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Age-dependent modulation of inhibitory control: behavioral and EEG evidence from the Stroop paradigm

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Abstract

Aim: Aging is associated with reduced inhibitory control, leading to challenges in attention, decision-making, and everyday cognitive tasks. To better understand these difficulties, it is important to adopt well-designed experimental approaches that specifically assess inhibitory control mechanisms. A commonly used tool to assess how inhibitory control changes with age is the Stroop Color and Word Test, which evaluates the capacity to suppress automatic responses in favor of appropriate behavior.

Methods: In the present study, a sample of 91 healthy individuals was examined to investigate how cognitive functions underlying Stroop task performance vary across the adult lifespan. Pearson correlations were computed between participants' age and response times (RTs) recorded in each of the three Stroop conditions, as well as the mean RTs across all conditions. Furthermore, to assess whether these behavioral patterns were mirrored at the neurophysiological level, power spectral density (PSD) analyses were performed on resting-state electroencephalographic recordings.

Results: In all cases, Pearson correlations were strongly significant, with stronger effects observed as task difficulty increased. At the neurophysiological level, a correlation emerged between RTs and PSD in the occipital region within the alpha 2 frequency band, which, like the behavioral effects, became progressively stronger with increasing task difficulty. In contrast, no significant correlations were observed for the alpha 1 band, suggesting that these neurophysiological changes are specific to higher alpha frequencies linked to increased cognitive demands and inhibitory control processes.

Conclusions: These findings contribute to a better understanding of the neural mechanisms underlying age-related declines in inhibitory control and may inform the development of interventions aimed at mitigating cognitive deficits in older adults.

Keywords

inhibitory control, Stroop, EEG, power spectral density

Introduction

Physiological aging is characterized by a gradual and multifaceted decline in cognitive functioning, even in the absence of neurodegenerative pathology. The degree and pattern of these cognitive changes vary widely among individuals, influenced by a complex interplay of genetic, biological, environmental, and lifestyle factors [1–3]. Processing speed tends to slow with age, resulting in longer reaction times and reduced efficiency in information processing [4]. As individuals age, the working memory capacity generally diminishes, leading to a reduced ability to control information [5]. This decline can negatively influence various cognitive functions, particularly those involved in engaging in complex reasoning tasks [6]. Executive functions, covering a set of cognitive control processes such as planning, cognitive flexibility, and inhibitory control, are particularly vulnerable to the aging process [7]. Deficits in inhibitory control, understood as the capacity to suppress prepotent, habitual, or contextually irrelevant responses in favor of resolute behavior, have been consistently observed in healthy aging populations [8]. This decline in inhibitory function not only compromises task performance in situations requiring selective attention and conflict resolution but also contributes to difficulties in everyday activities that demand focused cognitive control. As a result, older adults may be more easily distracted, have more difficulty ignoring irrelevant information, and take longer to resolve cognitive conflict, all of which contribute to age-related cognitive decline [9]. Given the centrality of inhibitory control in everyday functioning, it is crucial to employ robust experimental paradigms that can isolate and quantify these control mechanisms.

A well-established paradigm for assessing inhibitory control is the Stroop Color and Word Test, which is based on the Stroop effect first described in 1935 [10]. The Stroop test consists of three main conditions: the Word Reading Condition, where participants read color words printed in black; the Color Naming Condition, where they name the colors of patches; and the Interference Condition, where they name the ink color of incongruent color words [11]. Each of these conditions engages different cognitive mechanisms. The Word Reading Condition primarily assesses automatic processing, as reading single words, particularly in the Stroop paradigm, tends to require limited allocation of attentional resources compared to other tasks. This process remains largely unaffected by age, and performance in this condition tends to remain stable in older adults. The Color Naming Condition requires greater attentional engagement and controlled processing compared to the Word Reading Condition. Participants must name the color of non-word stimuli, which engages selective attention and processing speed—abilities known to decline gradually with age [12]. In contrast to reading, which is highly automatized, color naming relies on controlled attention and label selection, which increases cognitive effort and response latency. Slower responses in this condition among older adults may reflect general cognitive slowing and reduced efficiency in attentional resource allocation.

