .15 – .83, p_{BH} = .024), and for the frontoparietal (β = .43, CI = .11 – .75, p_{BH} = .045), central (β = .5, CI = .13 – .86, p_{BH} = .046), and occipital (β = .43, CI = .14 – .72, p_{BH} =

.018) clusters. Johnson-Neyman plots revealed that associations were significant from 33 – 37 years of age. Simple slopes revealed that the scalp-wide association was not significant at -1 SD of age (β = 1.29, p = .740) while significant at +1 SD of age (β = 15.00, p < .001; Figure 5A and 5B). The frontoparietal cluster association was not significant at -1 SD of age (β = .39, p = .920) while significant at +1 SD of age (β = 13.49, p < .001; Figure 5C and 5D). The central cluster association was not significant at -1 SD of age (β = 1.65, p = .665) while significant at +1 SD of age (β = 13.93, p < .001; Figure 5E and 5F). The occipital cluster association was not significant at -1 SD of age (β = .60, p = .850) while significant at +1 SD of age (β = 12.64, p < .001; Figure 5G and 5H).

Figure 5 here

DISCUSSION

This study identified how resting aperiodic activity is associated with cognitive function across adulthood. Poorer performance during the Colour-Word Interference Test and Verbal Fluency Test was associated with lower exponents scalp-wide and in the frontoparietal, occipital, and midline electrode clusters. Poorer performance during the Verbal Fluency Test was also associated with smaller offsets scalp-wide and in the frontoparietal and occipital electrode clusters. Interestingly, these offset associations are moderated by age, such that better verbal fluency is associated with greater offsets in adults from 33 years of age, and this relationship strengthens across adulthood.

Increasing age was associated, to a varying degree, with poorer performance in the battery of cognitive tests consistent with Salthouse (2017). Age was also associated with lower exponents and smaller offsets, indicating greater E:I balance

and neural spiking rates in younger adults. Previous studies have 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 in the current study, partial correlations reveal that changes in aperiodic activity contribute to variation in verbal fluency performance and executive functioning independent of age. Furthermore, the regression analyses suggest the association between the aperiodic offset and verbal fluency strengthens with age, suggesting that the influence of aperiodic activity on cognitive performance becomes more pronounced across adulthood (Voytek et al., 2015). Previous studies suggest 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.

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 age-related changes that can affect cognitive function (Buckner, 2004). This can result in difficulty performing cognitively demanding tasks as aging progresses, including 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 then declining around 60 years of age (Whitley et al., 2016) but has also been demonstrated to remained 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, with new evidence suggesting differences in resting theta activity are likely due to aperiodic activity (Cesnaite et al., 2023; Finley et al., 2022; D. J. 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 EEG recordings warrants further investigation.

We identified that smaller offsets at frontoparietal, central, and occipital clusters and scalp-wide averages, were associated with poorer performance on the Verbal Fluency Test. What we did not initially expect was that these associations were present in adults as early as 33 years of age (Clark et al., 2009; Price et al., 2012; Whitley et al., 2016). As smaller offsets indicate a decrease in neural spiking rate (Donoghue et al., 2020; Gao et al., 2017), the presence of poorer performance during the Verbal Fluency Test indicates that maintenance of neural spiking from early adulthood onwards may be beneficial for maintaining higher-order cognitive processing throughout the lifespan.

Considerations

Investigations into the associations between aperiodic EEG activity and cognition are still in their infancy, however, 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 contributing 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

containing a larger age range may explain why aperiodic activity and age interactions were found for Verbal Fluency.

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. Education level should be considered in future studies and should be controlled for and examined as a potential moderator.

Conclusion

Our study examined variations in resting aperiodic EEG activity with age 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 performance during the Colour-Word Interference Test and Verbal Fluency Test. Aperiodic activity and age interactions were observed for the Verbal Fluency Test, where smaller offsets were associated with progressively worse Verbal Fluency Test performance with age, with associations appearing as early as 33 years of age. The presence of 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 understood, even as the relationship becomes more pronounced with age.

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TABLES

Table 1: Electrodes contained within each cluster.

