

PUPILLARY RESPONSE FUNCTION TO SPONTANEOUS FLUCTUATIONS IN EEG ALPHA POWER

by

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Abstract

EEG alpha rhythm (8-13 Hz.) is thought to provide an index of brain 'idling' or relaxation, with increases in alpha power associated with increased relaxation. Conversely, decreases in alpha power or the 'alpha desynchronization' are associated with increased attention or engagement of the brain. Similarly, if ambient light is kept constant, pupil diameter changes can serve as an index of attention, with dilated pupils indicating increased attention or excitement, and constricted pupils indicating decreased attention. Despite the similarity in response of pupil diameter and EEG alpha power to changes in attention, little is known about how pupil diameter and EEG alpha power co-vary under spontaneous recordings. In particular, it is not known whether changes in pupil diameter precede changes in alpha (or vice versa) and what is the time lag of the correlation between the two signals. Here, we present for the first time results from a study examining in 73 healthy subjects the relationship between spontaneously recorded pupil diameter and alpha power. Our study investigated the relationship between alpha power and pupil diameter in younger and older adults during passive, go/nogo, and simple reaction time tasks. Results indicated that both age groups had high pupil diameters at alpha power peaks, followed by a decrease. Younger participants exhibited higher and quicker dilation peaks compared to older adults, with a pupil diameter decrease lagging 1-2 seconds after the alpha peak. Cross-correlation analysis showed that younger adults had more positive correlations at specific time lags, indicating a quicker and stronger relationship between alpha power and pupil diameter, with a positive correlation around 250-300 milliseconds, whereas older adults exhibited more delayed and weaker correlations.

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Contents

1	Introduction	1
2	Literature Review	3
3	Materials and Methods	6
3.1	Participants	6
3.2	Task design	7
3.3	EEG data acquisition and analysis	8
3.4	Pupil data acquisition and analysis	9
4	Results	12
4.1	Young and Old Pupil Response to Increased Alpha Power .	12
4.1.1	Task-Specific Observations	12
4.2	Young and Old Alpha Response to Increased Pupil Diameter	16
4.2.1	Task-Specific Observations	16
4.3	Cross-Correlation of Alpha and Pupil Diameter Time Series	19
4.3.1	Task-Specific Observations	20
5	Discussion	22
6	Conclusion	24
	Bibliography	25

List of Figures

3.1	Participants' characteristics.	6
3.2	Schematic representation of the task design.	11
4.1	The pupil diameter changes at the peak of alpha power (time = 0) across passive experimental task for two groups.	13
4.2	Pupil diameter comparison in passive task between older and younger groups	13
4.3	The pupil diameter changes at the peak of alpha power (time = 0) across go/nogo experimental task for two groups.	14
4.4	Pupil diameter comparison in go-nogo task between older and younger groups	14
4.5	The pupil diameter changes at the peak of alpha power (time = 0) across simple reaction time (RT) experimental task for two groups.	15
4.6	Pupil diameter comparison in simple reaction time (RT) task between older and younger groups	15
4.7	The alpha power changes at the pupil diameter peak (time = 0) across passive experimental task for two groups. . . .	16
4.8	Alpha power comparison in passive task between older and younger groups	17
4.9	The alpha power changes at the pupil diameter peak (time = 0) across go/nogo experimental task for two groups. . .	17
4.10	Alpha power comparison in go-nogo task between older and younger groups	18
4.11	The alpha power changes at the pupil diameter peak (time = 0) across simple reaction time (RT) experimental task for two groups.	18
4.12	Alpha power comparison in simple reaction time task between older and younger groups	19
4.13	The cross-correlation between alpha power and pupil diameter across passive experimental task for two groups. . .	20
4.14	The cross-correlation between alpha power and pupil diameter across go/nogo experimental task for two groups. .	21

4.15 The cross-correlation between alpha power and pupil diameter across simple reaction time (RT) experimental task for two groups.	21
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Chapter 1

Introduction

The relationship between neural oscillations and cognitive processes has been extensively studied in neuroscience. Electroencephalography (EEG) is a non-invasive technique used to record the brain's electrical activity. The EEG signal arises from the synchronous activity of numerous neurons, especially cortical pyramidal cells. EEG measurements involve placing electrodes on the scalp according to the international 10-20 system, which detect voltage fluctuations due to ionic currents within the brain's neurons. EEG is widely utilized in both clinical and research settings to diagnose and investigate neurological disorders, sleep patterns, and cognitive functions.

One of the key signals captured by EEG is the alpha rhythm, oscillating between 8-13 Hz. The EEG alpha rhythm is a well-known indicator of brain states, particularly relaxation and attention. The average alpha power decreased when performing attention tasks compared to the average alpha power in a relaxed state in the frontal and occipital regions of the brain [26]. These rhythms have been implicated in various functions, including attention, perception, and the regulation of cortical excitability [12]. Increased alpha power is generally associated with relaxation and decreased cognitive load, often referred to as the brain's 'idling' state. Conversely, alpha desynchronization, characterized by decreased alpha power, is linked to heightened attention and cognitive engagement. This rhythm is most prominent when a person is awake but relaxed [27] [1], with minimal sensory input, and is typically recorded over the occipital lobe, though it can be detected in other brain regions as well [29].

In addition to brain signals, physiological responses such as pupil diameter provide insight into cognitive states [4]. Pupillometry, the measurement of pupil size and reactivity, is often used to assess autonomic nervous system activity and cognitive processes [19]. Under constant ambient lighting, pupil dilation suggests increased attention or excitement, while pupil constriction indicates reduced attention or relaxation.

Changes in pupil size are controlled by the autonomic nervous system [17].

The autonomic nervous system (ANS), part of the peripheral nervous system, regulates involuntary physiological functions such as heart rate, blood pressure, respiration, and digestion. The ANS is divided into the sympathetic and parasympathetic branches. The sympathetic nervous system prepares the body for 'fight-or-flight' responses by increasing heart rate, dilating pupils, and mobilizing energy stores. Conversely, the parasympathetic nervous system promotes 'rest-and-digest' functions by slowing heart rate, constricting pupils, and facilitating digestion and energy storage. The balance between these two branches maintains homeostasis in the body. [7]

Despite the observed parallels between pupil diameter changes and EEG alpha power in response to attentional states, the relationship between these two physiological signals remains underexplored, particularly in spontaneous, real-world conditions. Understanding the covariation between pupil diameter and EEG alpha power can provide valuable insights into the neural mechanisms governing attention and arousal. Specifically, examining whether changes in pupil diameter precede alterations in alpha power or vice versa, and determining the temporal dynamics of this relationship, can enhance our comprehension of attentional processes.