The Interference Condition places the highest demand on executive functioning, as it requires the participant to inhibit the automatic tendency to read a word to correctly name the ink color in which the word is printed. Older adults tend to exhibit greater difficulty and longer response times (RTs) in this condition, highlighting impairments in the ability to manage cognitive conflict and inhibit irrelevant information—a key feature of healthy cognitive aging [13]. This differential pattern of performance across conditions underscores the utility of the Stroop task not only in isolating components of cognitive control but also in highlighting how these components are selectively affected by the aging process [14].

For its investigation, advances in functional neuroimaging techniques have significantly improved our ability to non-invasively investigate age-related changes in brain function [15, 16]. Among these methods, electroencephalography (EEG) stands out as a particularly sensitive and temporally precise tool for detecting alterations in neural dynamics associated with aging [17, 18]. Several studies have documented systematic age-related changes in EEG rhythmic activity across frequency bands [19–21]. For instance, aging is associated with a general slowing of EEG rhythms, including a gradual reduction in alpha band power and peak frequency, which correlate closely with cognitive decline [22]. Furthermore, age-related increases in slower bands, alterations in coherence patterns, and decreased alpha reactivity during cognitive tasks have been consistently reported [23, 24]. EEG's high temporal resolution allows for the analysis of rapid neural processes that underlie cognitive functions such as attention, working memory, and inhibitory control [25]. In particular, EEG is compatible with capturing dynamic brain states during task execution, offering real-time insights into how cognitive control processes are modulated across the lifespan [26]. Its portability, cost-effectiveness, and ability to be applied in both laboratory and clinical contexts further underscore its value [27]. These EEG markers provide non-invasive neurophysiological correlates of the variability in cognitive performance observed across the lifespan, making EEG an ideal tool to explore executive function decline, including inhibitory control [28, 29].

The primary objective of the present study is to extend previous findings on age-related cognitive decline by examining how inhibitory control and interference resolution—assessed through performance on the Stroop task—vary across the adult lifespan [30, 31]. Specifically, the study aims to confirm prior evidence indicating that executive functions, including inhibitory control, are particularly susceptible to age-related deterioration and to investigate their neural correlates at rest, which remain largely underexplored [32]. To this end, Stroop performance metrics were analyzed in relation to participants' chronological age and subsequently correlated with neurophysiological markers derived from EEG spectral analysis. Special focus was directed toward alpha frequency bands (alpha 1 and alpha 2), which have been increasingly associated with cognitive control processes such as selective attention, inhibitory regulation, and the management of goal-directed actions. While previous research has often examined task-evoked EEG responses during cognitive tasks, a novel aspect of the present study is the correlation of Stroop performance with resting-state alpha activity. This approach allows us to investigate baseline neural network states underlying inhibitory control and to explore their predictive value for behavioral performance. Another innovative feature is that such an approach may also be extended to more ecologically valid or real-world contexts, offering the possibility to capture neural markers of inhibitory control beyond the constraints of laboratory-based paradigms. By exploring the relationship between behavioral performance and oscillatory activity, this study aims to advance our understanding of the electrophysiological mechanisms highlighting cognitive variability and decline in healthy aging.

Materials and methods

Participants

Ninety-one neurologically and psychiatrically healthy individuals, aged between 18 to 89 years (mean age = 50.43 years, standard error (SE) age = 1.94 years; education = 16.18 years, SE education = 0.42 years), participated in the present study. Written informed consent to participate in the study was obtained from all participants in accordance with the World Medical Association Code of Ethics. The study procedures were conducted in compliance with the Declaration of Helsinki and national guidelines and received approval from the author's institutional review board at IRCCS San Raffaele Roma.

Participants completed a battery of neuropsychological tests aimed at evaluating various cognitive domains, including the mini-mental state examination (MMSE) [33], whose score was used to confirm their cognitive health status (mean MMSE raw score = 29.10, SE MMSE score raw = 0.15). Among the tasks administered, the Stroop Color and Word Test was included and constitutes the primary focus of the present investigation.