	Electrodes
Exponent clusters	
Frontoparietal	Fp1, AF7, AF3, F1, F3, F5, F7, FC1, TP7, P1, P3, P5, P7, Pz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F8, FC2, FCz, TP8, P2, P4, P6, P8, P10
Occipital	PO7, PO3, O1, Iz, Oz, POz, PO8, PO4, O2
Midline	Fp1, AF3, F1, FC1, C1, CP1, P1, P3, PO3, POz, Pz, CPz, Fpz, AF4, AFz, Fz, F2, FC2, FCz, C2, CP2, P2, P4, PO4
Fronto/Centrotemporal	FT7, FC5, FC3, C1, C3, C5, T7, CP5, CP3, CP1, P9, CPz, F6, FT8, FC6, FC4, Cz, C2, C4, C6, T8, CP6, CP4, CP2
Offset clusters	
Frontoparietal	Fp1, AF7, AF3, F1, F3, F5, F7, FC1, TP7, P1, P3, P5, P7, Pz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F8, FC2, FCz, TP8, P2, P4, P6, P8, P10
Occipital	PO7, PO3, O1, Iz, Oz, POz, PO8, PO4, O2
Central	FT7, FC5, FC3, C1, C3, C5, T7, CP5, CP3, CP1, P9, CPz, F6, FT8, FC6, FC4, Cz, C2, C4, C6, T8, CP6, CP4, CP2

Table 2: Descriptive statistics, bivariate correlation (upper right quadrant), and partial correlations controlling for age (lower left quadrant).

	Mean SD	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12
i. Age	37.5 13.99	**-.38**	**-.41**	**-.40**	**-.38**	-.16	**-.37**	**-.41**	**-.39**	**-.36**	**.25**	-.15	**-.24**	**.38**	.004
ii. Exponent scalp-wide average	1.36 .17		**.80**	**.96**	**.88**	**.73**	**.94**	**.79**	**.74**	**.74**	**-.30**	.08	.18	**-.25**	**.29**
iii. Offset scalp-wide average	-12.84 .27	**.76**		**.79**	**.72**	**.53**	**.79**	**.98**	**.95**	**.86**	**-.23**	.11	**.23**	**-.22**	**.22**
Exponent clusters															
1. Frontoparietal	1.35 .18	**.96**	**.75**		**.87**	**.63**	**.88**	**.79**	**.77**	**.67**	**-.31**	.09	.18	**-.26**	**.27**
2. Fronto/Centrotemporal	1.26 .22	**.86**	**.66**	**.85**		**.42**	**.74**	**.71**	**.74**	**.52**	**-.23**	.08	.12	-.20	.19
3. Occipital	1.17 .30	**.73**	**.47**	**.61**	**.39**		**.7**	**.49**	**.39**	**.77**	**-.24**	.14	**.21**	**-.20**	**.28**
4. Midline	1.48 .15	**.93**	**.74**	**.86**	**.68**	**.68**		**.79**	**.69**	**.77**	**-.28**	.03	.16	**-.25**	**.31**
Offset clusters															
5. Frontoparietal	-12.76 .28	**.75**	**.98**	**.74**	**.65**	**.44**	**.75**		**.91**	**.82**	**-.23**	.10	**.22**	**-.23**	**.24**
6. Central	-12.95 .26	**.70**	**.95**	**.72**	**.69**	**.33**	**.62**	**.89**		**.72**	-.22	.09	**.21**	-.19	.16
7. Occipital	-12.95 .26	**.70**	**.84**	**.61**	**.42**	**.74**	**.72**	**.81**	**.68**		-.20	.15	**.25**	**-.22**	**.24**
Cognitive Test Battery															
8. CWIT	39.06 7.81	**-.22**	-.14	**-.23**	-.15	-.21	-.20	-.15	-.13	-.11		**-.41**	**-.45**	**.66**	**-.62**
9. WAIS-IV DST	28.16 5.02	.03	.05	.03	.02	.11	-.03	.05	.03	.10	**-.39**		**.28**	**-.46**	**.37**
10. RAVLT	60.41 7.67	.11	.15	.10	.03	.18	.09	.14	.13	.18	**-.42**	**.26**		**-.49**	**.34**
11. DKEFS TMT	41.42 16.31	-.13	-.08	-.12	-.05	-.15	-.13	-.08	-.04	-.09	**.64**	**-.44**	**-.45**		**-.39**
12. VFT	38.12 8.10	**.32**	**.24**	**.29**	.20	**.29**	**.34**	**.26**	.18	**.25**	**-.65**	**.37**	**.35**	**-.42**	

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, Reys Adult Verbal Learning Test score; DKEFS TMT, Delis-Kaplan Executive Function System Trail Making Test score; VFT, Verbal Fluency Test score.

Table 3: Exponent by age robust regression models.