This study aims to fill this gap by investigating the temporal relationship between recorded pupil diameter and alpha power in a large cohort of healthy subjects. By doing so, it seeks to elucidate the underlying neural mechanisms that govern attention and arousal, providing a more comprehensive understanding of these cognitive processes.

Chapter 2

Literature Review

The interaction between EEG alpha oscillations and pupillary responses provides a rich area of study in understanding brain function and cognitive processes. This section reviews key findings from research on the relationship between spontaneous fluctuations in EEG alpha power and pupillary response, as well as related brain activity.

The EEG alpha rhythm has been a subject of extensive research since its discovery. Different brainwave patterns (alpha and beta rhythms) are linked to specific types of brain activity during rest, where alpha waves are related to a state of inattention, and beta waves are associated with spontaneous thought processes [13]. Alpha power has been associated with a resting state of the brain, often referred to as the 'idling' state. This rhythm is most prominent when individuals are awake but relaxed, with eyes closed, and is thought to reflect a state of cortical inhibition. Alpha waves are a good indicator of general arousal in resting states, but other brainwave changes in specific areas reflect how the brain processes visual input when the eyes are open, rather than just an increase in overall arousal [1]. The average alpha power decreases in the frontal and occipital brain regions when someone is focused, compared to when they are relaxed [18]. Brain activity in the alpha frequency band changes during attention tasks. For instance, in the frontal and occipital regions of the brain, the average alpha power decreased when people focused on a task compared to when they were relaxed. However, in the prefrontal region, there were no significant changes in alpha power during these tasks [26].

A study on simultaneous EEG/fMRI, found that spontaneous fluctuations in alpha power were negatively correlated with BOLD signal changes in parietal and frontal cortical areas [12]. Additionally, another study by the same group found widespread negative correlations in areas supporting attentional processes, indicating that alpha oscillations might signal a neural baseline of "inattention"[13]. These findings are

extended by showing that alpha oscillations interact with positive and negative BOLD responses in the visual and auditory cortices, modulating the brain's response to stimulation [16]. This indicates that alpha power fluctuations contribute to the trial-to-trial variability in cortical responses.

Alpha desynchronization, or the reduction in alpha power, is a well-documented phenomenon occurring during tasks that demand attention. For instance, The brain's alpha wave activity in written language comprehension decreases just before encountering words that are strongly predicted by the context. This pattern also occurs during spoken language comprehension, though the effect is weaker [14]. This desynchronization is indicative of the brain's transition from a relaxed state to an engaged state, highlighting the alpha rhythm's role as a marker of attentional processes.

Pupil diameter has long been recognized as a non-invasive measure of cognitive and emotional states. Pupil diameter changes in response to emotional arousal and is initially linked to the mental effort needed to control automatic emotional reactions [10]. Pupils of the eyes can reveal a lot about the human mind and brain. Pupil size changes mainly due to light conditions, controlled by the autonomic nervous system, which is influenced by the brain's subcortical regions. However, pupil size also changes even without changes in light, due to overall arousal levels and cognitive factors. These changes are influenced by various brain inputs. The pupillary response is linked to both emotional arousal and cognitive workload, making it a useful indicator of brain activity [5]. Pupillary responses have been shown to correlate with task difficulty, mental effort, and emotional arousal, with dilation occurring during increased cognitive demands and constriction during relaxation or reduced attention. For instance, when people experience emotional reactions to pictures, their sympathetic nervous system (which controls responses like sweating and pupil dilation) influences their pupil size. Therefore, pupil response during emotional picture viewing is related to the level of emotional arousal and sympathetic activity [2].

Pupil measurements and EEG responses are closely linked to the brainstem's locus coeruleus-norepinephrine (LC-NE) system, which plays a crucial role in attention and arousal. A study found that alpha-band amplitude and pupil diameter are temporally correlated, suggesting that these measures reflect changes in attentional states [20]. The size of the pupil has been shown to modulate detection sensitivity and response criteria in perceptual tasks. For instance, higher alpha power is associated with a more conservative response criterion, leading to fewer "yes" responses in detection tasks [15]. Baseline pupil diameter, serving as a measure of tonic LC-NE activity, exhibits a significant correlation with

specific EEG responses, highlighting a strong relationship between LC-NE activity and EEG. The intricate relationship between attention and neural activity encompasses both cortical and subcortical networks [28].

Despite the extensive body of research on EEG alpha rhythm and pupil diameter as separate measures of brain and physiological states, studies investigating their concurrent behavior are scarce. The few existing studies suggest a potential link between these two measures, given their similar responses to changes in attentional states. Measuring both EEG alpha amplitude and pupil diameter together offers an effective way to track variations in attention [20]. Pupil dilation is an indicator of cognitive processes and it is related to brain activity before and after a stimulus is presented. The brain's higher levels of alpha activity before the stimulus result in reduced pupil dilation in response to the stimulus. This underscores the close association between attentional states and the brain's response to stimuli [9].

However, the temporal dynamics of this relationship remain unclear. It is not well understood whether changes in pupil diameter precede changes in alpha power, suggesting a preparatory role of the autonomic nervous system, or whether alpha power changes drive pupil responses, indicating a cortical influence on autonomic function. Addressing this gap in knowledge is crucial for a comprehensive understanding of the interplay between cortical and autonomic systems in attention regulation.

The primary objective of this study is to elucidate the temporal relationship between spontaneously recorded pupil diameter and EEG alpha power in a cohort of 73 healthy subjects. By examining the time lag and directionality of the correlation between these two signals, we aim to uncover the underlying neural and physiological mechanisms that govern their covariation. This investigation will contribute to the broader field of cognitive neuroscience by providing novel insights into the synchronization of cortical and autonomic processes during spontaneous attention fluctuations.

Chapter 3

Materials and Methods

3.1 Participants

As previously described [23], Thirty-six young adults and 39 older adults were included in this study. All participants had normal hearing and normal or corrected to normal vision; had no history of neurological, psychiatric, or vascular disease; and were not taking any psychotropic medications. Current medication with beta-blockers was an exclusion criterion. Six participants were taking other types of nonadrenergic medication to control blood pressure. Participants were asked to sleep sufficiently the night before the recording and to avoid the use of alcohol. Below the cutoff result in the Montreal Cognitive Assessment–MoCA, a dementia screening tool [6], was also an exclusion criterion. Figure 3.1 shows participants’ characteristics.