Stroop Color and Word Test

The Stroop Color and Word Test is a widely used neuropsychological tool designed to evaluate inhibitory control, a central component of executive functioning. Although several versions of the test have been developed over time, the most commonly adopted in both clinical and research settings is the standardized version proposed by Golden in 1978 [11]. In the present study, participants completed the three standard conditions of the Stroop Test paradigm:

(1) Word Reading Condition: participants read aloud color words printed in black ink.

(2) Color Naming Condition: participants named the ink color of solid-colored circles.

(3) Interference Condition: participants named the ink color of color words that were printed in an incongruent ink color.

The color stimuli used in all conditions were green, red, and blue. Thirty stimuli were presented in total, organized into three sheets (10 stimuli per sheet, arranged in columns). The task was administered using physical sheets rather than computerized tests to simulate a real-world setting. Participants viewed each sheet and provided their responses vocally. RTs for each condition were recorded using a stopwatch and served as the primary outcome measures of the present study. These RTs provided a quantitative index of participants' cognitive processing speed and inhibitory control. In addition, the number of errors committed in each trial was also recorded as an index of accuracy for each specific condition. The analysis first examined RTs recorded in each condition of the Stroop task. Subsequently, to obtain a single index that could capture overall performance across conditions, the mean RT of the three conditions was calculated and analyzed. This composite measure served to provide a general overview of participants' cognitive processing efficiency.

EEG recordings and processing

EEG data were recorded from participants with eyes closed under resting-state conditions for at least 5 min, with individuals seated comfortably in an armchair located in a room that was electrically shielded and weakly illuminated to minimize external interference. EEG signals were collected using 27 scalp electrodes placed according to the international 10–20 system. Ocular activity was concurrently monitored via vertical and horizontal electrooculographic (EOG) channels, while an electrocardiogram (ECG) channel placed on the left clavicle recorded cardiac electrical activity. Electrode impedances were routinely checked and maintained below 5 kΩ to guarantee optimal signal quality. Data preprocessing and analysis were conducted in MATLAB (2022, MathWorks, Inc.) using custom routines built upon the EEGLAB toolbox (2024, Swartz Centre for Computational Neuroscience). The EEG signal was digitized at a sampling rate of 512 Hz and subjected to band-pass filtering using a finite impulse response (FIR) filter with cutoff frequencies set at 0.2 Hz and 47 Hz. To mitigate the influence of artifacts, a multi-step approach was utilized. First, the data were divided into epochs of 2 s, and segments displaying atypical waveforms or noise were visually inspected and excluded by an experienced technician. Following this first step, a minimum of 3 min of artifact-free EEG data was retained for each participant. Subsequently, independent component analysis (ICA) was applied via EEGLAB to further identify and reject artifacts. To preserve the integrity of the neural signal, no more than 20% of the independent components were excluded during this step.

Power spectral density

The power spectral density (PSD) offers a quantitative characterization of the distribution of signal power across frequency components, thereby facilitating the identification of dominant oscillatory patterns within distinct frequency bands. This metric provides a detailed depiction of the spectral composition of neural activity and enables the assessment of frequency-specific functional contributions. In the present study, PSD was estimated from EEG recordings using MATLAB's built-in spectral analysis routines, which employ robust frequency decomposition algorithms and apply Welch's method. For each participant, PSD was computed independently for each EEG channel for alpha frequency bands: alpha 1 (8–11 Hz) and alpha 2 (11–13 Hz). This analysis allowed for a comprehensive evaluation of power distribution across spatial and spectral dimensions, providing insight into age-related modulations in neural oscillatory activity.

Statistical evaluation

To examine the relationship between participants' age and Stroop performance, Pearson correlation analyses were conducted. RTs from each of the three Stroop conditions (Word Reading Condition, Color Naming Condition, and Interference Condition) were separately correlated with chronological age. In addition, a global performance index—computed as the mean RT across the three conditions—was included to assess overall response speed as a function of aging.