		CWIT			WAIS-IV DST			RAVLT			DKEFS TMT			VFT		
	Predictor	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}
Scalp-wide average	*Intercept*	27.70	-4.81 60.22	.09	21.99	-.12 44.11	.05	**28.62**	**11.62** **45.62**	**<.01**	31.29	-35.41 98.01	.36	**49.73**	**16.28** **83.18**	**<.01**
	Exponent	5.81	-17.46 29.07	.61	5.88	-9.94 21.76	.61	1.54	-10.62 13.71	.97	-3.22	-50.95 44.52	.72	-10.60	-34.54 13.33	.60
	Age	.67	-.103 1.44	.07	.12	-.39 .64	.56	-.09	-.49 .31	.56	.70	-.87 2.27	.17	-.86	-1.65 -.07	.10
	Exponent X Age	-.43	-1.00 .141	.09	-.13	-.51 .25	.55	.02	-.27 .32	.64	-.23	-1.39 .93	.45	.70	.12 1.28	.09
Frontoparietal	*Intercept*	30.21	-1.52 61.93	.06	**24.99**	**3.37** **46.63**	**.02**	**28.91**	**12.31** **45.52**	**<.01**	26.38	-38.75 91.52	.43	**46.51**	**13.32** **79.69**	**<.01**
	Exponent	4.06	-18.64 26.76	.69	3.66	-11.82 19.14	.69	1.34	-10.53 13.23	.98	.36	-46.25 46.97	.69	-8.1	-31.85 15.65	.69
	Age	.61	.14 1.36	.10	.05	-.47 .56	.82	-.08	-.48 .31	.57	.79	-.75 2.34	.15	-.71	-1.5 .07	.17
	Exponent X Age	-.39	-.95 .17	.16	-.07	-.45 .31	.68	.02	-.27 .32	.68	-.30	-1.45 .84	.29	.59	.00 1.18	.16
Fronto/ Centrotemporal	*Intercept*	**25.33**	**1.71** **48.96**	**.03**	**24.63**	**8.76** **40.49**	**<.01**	**32.20**	**19.96** **44.45**	**<.01**	17.99	-30.1 66.1	.46	**47.78**	**22.79** **72.77**	**<.01**
	Exponent	7.57	-10.33 25.48	.53	4.31	-7.71 16.34	.53	-.93	-10.21 8.35	.72	6.08	-30.37 42.54	.53	-8.94	-27.89 9.99	.53
	Age	.53	-.01 1.07	.05	.07	-.29 .44	.65	-.11	-.39 .16	.34	.75	-.34 1.85	.05	-.49	-1.06 .07	.23
	Exponent X Age	-.34	-.76 -.08	.23	-.10	-.39 .19	.53	.04	-.18 .26	.53	-.27	-1.14 .6	.23	.43	-.02 .89	.23
Occipital	*Intercept*	**31.14**	**14.57** **47.72**	**<.01**	**26.04**	**14.89** **37.19**	**<.01**	**16.00**	**17.49** **34.51**	**<.01**	**33.66**	**-.01** **67.33**	**.05**	**45.11**	**27.93** **62.28**	**<.01**
	Exponent	2.86	-10.82 16.56	.52	3.32	-5.89 12.53	.52	4.19	-2.84 11.22	.52	-6.72	-34.54 21.1	.81	-6.95	-21.14 7.24	.52
	Age	**.38**	**-.03** **.80**	**.04**	.00	-.28 .28	.93	.002	-.21 .21	.93	.45	-.4 1.3	.39	-.44	-.88 -.01	.10
	Exponent X Age	-.22	-.58 .13	.18	-.04	-.28 .20	.90	-.05	-.24 .13	.90	-.02	-.76 .70	.90	.41	.04 .78	.16
Midline	*Intercept*	28.16	-12.36 68.69	.17	22.17	-5.15 49.5	.11	**31.52**	**10.49** **52.54**	**.003**	39.71	-42.77 122.18	.35	**52.89**	**11.94** **93.85**	**.01**
	Exponent	4.83	-21.98 31.65	.85	5.49	-12.59 23.57	.85	-.47	-14.38 13.44	.85	-8.69	-63.27 45.88	.89	-11.91	-39.01 15.18	.85
	Age	.68	-.25 1.63	.13	.18	-.46 .82	.46	-.16	-.65 .33	.34	.58	-1.35 2.5	.34	-1.10	-2.06 -.15	.10

Exponent X Age	-.40	-1.04	.25	-.17	-.6	.49	.07	-.26	.48	-.13	-1.44	.52	.80	.16	.06
		.24			.27			.41			1.18			1.46	

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, Reys Adult Verbal Learning Test score; DKEFS TMT, Delis-Kaplan Executive Function System Trail Making Test score; VFT, Verbal Fluency Test score.