N	Age (y)			Sex		Education (y)			MoCA scores			Handedness		Smokers	
	Mean	Min	Max	F	M	Mean	Min	Max	Mean	Min	Max	Left	Right		
Young	36	23	19	30	29	7	16	12	21	27	22	30	3	33	3
Older	39	60	52	70	31	8	16	4	23	25	18	30	3	36	9

Figure 3.1: Participants’ characteristics.

EEG data from 1 older participant were not included in the analyses due to bad signal quality. Pupil data from 1 young adult and 1 older adult with light colored eyes were not included due to poor data quality.

The study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the Ethics Committee of the Faculty of Medicine of the University of Coimbra (reference number CE-002–2016). Written informed consent was obtained from the participants, after explanation of the nature and possible consequences of the study.

3.2 Task design

As previously described [23], We designed a cued auditory task consisting of 3 different conditions: a passive listening condition, a cued simple reaction time (RT) condition, and a cued go/no-go condition. The task was designed and run with the Psychophysics Toolbox, version 3 [3], for Matlab (The MathWorks Company Ltd). The auditory stimuli were single-frequency signals (pure tones) with duration 250 ms, with the following frequencies: cue, 1500 Hz; go stimulus (S1), 1700 Hz; no-go stimulus (S2), 1300 Hz; and error feedback signal, 1000 Hz. The sounds were played at around 67 dB(A) from a hi-fi speakers system (Genius, KYE Systems Corp). All stimuli were suprathreshold.

Participants were requested to fixate a plus sign presented on a gray background, on the center of a computer screen (19-inch Dell monitor), set to 60 Hz refresh rate. The luminance of the background was 43 cd/m², and the luminance of the fixation cross was 58 cd/m². Participants were also requested to minimize blinking rate.

A schematic representation of task design is presented in Figure 3.2. The experiment started with the passive listening condition containing 30 trials and lasting around 4 minutes. In this condition, participants were instructed to fixate their gaze on the plus sign displayed on the center of a computer screen and to pay attention to the sounds being presented without any other overt task. This condition allowed us to isolate the effect of auditory processing from motor preparatory processes in task-related pupillary responses. After a self-paced break, participants performed the 2 active tasks: cued simple RT and cued go/no-go. The order of these 2 conditions was counterbalanced across participants, that is, half of the participants started with the simple RT and the other half with the go/no-go. Each task was divided in two 8-minute runs with self-paced breaks between runs and between tasks. Just before starting each task, the rules of the task were explained and participants engaged in a practice run ensuring he/she understood the rules and was able to detect and discriminate the different sounds. In the simple RT condition, the cue was followed by a go stimulus (S1: 100 trials) to which participants were instructed to respond by pressing a button on the keyboard as fast as possible with their right index finger. In 17% of the trials, distributed pseudorandomly throughout the run, the go stimulus was not presented and no response was required (cue-only trials: 20 trials). In the go/no-go task, the cue was followed or by the go stimulus (S1: 80 trials) or by the no-go stimulus (S2: 20 trials). Participants were instructed to respond as fast as possible to the go stimuli with their right index finger, while refraining from responding to the no-go stimuli. Cue-only trials were also included in this condition (20 trials). Total number of trials in

each condition was 120. To ensure fast responses in both task conditions, slow responses (RT slower than 700 ms) were signaled with a feedback tone presented 1200 ms after the go stimulus. The aim of signaling slow trials was to apply time pressure [21].

We considered as error trials all trials where the participants responded after cue presentation, failed to respond to the go stimulus (misses), responded to the go stimulus too slowly (slower than 700 ms), or responded to the no-go stimulus in the go/no-go condition. These trials were signaled with a feedback tone warning the participants that an error was committed. The tone was presented 200 ms after the button press when participants responded between cue and target and 1200 ms after the target in slow trials or responses to no-go.

The intertrial interval was quite long, with a median of 7.6 seconds (min 6.7 and max 19.6 seconds), to ensure pupil diameter returned to baseline values before the beginning of the next trial. The interval between the cue and the target stimuli and between target and the beginning of the next trial were drawn from a nonaging distribution $-W \cdot \ln(P)$, where W is the mean value of the interval distribution and P is a random number between 0 and 1. In our task design, the cue-target interval was $1.5 - 0.25 \cdot \ln(P)$ in seconds, and the interval between the target and the beginning of the next trial (cue) was $5.2 - 1 \cdot \ln(P)$ in seconds.

As previously described [23] To evaluate task accuracy, we calculated the number of errors, including missed go trials, responses to the cue, and responses to the no-go stimulus in the go/no-go condition. Numbers of errors were very low. Participants committed on average 2 errors in the simple RT condition and 4 errors in the go/no-go condition. Misses and responses to the cue occurred more often in the older group than in the young group. Mann-Whitney comparisons on the number of errors per group revealed a significant effect of group, in both task conditions, in the number of misses ($p < 0.05$; simple RT: mean \pm SD young group = 0.17 ± 0.38 , older group = 0.82 ± 1.25 ; go/no-go: mean \pm SD young group = 0.22 ± 0.42 , older group = 1.15 ± 2.16) and responses to the cue ($p < 0.05$; simple RT: mean \pm SD young group = 0.42 ± 0.69 , older group = 1.10 ± 1.33 ; go/no-go: mean \pm SD young group = 0.14 ± 0.35 , older group = 0.64 ± 1.33). In contrast, the number of button presses to the no-go stimulus was not significantly different across groups ($p = 0.400$; mean \pm SD young group = 0.94 ± 0.95 , older group = 1.49 ± 1.90).

3.3 EEG data acquisition and analysis

As previously described [23], the EEG signal was recorded using a 64-channel Neuroscan system (Compumedics EUROPE GmbH) with scalp

electrodes placed according to the International 10–20 electrode placement standard, with reference between the electrodes CPz and Cz and ground between FPz and Fz. Acquisition rate was 500 Hz. Vertical and horizontal electrooculograms were recorded to monitor eye movements and blinks. The participants' head was stabilized with a chin and forehead rest to record pupillographic data simultaneously. Consequently, the electrodes on the forehead, FP1, FPz, and FP2, displayed signal fluctuation artifacts due to the pressure on the forehead rest. These were excluded from the analyses. A trigger pulse was generated at the onset of each stimulus and at every button press. EEG data analysis was performed with Python custom scripts.

The data was re-referenced, then band pass was filtered with cut off frequencies of 0.1 and 40 Hz. Alpha power was extracted from channels in posterior cortical areas, filtered the data to isolate the alpha band frequencies, and then detected peaks of the alpha power. For each run, data were cut into epochs locked with the peaks of alpha power from 4 s before peak onset up to 4 s after.