Additionally, Pearson correlation analyses were conducted to investigate the relationship between spectral EEG features and behavioral performance. Specifically, correlations were computed between PSD values and the mean RT across the three conditions. These analyses were performed separately for each EEG channel, with a specific focus on the alpha frequency band (alpha 1 and alpha 2), due to its well-established involvement in attentional regulation and executive control processes, both of which are critically engaged during Stroop task performance.

To enhance interpretability and highlight the spatial distribution of the results, topographical maps were generated for the alpha bands. These scalp plots employed a color scale ranging from blue (indicating negative correlations) to red (indicating positive correlations), capturing both the direction and magnitude of the observed associations. Only statistically significant correlations were visualized, with color intensity proportional to the strength of the effect—brighter shades reflecting more robust associations. To account for multiple comparisons, all *p*-values were adjusted using the Benjamini-Hochberg false discovery rate (FDR) correction procedure, with a significance threshold set at $p < 0.05$.

Results

Correlation analysis

Pearson correlation analysis revealed significant positive associations between age and RTs recorded in each of the three Stroop conditions. Specifically, age was positively correlated with RT in the Word Reading Condition [$p = 3.18 \times 10^{-4}$, $r = 0.37$, 95% CI: (0.1766, 0.5344)], the Color Naming Condition [$p = 1.04 \times 10^{-7}$, $r = 0.52$, 95% CI: (0.3555, 0.6582)], and the Interference Condition [$p = 3.95 \times 10^{-15}$, $r = 0.71$, 95% CI: (0.5885, 0.7980)]. Additionally, another significant correlation was observed between age and the mean RTs across the three conditions [$p = 4.02 \times 10^{-14}$, $r = 0.69$, 95% CI: (0.5638, 0.7843)]. Furthermore, the Pearson correlation between age and the number of errors reached statistical significance in the Interference Condition [$p = 4.73 \times 10^{-2}$, $r = 0.20$, 95% CI: (0.0026, 0.3974)]. Results concerning Pearson correlations between age and RTs are presented in Figure 1.

Topographical representation

To further explore the spatial characteristics of the neurophysiological correlates of aging, topographical analyses were conducted on EEG spectral data. Analyses were performed considering both the RTs recorded in each of the three Stroop task conditions (Word Reading, Color Naming, and Interference), as well as the mean RT across all conditions. Following FDR correction ($p < 0.05$) to control multiple comparisons, statistically significant negative correlations were observed between age and alpha 2 power in occipital regions. Topographical distributions are represented in Figure 2.

Discussion

Aging is commonly associated with a gradual decline in various cognitive functions, a process that can significantly influence daily functioning and overall quality of life [34]. Processing speed and inhibitory control are among the cognitive domains that may be particularly sensitive to, or affected by, age-related changes, given their role in efficient information processing and the regulation of goal-directed behavior [35]. For instance, the study by Ferguson et al. [36] (2021) showed that inhibitory control begins to decline from around 35 years of age, while working memory capacity starts to decline even earlier, from approximately 30 years of age, indicating that different cognitive functions may follow distinct trajectories of age-related decline. Understanding how these cognitive domains are influenced by aging is essential for interpreting performance differences across age groups and for developing interventions aimed at maintaining cognitive health. Exploring these processes can also help uncover the factors that support cognitive preservation and illuminate the mechanisms of successful cognitive aging. In this context, the concept of cognitive reserve has received increasing attention, referring to the brain's capacity to manage age-related neural changes or pathology by utilizing more efficient neural networks and alternative cognitive strategies [37–39]. Building on this perspective, it becomes crucial to investigate how specific cognitive functions evolve with age.