Table 4: Offset by age robust regression models

		CWIT			WAIS-IV DST			RAVLT			DKEFS TMT			VFT		
	Predictor	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}	*β*	*CI*	p_{BH}
Scalp-wide average	*Intercept*	52.61	-123.64 228.86	.56	36.89	-80.49 154.28	.54	39.99	-49.49 129.47	.38	126.25	-228.01 480.52	.49	-95.91	-275.26 83.44	.29
	Offset	1.36	-12.38 15.11	.96	.55	-8.61 9.71	.96	.74	-6.24 7.72	.96	7.77	-19.86 35.41	.68	-10.22	-24.21 3.77	.67
	Age	-1.89	-6.22 2.42	.82	.14	-2.73 3.03	.96	.50	-1.68 2.70	.78	-3.88	-12.57 4.81	.30	**6.38**	**1.98** **10.78**	**.02**
	Offset X Age	-.15	-.49 .18	.76	.01	-.21 .24	.94	.04	-13 .21	.73	-.33	-1.01 .34	.24	**.48**	**.15** **.83**	**.02**
Frontoparietal	*Intercept*	28.56	-141.07 198.19	.74	39.68	-73.18 152.53	.49	44.11	-42.06 130.28	.32	97.78	-242.86 438.43	.57	-68.51	-240.86 103.83	.44
	Offset	-.51	-13.82 12.79	.81	.76	-8.09 9.82	.88	1.06	-5.69 7.82	.88	5.58	-21.14 32.31	.79	-8.13	-21.64 5.4	.79
	Age	-1.18	-5.26 2.89	.93	.01	-2.71 2.72	.93	.29	-1.77 2.37	.93	-3.1	-11.28 5.09	.29	**5.59**	**1.44** **9.73**	**.04**
	Offset X Age	-.10	-.42 .22	.95	.01	-.21 .22	.95	.02	-.13 .18	.94	-.27	-.91 .37	.23	**.43**	**.11** **.75**	**.04**
Central	*Intercept*	79.65	-101.38 260.69	.39	27.91	-92.81 148.64	.65	16.89	-75.08 108.87	.72	172.55	-191.76 536.49	.35	-119.82	-307.58 67.94	.21
	Offset	3.45	-10.55 17.44	.97	-.15	-9.45 9.17	.97	-1.05	-8.16 6.05	.97	11.32	-16.84 39.49	.47	-12.04	-26.56 2.48	.47
	Age	-2.57	-7.17 2.01	.61	.23	-2.83 3.29	.91	1.04	-1.28 3.38	.45	-4.64	-13.88 4.6	.27	**6.49**	**1.74** **11.26**	**.04**
	Offset X Age	-.21	-.56 .14	.56	.02	-.21 .26	.88	.08	-.09 .26	.41	-.39	-1.1 .32	.22	**.5**	**.13** **.86**	**.04**
Occipital	*Intercept*	70.96	-76.25 218.17	.34	40.15	-57.26 137.56	.42	60.31	-13.97 134.60	.08	86.76	-208.14 381.68	.56	-85.91	-234.46 62.64	.26
	Offset	2.83	-8.69 14.36	.83	.82	-6.80 8.45	.83	2.33	-3.48 8.14	.83	4.71	-18.37 27.8	.83	-9.51	-21.14 2.12	.47
	Age	-1.83	-5.47 1.81	.73	.25	-2.16 2.66	.82	-.09	-1.93 1.74	.77	-2.82	-10.13 4.47	.72	**5.58**	**1.91** **9.26**	**.01**
	Offset X Age	-0.15	-.43 .13	.64	.02	-.17 .21	.77	-.003	-.14 .14	.77	-.25	-.82 .32	.59	**.43**	**.14** **.72**	**.01**

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, Reys Adult Verbal Learning Test score; DKEFS TMT, Delis-Kaplan Executive Function System Trail Making Test score; VFT, Verbal Fluency Test score.