For visualization of the EEG analyses results, we used Matplotlib and MNE-Python [8].

3.4 Pupil data acquisition and analysis

As described previously [23], the pupil diameter of the right eye was measured by an infrared eye-tracker (iView X Hi-Speed 1250 system from SMI) with a sampling rate of 240 Hz. A trigger pulse was generated at the onset of each stimulus and at every button press.

Analysis of pupil data was performed using custom scripts in Python. Artifacts and blinks were corrected using the custom script in Python. Pupil data is extracted from the raw EEG data, and periods of abnormally low pupil diameter, likely caused by blinks, are identified as artifacts. Blinks are detected by finding data points where the pupil diameter falls below half of the mean value. A binary dilation is then applied to extend these identified blink regions, ensuring the removal of all blink-related artifacts. Finally, the affected data points are replaced using nearest-neighbor interpolation based on the surrounding non-blink data. Pre-cue pupil diameter (pupil baseline), measured as the average dilation over the 200 ms preceding the onset of the cue, was subtracted from the pupil diameter values to produce task-related pupil dilation responses.

Pupil diameter peaks are detected in pupil data by smoothing the data using a Gaussian filter with a standard deviation (sigma) of 250, then identifying peaks that are at least 3000 data points (6 s) apart. After detecting the peaks, epochs of alpha data are extracted centred around

each detected pupil peak. Each epoch is 4000 alpha data points long or 8 s, with the pupil peak at the center, meaning 2000 data points or 4 s before and 2000 data points or 4 s after the peak.

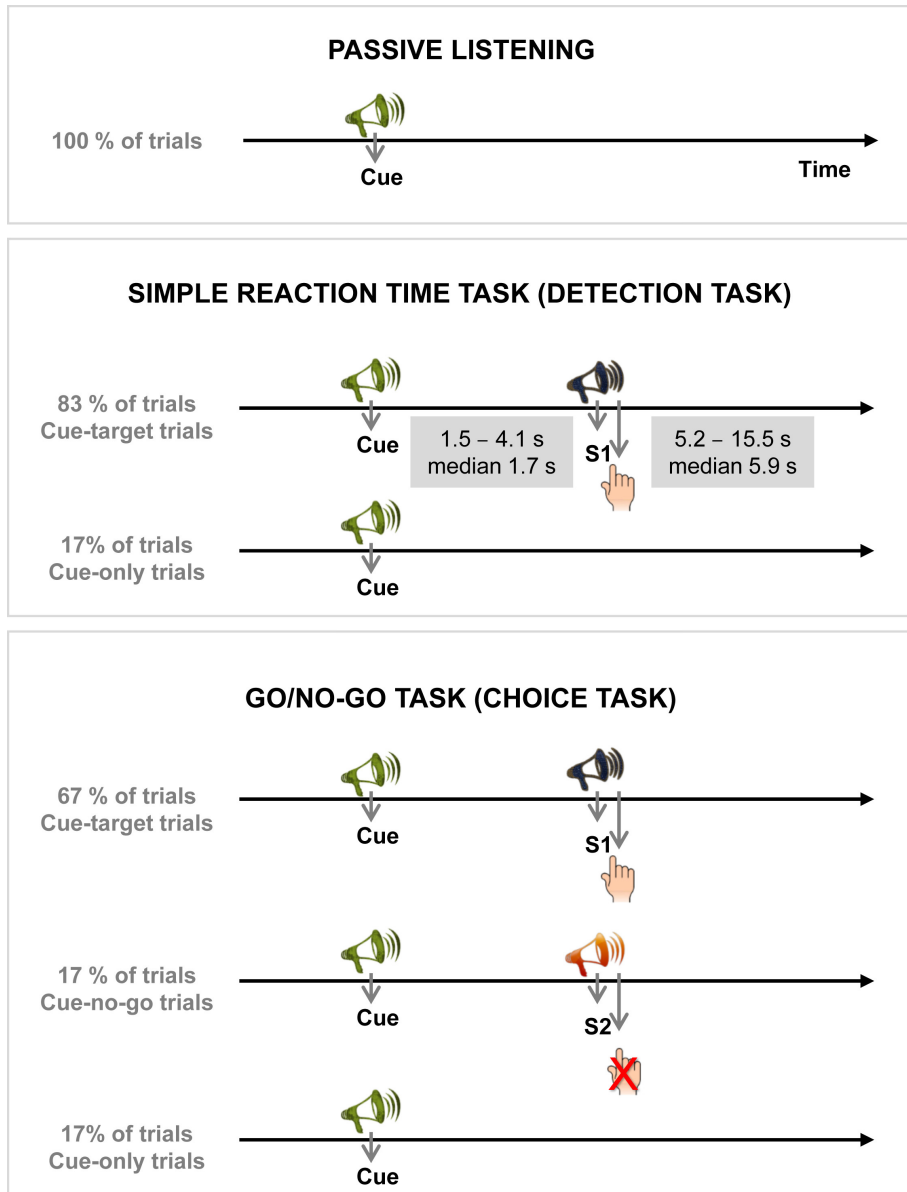


Figure 3.2: Schematic representation of the task design.

Chapter 4

Results

4.1 Young and Old Pupil Response to Increased Alpha Power

The plots in the Figures 4.1, 4.3, and 4.5 show the pupil diameter changes at the peaks of alpha power across three different experimental tasks: passive task, go/nogo task, and simple reaction time (RT) task. Each plot includes two groups: older participants (blue line) and younger participants (green line). Alpha power peaks are detected and then the pupil diameter data are extracted around the peak points within -4 s and +4 s, in other words, at the point that time is equal to 0 (time = 0) alpha power is high.

The shaded areas around the lines represent the standard error of the mean (SEM), calculated as the standard deviation divided by the square root of the number of subjects.

4.1.1 Task-Specific Observations

Passive Task

In Figure 4.1 at the peak point that time is equal to zero and alpha power is high, pupil diameter is also high but is followed by a decrease in pupil diameter. The pupil diameter begins to increase around 1500-750 ms before the alpha peak and reaches a minimum around 1-2 s after the alpha peak. The younger participants (green line) show a higher dilation peak compared to older participants (blue line). Moreover, there is a time lag of 600-700 ms between changes in pupil diameter in the two groups.