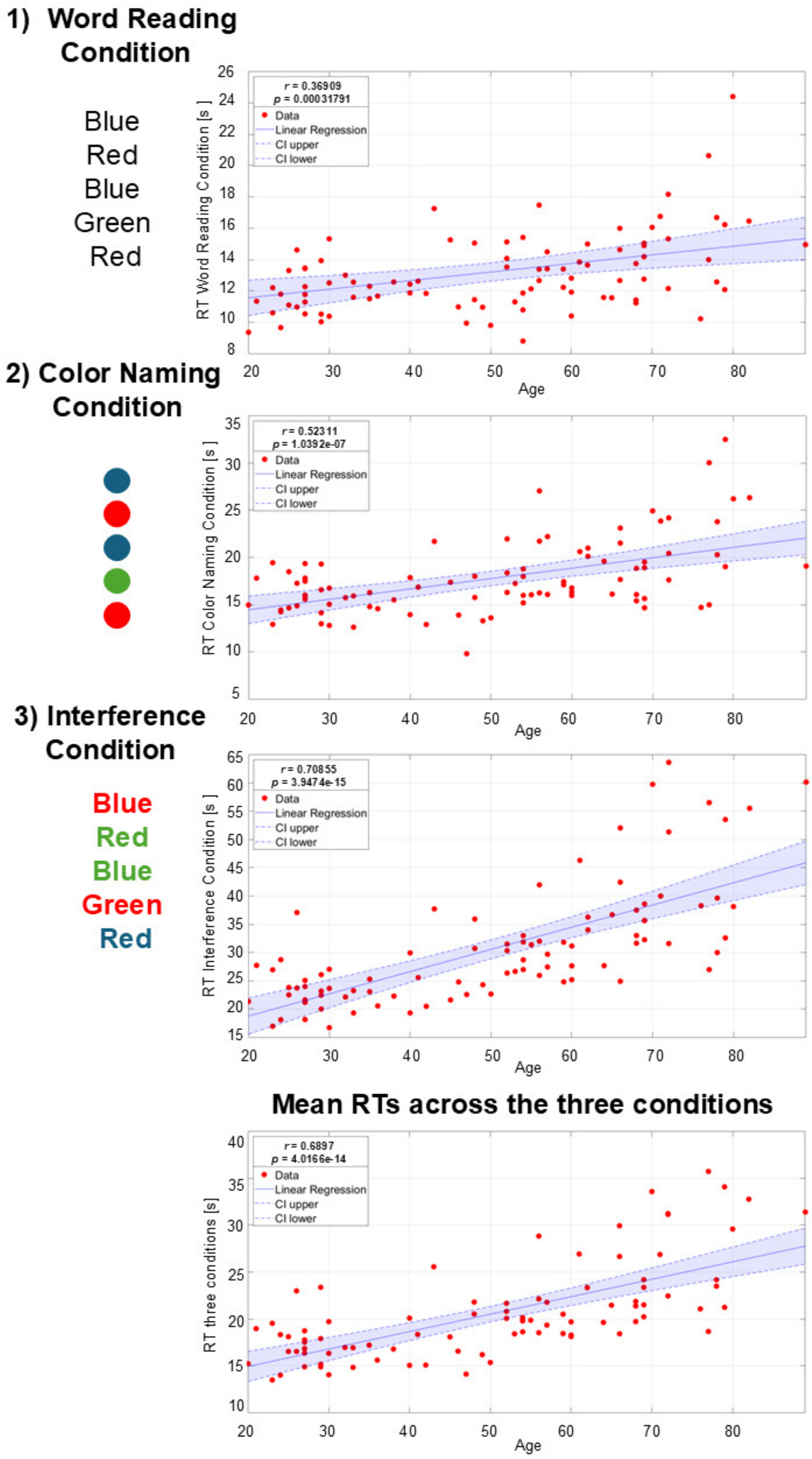

Figure 1. Pearson correlations between age and response time (RT). Scatterplots for the three Stroop task conditions: (**1**) Word Reading, (**2**) Color Naming, and (**3**) Interference Condition, reveal positive linear associations, with older age linked to longer RT. The final plot shows the correlation between age and mean RT across conditions.