FIGURES

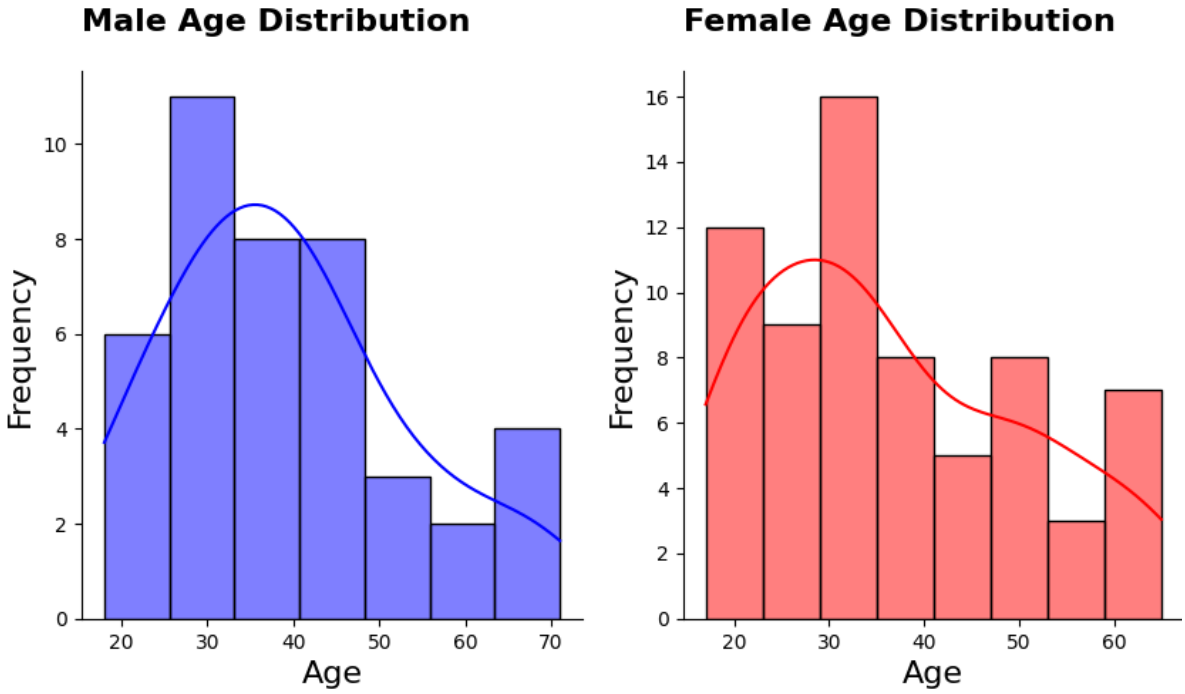

Figure 1. Age distribution for male and female participants.