When comparing age-related differences, we conducted a t-test to analyze the average pupil diameter of two groups at peak point. The results are depicted in Figure 4.2. In the passive task, the t-test revealed a statistically significant disparity in average pupil diameter between

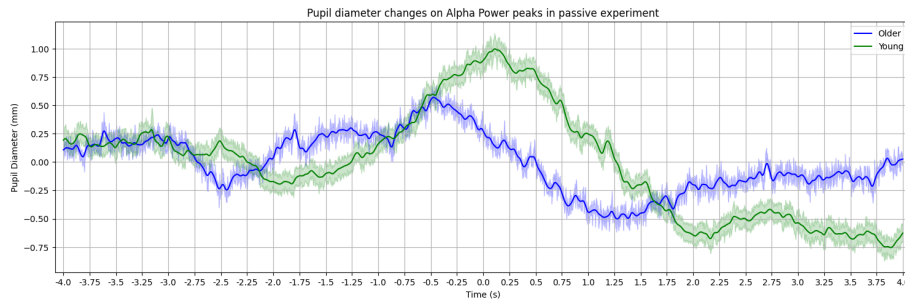


Figure 4.1: The pupil diameter changes at the peak of alpha power (time = 0) across passive experimental task for two groups.

young and old subjects (p-value 3.855e-06). The negative t-statistic value (-5.089) indicates that the older group has a significantly lower average pupil diameter compared to the younger group.

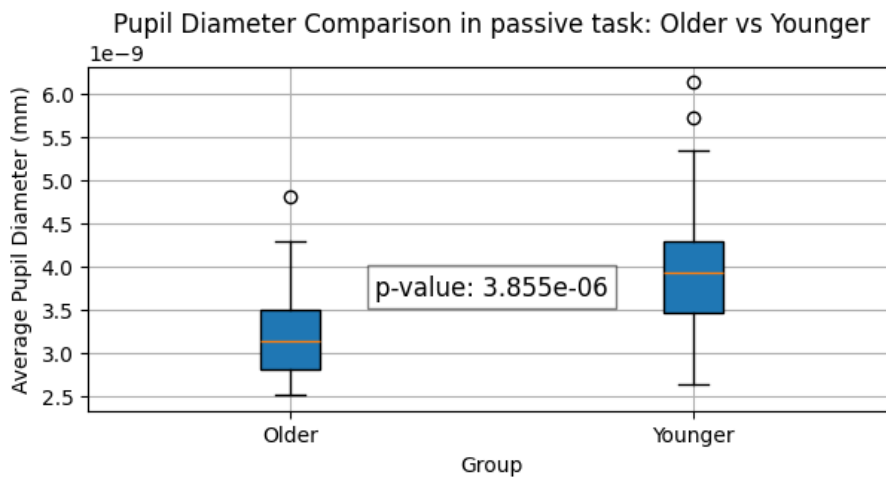


Figure 4.2: Pupil diameter comparison in passive task between older and younger groups

Go/Nogo Task

In Figure 4.3, a similar pattern to the passive task is observed and at the alpha power peak point that time is equal to zero, pupil diameter is high but is followed by a decrease in pupil diameter. The pupil diameter begins to increase around 2-1 s before the alpha peak and reaches a minimum around 350-1500 ms after the alpha peak. The older group shows greater but slower constriction compared to the younger group. Additionally, there is a time lag of 1-2 s between changes in pupil diameter in the two groups.

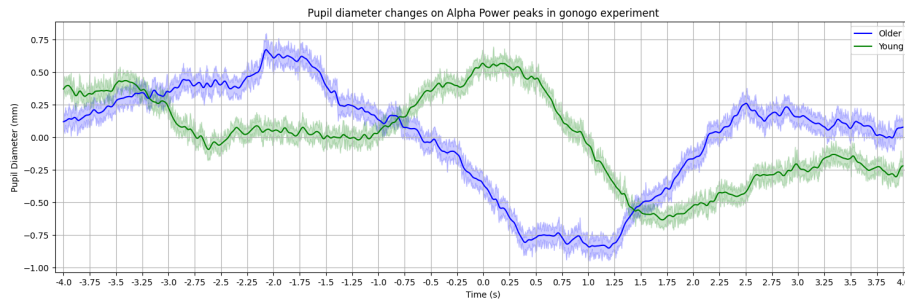


Figure 4.3: The pupil diameter changes at the peak of alpha power (time = 0) across go/nogo experimental task for two groups.

When comparing age-related differences, we conducted a t-test to analyze the average pupil diameter of two groups at peak point. The results are depicted in Figure 4.4. In the Go-Nogo task, the t-test revealed a statistically significant disparity in average pupil diameter between young and old subjects (p -value $1.387e-04$). The negative t-statistic value (-4.045) indicates that the older group has a significantly lower average pupil diameter compared to the younger group.

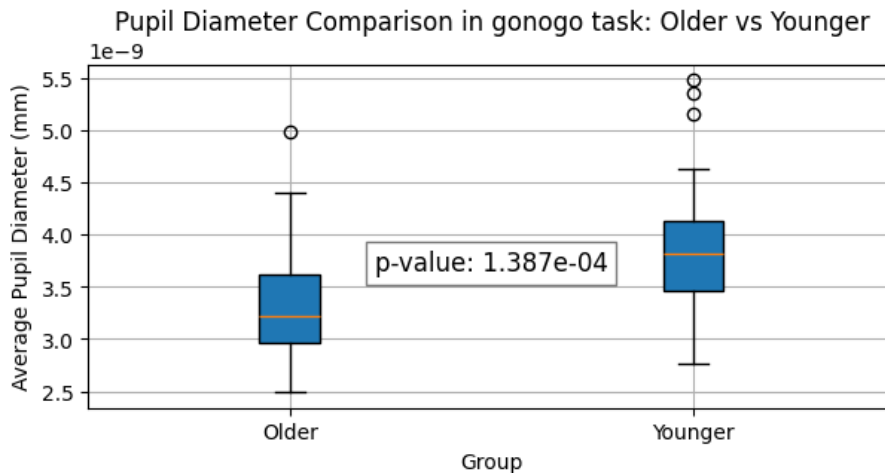


Figure 4.4: Pupil diameter comparison in go-nogo task between older and younger groups

Simple Reaction Time (RT) Task

In Figure 4.5, the pattern is consistent with the previous tasks and at the alpha power peak point that time is equal to zero, pupil diameter is high but is followed by a decrease in pupil diameter. The pupil diameter begins to increase around 1.5 s before the alpha peak and reaches a

minimum around 1-2 s after the alpha peak. The younger group shows higher dilation compared to the older group. Additionally, there is a time lag of 800 ms between changes in pupil diameter in the two groups.