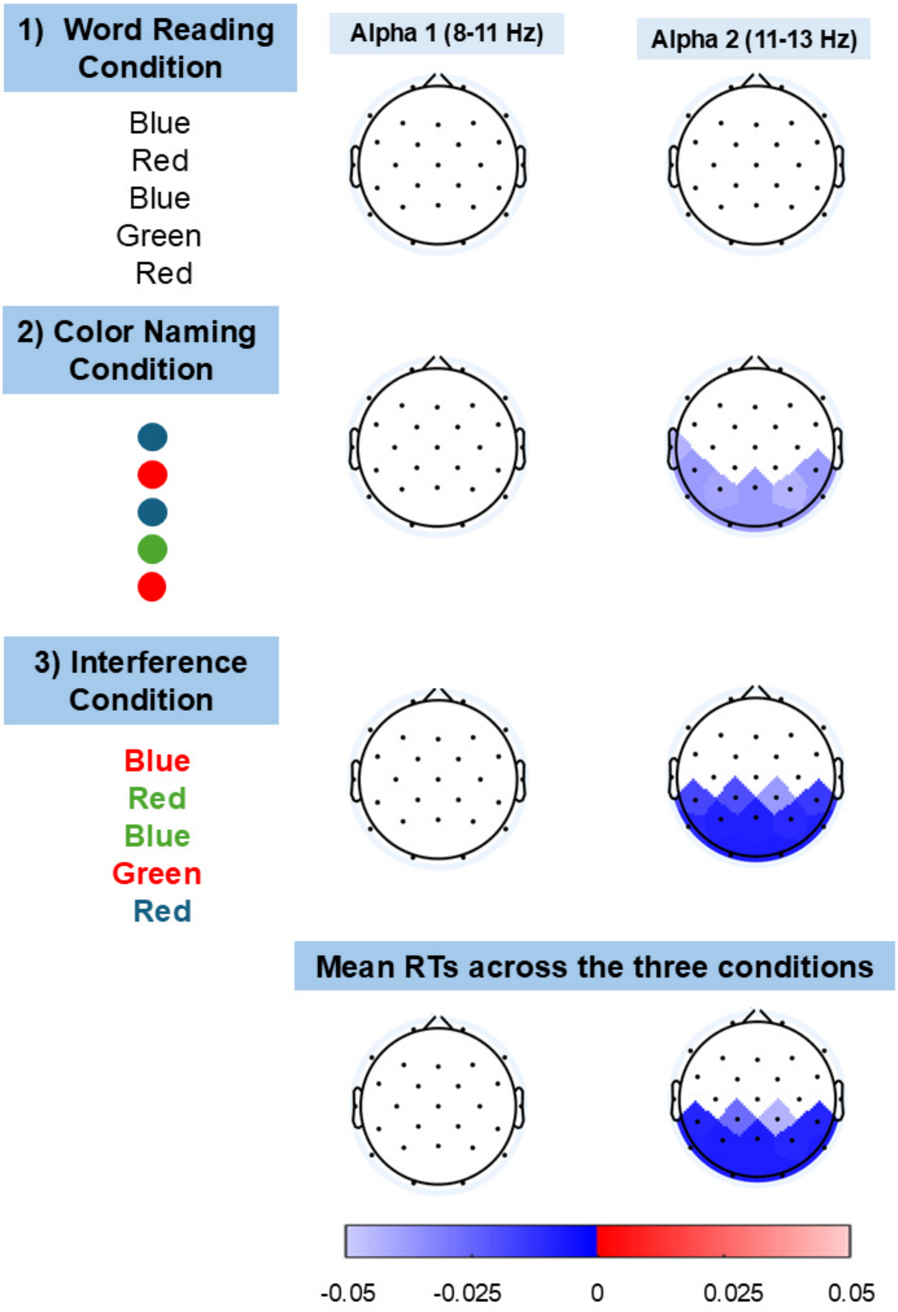

Figure 2. Topographical distribution of the correlations between response times (RTs) and alpha band power spectral density (PSD). Scalp maps display statistically significant negative correlations (false discovery rate (FDR)-corrected, *p* < 0.05) between RTs and PSD in the alpha 2 band. Warmer colors indicate stronger associations, with notable effects localized in occipital regions, suggesting an age-related reduction in posterior alpha 2 activity. This pattern reflects potential declines in attentional and inhibitory processes mediated by posterior cortical networks. No significant correlation emerged in (**1**) the Word Reading Condition, whereas a weak occipital effect was observed in (**2**) the Color Naming Condition. The correlation became stronger in (**3**) the Interference Condition, and a comparable effect was also observed when RTs were averaged across all three conditions. No significant correlations were found for the alpha 1 band.

This study aimed to investigate the trajectory of inhibitory control and interference resolution in physiological aging, using Stroop task performance as a behavioral marker of these cognitive functions. To this end, 91 healthy participants spanning a wide age range were recruited and administered all three conditions of the Stroop Color and Word Task—Word Reading, Color Naming, and Interference Condition—to assess how behavioral performance varies with age under different levels of cognitive demand. RTs and error rates were analyzed for each of the three conditions individually, as well as for the average performance across all conditions, and correlated with participants' chronological age. Additionally, behavioral performance was also correlated with PSD derived from participants' EEG recordings, with a particular focus on the alpha frequency band. Previous research has emphasized the importance of accounting for individual variability in alpha frequency when analyzing EEG data. This particular focus on the alpha band is also supported by other studies showing that individual variability in alpha activity is closely linked to cognitive performance. For instance, Klimesch et al. [40] (1993) reported that participants with higher task performance tended to exhibit increased alpha activity during cognitively demanding phases, such as memory retrieval, highlighting fundamental links between alpha oscillations and cognitive efficiency. This approach aimed to integrate neuropsychological and neurophysiological measures to explore age-related changes at both behavioral and neural levels.