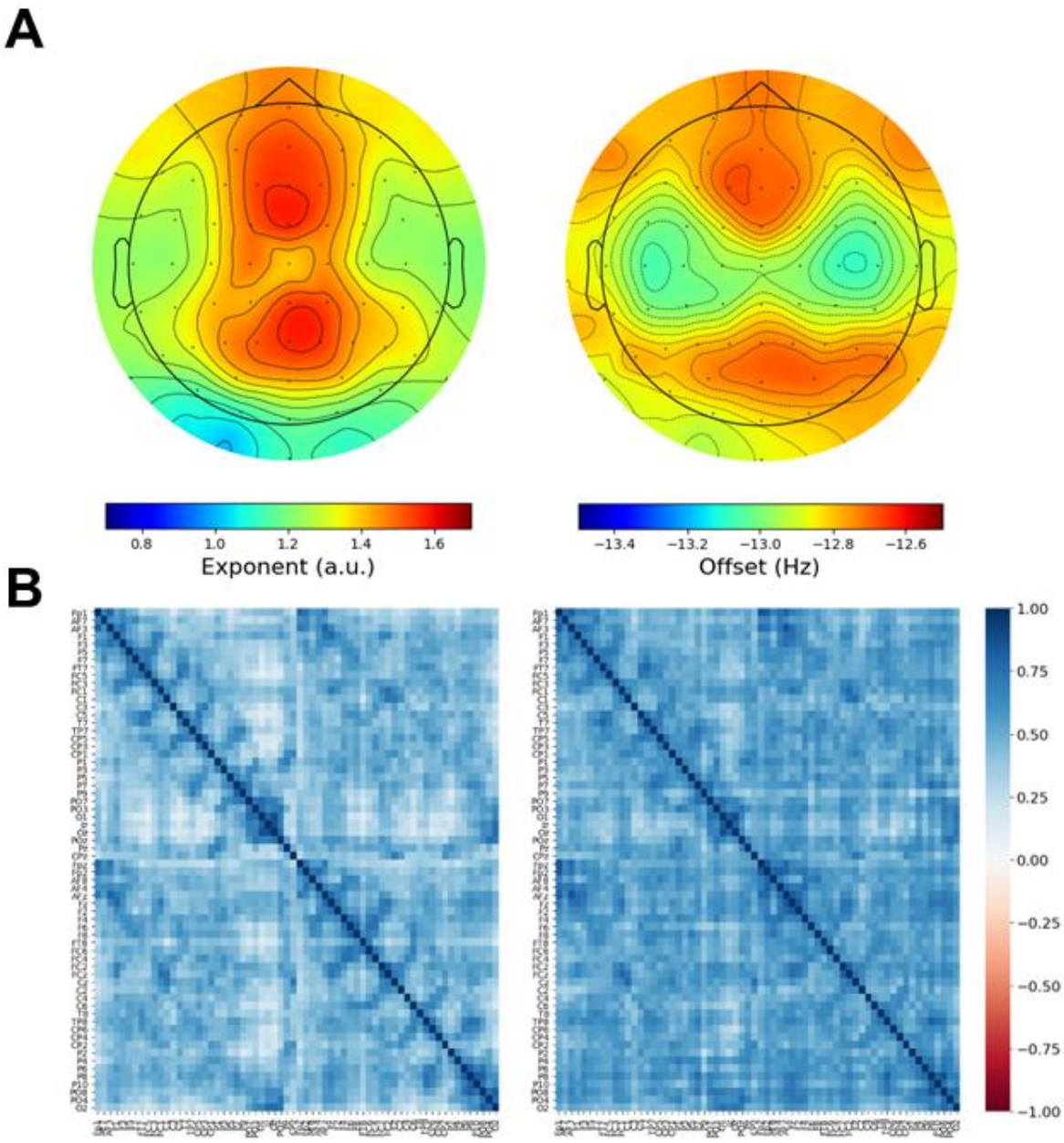

Figure 2. Group average topographies of the exponent and offset during eyes-closed resting EEG (A) and electrode correlation matrices for the exponent and offset (B).