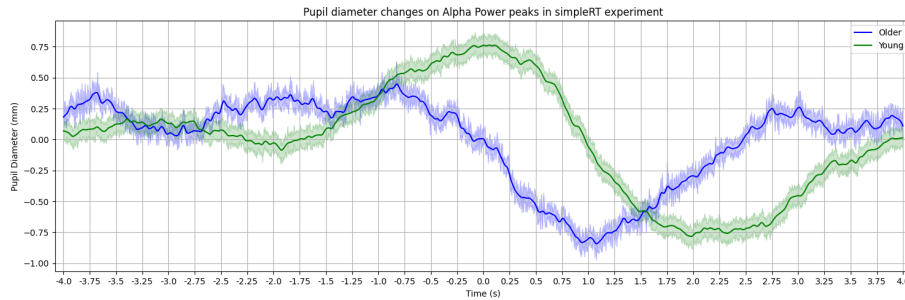


Figure 4.5: The pupil diameter changes at the peak of alpha power (time = 0) across simple reaction time (RT) experimental task for two groups.

In this task, we conducted a t-test to analyze the average pupil diameter of two groups at peak point. The results are depicted in Figure 4.6. The t-test revealed a statistically significant disparity in average pupil diameter between young and old subjects (p-value $1.385e-04$). The negative t-statistic value (-4.044) indicates that the older group has a significantly lower average pupil diameter compared to the younger group.

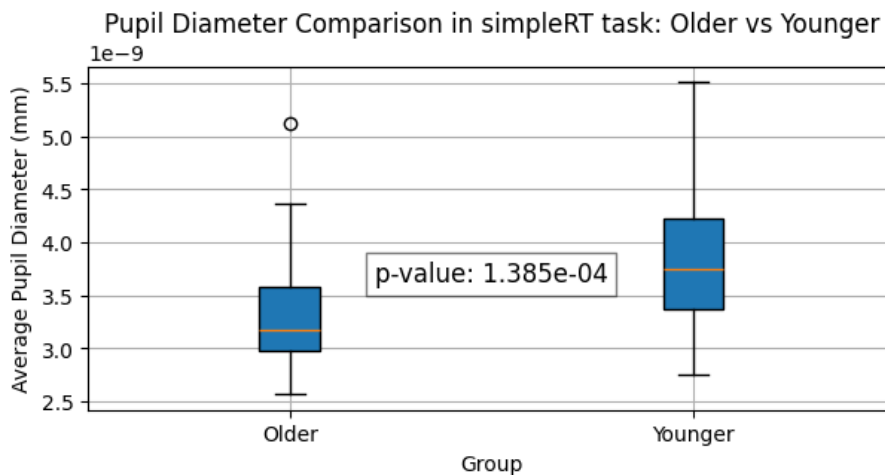


Figure 4.6: Pupil diameter comparison in simple reaction time (RT) task between older and younger groups

Generally, as you can see, all three plots in Figures 4.1, 4.3, and 4.5 exhibit that pupil diameter is high at the alpha peak and is followed by a decrease in pupil diameter. The patterns are relatively similar across

tasks, with notable decreases in pupil diameter centred around the peak of alpha power (time = 0). Additionally, according to Figures 4.2, 4.4, and 4.6 The differences in the magnitude of the decrease might reflect age-related changes in the neurophysiological mechanisms underlying the relationship between alpha power and pupil diameter.

4.2 Young and Old Alpha Response to Increased Pupil Diameter

Figures 4.7, 4.9 and 4.11 illustrate changes in alpha power at the pupil diameter peak across three different experimental tasks: passive task, go/nogo task, and simple reaction time (RT) task with the two participant groups. Pupil diameter peaks are detected and then the alpha power data are extracted around the peak points within -4 s and +4 s, in other words, at the point that time is equal to 0 (time = 0) pupil diameter is high.

The shaded areas around the lines represent the standard error of the mean (SEM), calculated as the standard deviation divided by the square root of the number of subjects.

4.2.1 Task-Specific Observations

Passive Task

In Figure 4.7, at the peak point that time is equal to zero and pupil diameter is high, alpha power is also high but is followed by a decrease in alpha power. The alpha power begins to increase around 150-50 ms before the pupil diameter peak and reaches a minimum around 500-750 ms after the pupil diameter peak. The younger group displays a higher peak and more decrease compared to the older group.

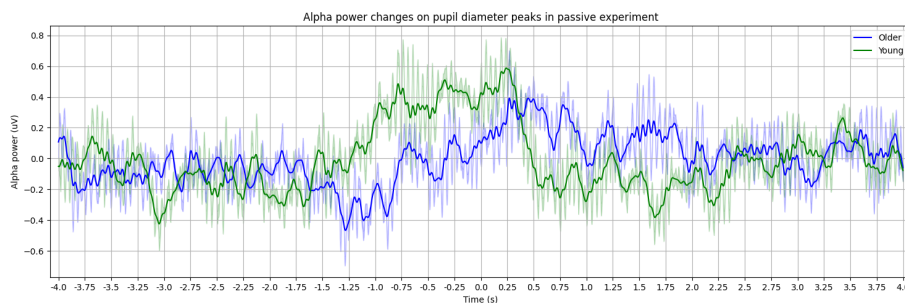


Figure 4.7: The alpha power changes at the pupil diameter peak (time = 0) across passive experimental task for two groups.

We utilized a t-test to examine the average alpha power of two groups at peak point, and the results are presented in Figure 4.8. The p-value (0.017) indicating a statistically significant difference between the older and younger groups. Additionally, the negative t-statistic (-2.457) suggests that the older group has lower alpha power than the younger group.