From a behavioral perspective, results indicated a decline in performance with increasing age across all three Stroop conditions, as demonstrated by significant positive correlations between RTs and age. The same pattern was observed when considering the average RTs across the three conditions. It is important to underline that the effect observed with RTs became increasingly pronounced as task difficulty increased, highlighting a stronger age-related impact on more demanding cognitive processes. Additionally, a significant positive correlation between error rates and age was observed specifically in the Interference Condition. Complementing the behavioral data, neurophysiological analyses focused on the alpha frequency band-known to play a critical role in attentional regulation and executive control, revealed no significant correlations for the alpha 1 band, which is typically linked to basic sensory processing and general arousal. Conversely, statistically significant differences were observed in the alpha 2 band. In particular, resting-state alpha 2 PSD in occipital regions was negatively correlated with RTs in the Color Naming and Interference Condition, as well as with mean RT across all Stroop conditions. This finding is particularly interesting and aligns with the pattern observed in age-related correlations, showing that the strength of the association between occipital alpha 2 activity and RTs increases progressively with task difficulty. Specifically, the negative correlations identified in the Interference Condition mirror those obtained when considering mean RT across all three Stroop conditions. This pattern emphasizes the specific sensitivity of interference resolution processes to alpha 2 oscillations, potentially reflecting their role in facilitating attentional control and inhibitory functions when executive demands are intensified. From a theoretical perspective, alpha 2 rhythms have been linked to top-down regulatory mechanisms that support the suppression of irrelevant information and the flexible allocation of attentional resources, suggesting that their modulation at rest may index an individual's baseline capacity for inhibitory control rather than representing a task-bound effect.