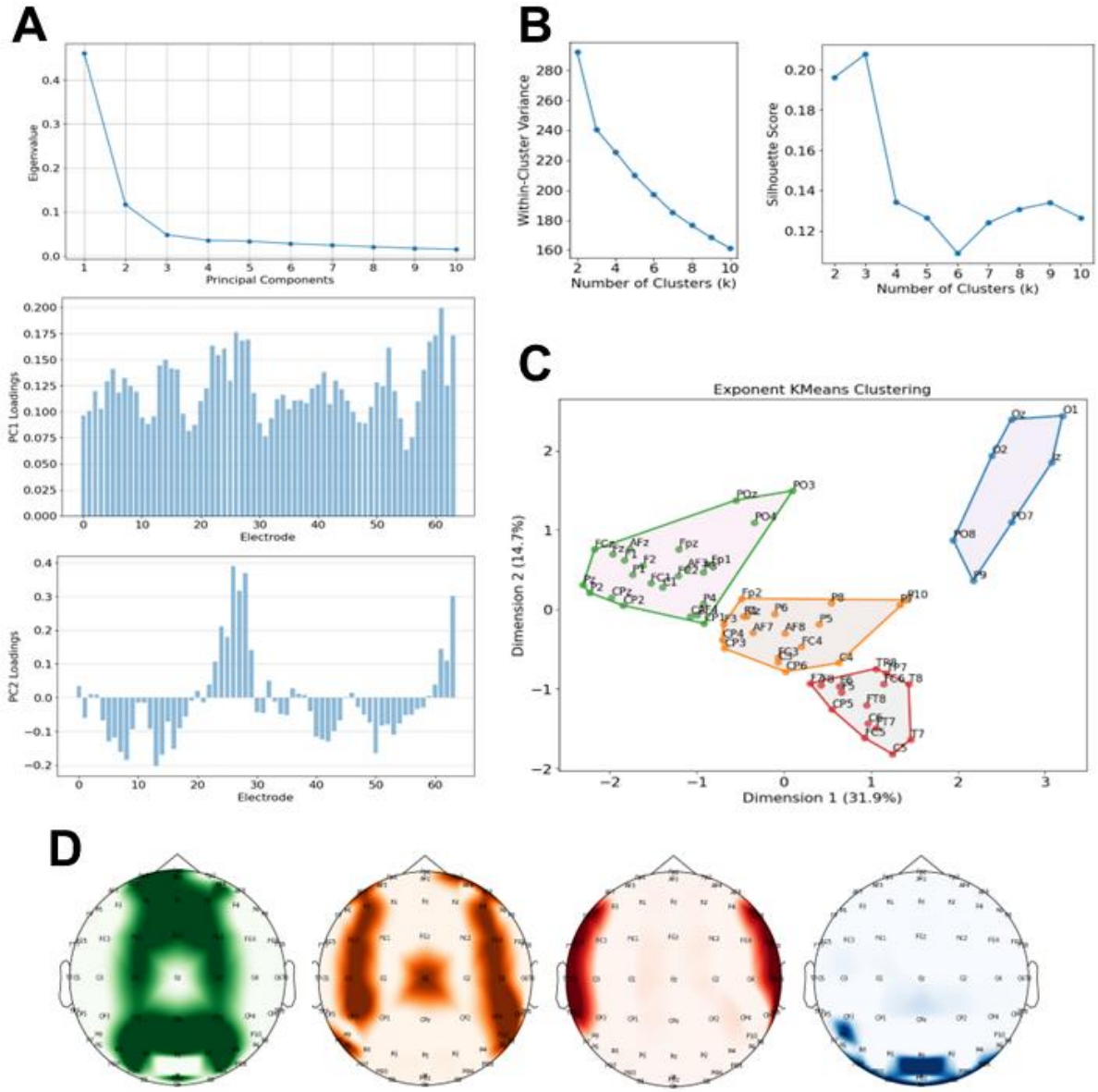

Figure 3. Data reduction protocol for exponent data. First, principal components analysis (PCA) was performed to identify sources of variability in the data (A). The number of clusters used in K-Means clustering was then determined by visualising the elbow plot and silhouette score of the exponent data. 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), frontotemporal and centrotemporal (red), and occipital (blue) electrode clusters were identified (D).

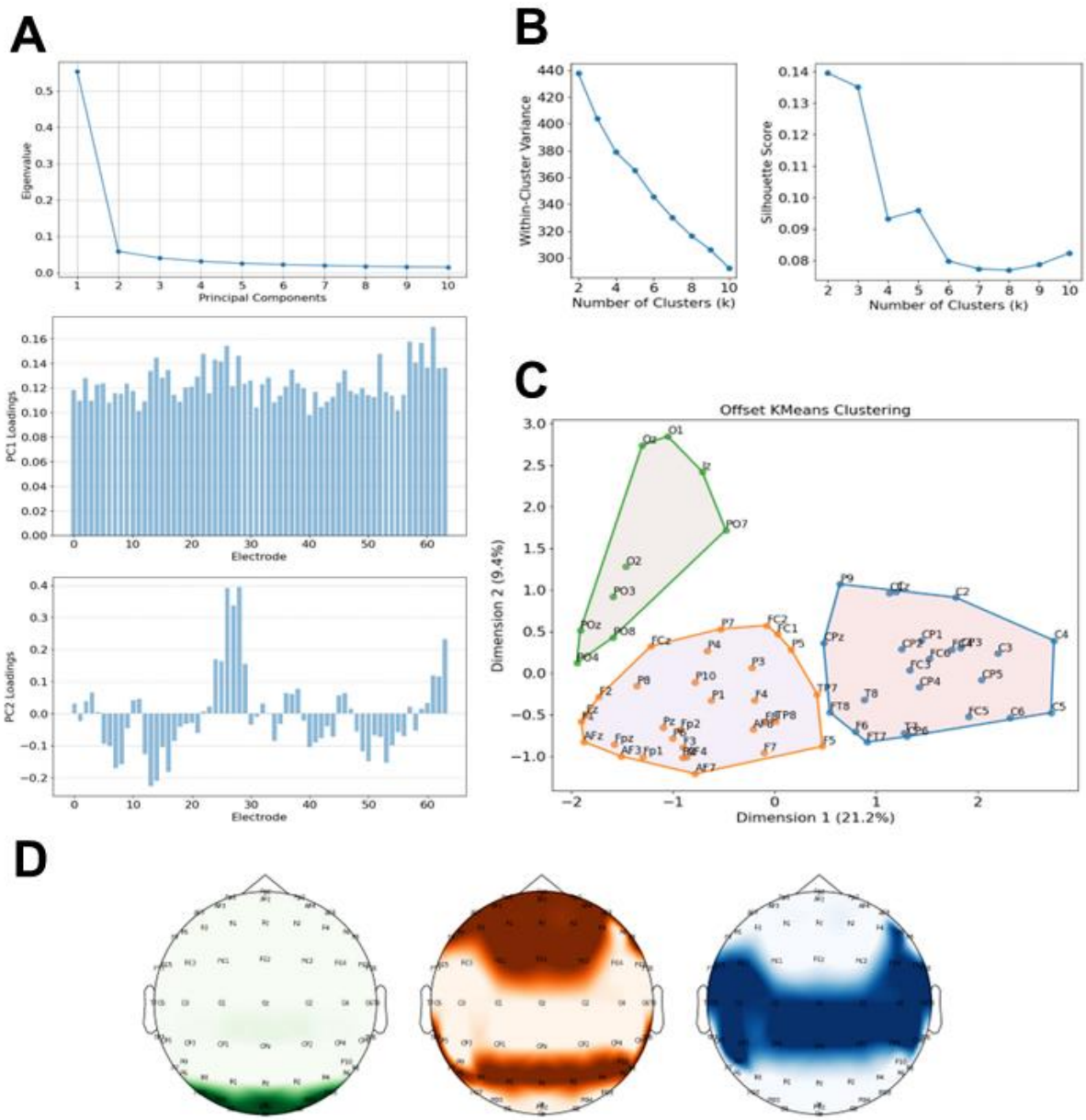

Figure 4. Data reduction protocol for offset data. First, principal components analysis (PCA) was performed to identify sources of variability in the data (A). The number of clusters used in K-Means clustering was then determined by visualising the elbow plot and silhouette score of the offset data. Three 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).