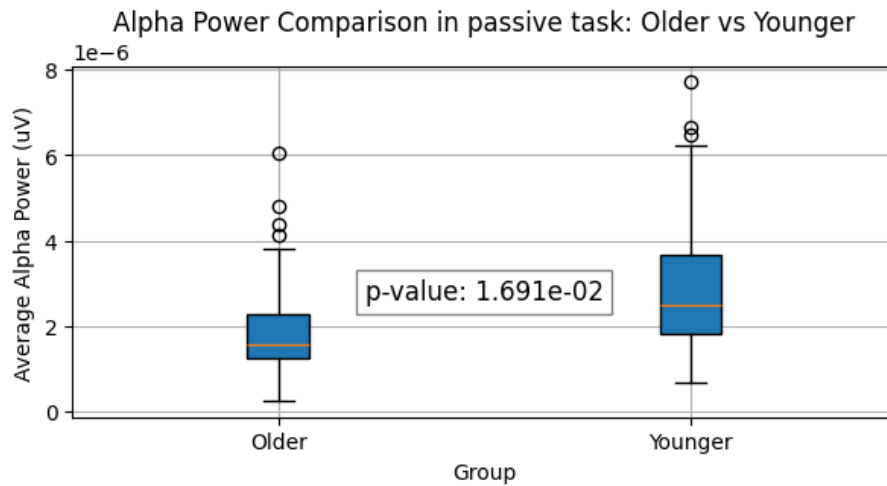


Figure 4.8: Alpha power comparison in passive task between older and younger groups

Go/Nogo Task

In Figure 4.9, there is a dip in alpha power before the peak of pupil diameter, followed by a recovery at the pupil peak. Alpha power is low 250ms before the peak point and begins to recover at peak point. The older group shows more decrease in alpha power before the pupil peak and also higher peak after the recovery compared to the younger group.

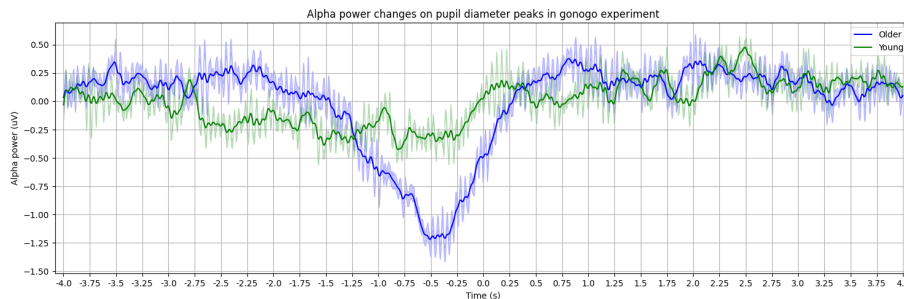


Figure 4.9: The alpha power changes at the pupil diameter peak (time = 0) across go/nogo experimental task for two groups.

We utilized a t-test to examine the average alpha power of two groups at peak point, and the results are presented in Figure 4.10. The p-value (0.020) indicating a statistically significant difference between the older and younger groups. Additionally, the negative t-statistic (-2.384) suggests that the older group has lower alpha power than the younger group.

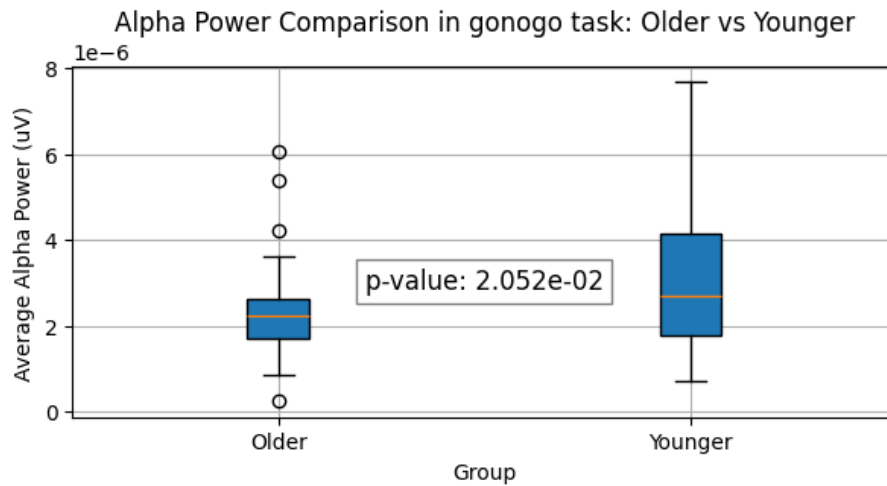


Figure 4.10: Alpha power comparison in go-nogo task between older and younger groups

Simple Reaction Time (RT) Task

In Figure 4.11, a similar pattern to go-nogo task is observed, with a dip in alpha power before the peak of pupil diameter and subsequent recovery. The older group shows more decrease in alpha power before the pupil peak compared to the younger group. Additionally, it seems there is 600-1000 ms time lag between two groups.

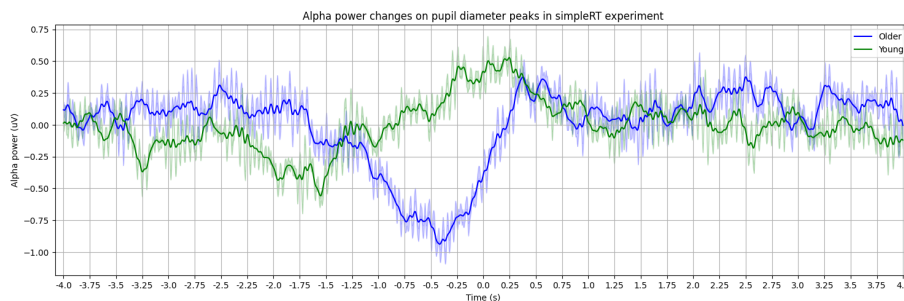


Figure 4.11: The alpha power changes at the pupil diameter peak (time = 0) across simple reaction time (RT) experimental task for two groups.

We utilized a t-test to examine the average alpha power of two groups at peak point, and the results are presented in Figure 4.12. The p-value (0.013), indicating a statistically significant difference between the older and younger groups. Additionally, the negative t-statistic (-2.579) suggests that the older group has lower alpha power than the younger group.

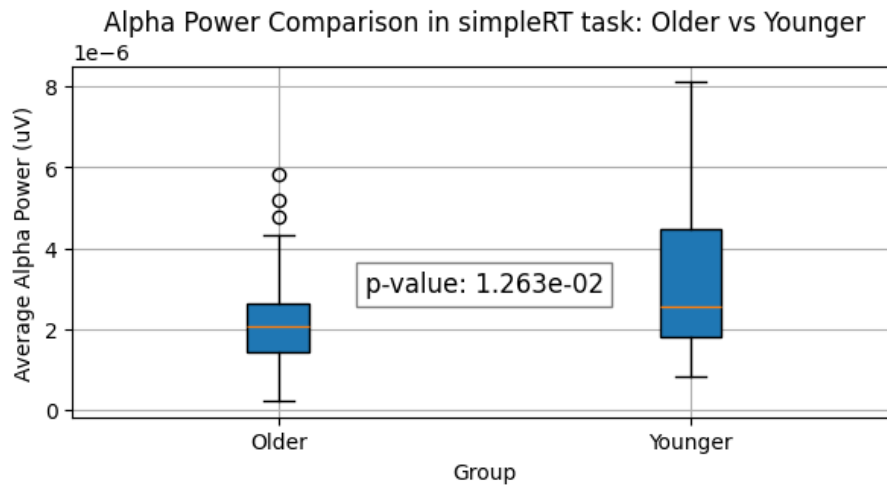


Figure 4.12: Alpha power comparison in simple reaction time task between older and younger groups

These results indicate a consistent, task-dependent relationship between alpha power and pupil diameter, influenced by cognitive demands and participant age.