This study's results are supported by existing literature, which consistently reports that inhibitory control tends to decline with age. However, the extent and nature of this decline may vary depending on the specific inhibitory process being assessed and the task employed [41]. For instance, Kramer et al. [42] (1994) explored the relationship between aging and reductions in inhibitory efficiency. They assessed a range of inhibitory functions in both young and elderly adults using various tasks. The analysis of different task components revealed that, in many cases, elderly adults performed similarly to younger participants, offering limited support for age-related variations in inhibitory function. These findings underscore the importance of a subcomponent-based approach, suggesting that aging impacts some inhibitory processes more than others [43]. In line with these results, the study by Forte et al. [44] (2024) further supports the observations made in the present research. Specifically, Forte and his colleagues differentiated between congruent and incongruent stimuli within the Stroop task and examined how performance in these conditions correlated with age. Their sample encompassed a wide age range, including children. Consistent with the findings of our study, they reported significantly faster RTs for congruent compared to incongruent stimuli. Furthermore, when analyzing these conditions separately, a U-shaped distribution of RTs emerged. This pattern was primarily attributable to the inclusion of children, whose prolonged RTs reflect the ongoing maturation of cognitive processes. Similarly, Ferguson et al. [36] (2021) observed a comparable pattern, reporting that inhibitory control tends to decline with advancing age, particularly starting in middle age.

The neurophysiological results are also supported by previous literature. For instance, Klimesch et al. [45] (1999) highlighted that alpha 2 power follows a similar lifespan trajectory—increasing from childhood to adulthood and declining in older age—reflecting underlying cognitive changes. Consequently, the modulation of alpha 2 activity across the lifespan may underlie age-related differences in cognitive control and inhibitory processes, supporting the use of resting-state alpha 2 PSD as a sensitive biomarker of cognitive efficiency and neural integrity. Further evidence for the functional relevance of distinct alpha sub-bands comes from cognitive studies such as Fink et al. [46] (2005), which demonstrated that lower and upper alpha frequencies are differentially involved in cognitive processing. These findings support the idea that alpha sub-bands reflect distinct cognitive functions and are selectively modulated depending on task demands.

In conclusion, the present study offers a valuable contribution to the understanding of cognitive control mechanisms by providing neurophysiological support for well-established concepts in the literature. Unlike previous studies focusing on task-evoked EEG [47], the present work links individual differences in Stroop performance to resting-state alpha 2 activity, providing a novel perspective on baseline neural predictors of inhibitory control. This integrated behavior-EEG approach allows us to identify predictive markers that extend beyond traditional task-based measures [48]. Additionally, a key advantage of this study is the ability to observe the direction and sign of correlations from a topographical perspective, allowing precise localization of these effects at the scalp level. A limitation of this study is the limited ecological validity of the Stroop task, which may not fully capture the complexity of inhibitory demands in everyday life. Thus, the generalizability of our findings to real-world contexts should be viewed with caution. Nevertheless, the observed EEG markers hold promise for practical applications, including early screening of inhibitory deficits, monitoring cognitive decline, and guiding personalized cognitive training. Future studies should further explore the role of resting-state activity in predicting performance across various cognitive domains and populations, and consider combining EEG with other physiological or behavioral markers to develop more robust models of individual cognitive capacity. Longitudinal studies will be particularly valuable to track changes over time and to distinguish true age-related effects from cohort or individual variability, and could also focus on refining methodological approaches and more advanced statistical models. These efforts may have potential applications in designing and monitoring personalized cognitive rehabilitation programs, bridging the gap between laboratory findings and clinical practice.

Abbreviations

EEG: electroencephalography

FDR: false discovery rate

MMSE: mini-mental state examination

PSD: power spectral density

RTs: response times

SE: standard error

Declarations

Author contributions

AF: Data curation, Investigation, Writing—original draft. AC: Data curation, Investigation, Writing—review & editing. CP: Data curation, Investigation, Writing—review & editing, Conceptualization, Formal analysis, Visualization. FV: Investigation, Writing—review & editing. All authors read and approved the submitted version.

Conflicts of interest

Fabrizio Vecchio, who is the Guest Editor of Exploration of Medicine, had no involvement in the decision-making or the review process of this manuscript. The other authors declare no conflicts of interest.

Ethical approval

The study procedures were conducted in compliance with the Declaration of Helsinki and national guidelines and received approval from the author's institutional review board at IRCCS San Raffaele Roma (RP 23/10).

Consent to participate

Written informed consent to participate in the study was obtained from all participants.

Consent to publication

Not applicable.

Availability of data and materials

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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