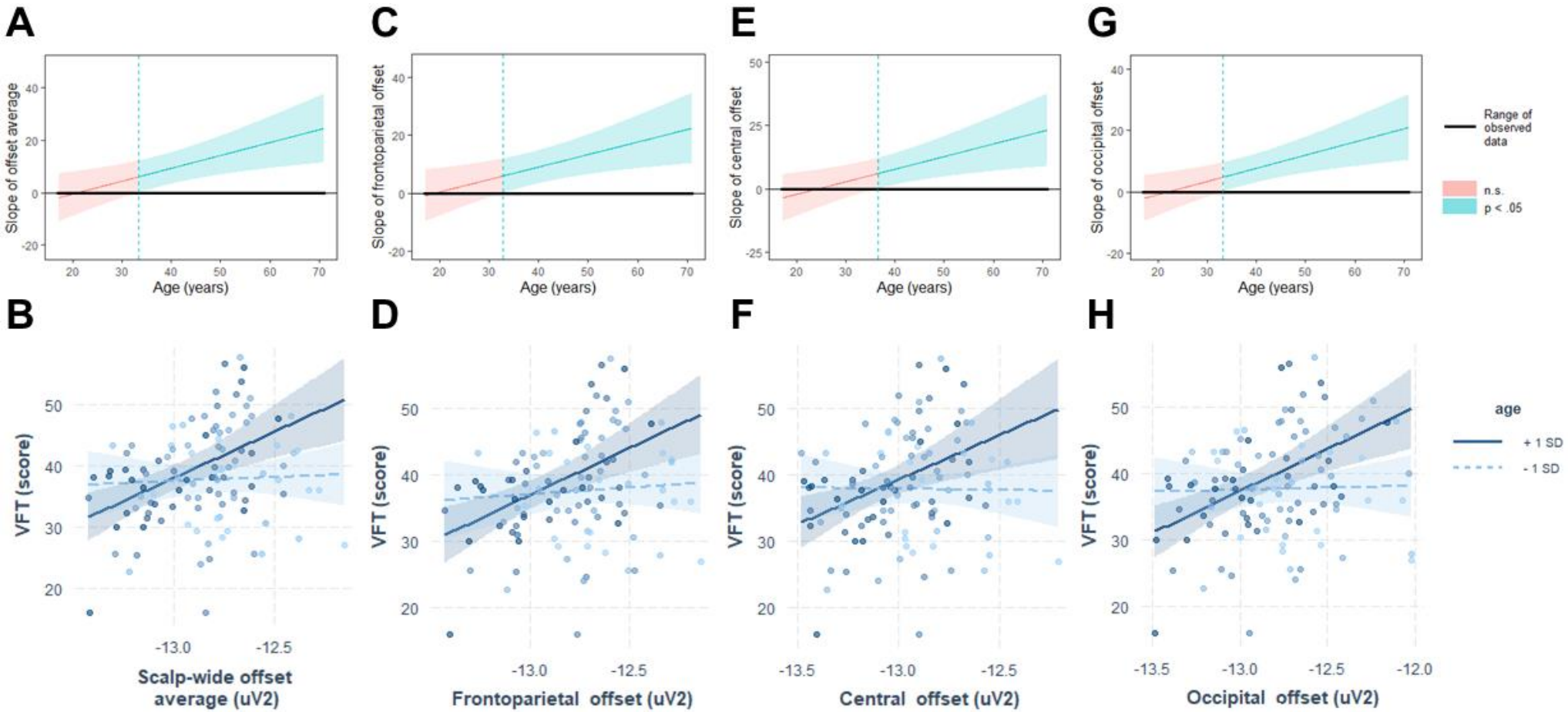

Figure 5. Johnson-Neyman plots (top row) and interaction plots (bottom row) for Verbal Fluency Test (VFT). Reductions in the scalp-wide average (A, B), frontoparietal (C, D), central (E, F), and occipital offset were associated with worse performance during the VFT for adults over the age of 33-37 years. Greater score indicates improving performance during the VFT. -1 SD age = 23.5 years, +1 SD age = 51.5 years. Error bars represent 95% confidence intervals.