4.3 Cross-Correlation of Alpha and Pupil Diameter Time Series

Figures 4.13, 4.14 and 4.15 show the correlation between alpha power and pupil diameter over entire of data in time frame 8 s across three different tasks: passive task, go/nogo task, and simple reaction time (RT) task. Each plot includes two groups: older participants (blue line), younger participants (green line). The shaded areas around the lines represent the standard error of the mean (SEM), calculated as the standard deviation divided by the square root of the number of subjects.

4.3.1 Task-Specific Observations

Passive Task

In Figure 4.13, the both groups show fluctuations in correlation over time, with peaks and troughs at different lags (time shifts). In the younger group, correlation begins on -2 s and followed by a negative correlation on -1.25 s and the most significant positive correlation for the young group occurs with time lag -300 ms. In other hand, the older group show beginning a correlation on -1.75 s and followed by a negative and positive correlation on -1.25 s and 125 ms. Around the time is equal to 0 (time=0), both groups exhibit a positive correlation that indicates relationship between alpha power and pupil diameter at this point.

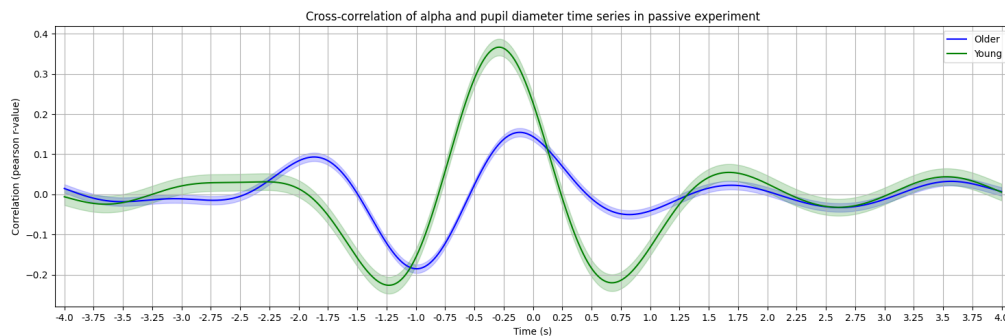


Figure 4.13: The cross-correlation between alpha power and pupil diameter across passive experimental task for two groups.

Go/Nogo Task

In Figure 4.14, the both groups show fluctuations in correlation over time, with peaks and troughs at different lags (time shifts). In the younger group, correlation begins on -2 s and followed by a negative correlation on -1.25 s and the most significant positive correlation for the young group occurs with time lag -250 ms. Additionally, the older group show beginning a correlation on -1.75 s and followed by a positive and negative correlation. The most significant negative correlation for the older group occurs with time lag -750 ms.

Simple Reaction Time Task

In Figure 4.15, the pattern in this task resembles the previous task (go-nogo task) and the both groups show fluctuations in correlation over time, with peaks and troughs at different lags (time shifts). In the younger group, correlation begins on -2 s and followed by a negative correlation

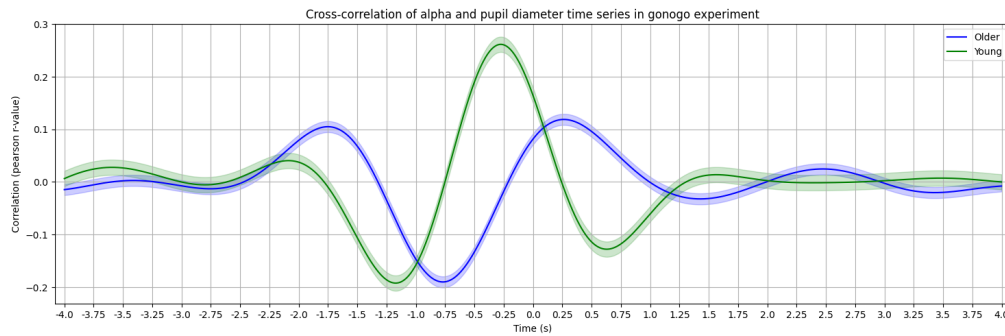


Figure 4.14: The cross-correlation between alpha power and pupil diameter across go/nogo experimental task for two groups.

on -1.25 s and the most significant positive correlation for the young group occurs with time lag -250 ms. Additionally, the older group shows beginning a correlation on -1.75 s and followed by a negative and positive correlation. The most significant correlation for the older group is a negative correlation that occurs with time lag -750 ms.

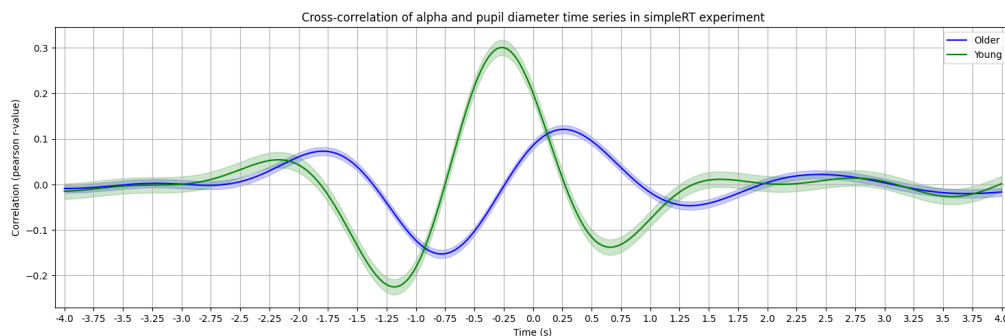


Figure 4.15: The cross-correlation between alpha power and pupil diameter across simple reaction time (RT) experimental task for two groups.

These results suggest a dynamic relationship between alpha power and pupil diameter, influenced by the cognitive demands of the task and the age of the participants.

Chapter 5

Discussion

Our study aimed to investigate the relationship between alpha power and pupil diameter in younger and older adults across various cognitive tasks, including passive viewing, go/nogo, and simple reaction time (RT) tasks. The findings provide valuable insights into age-related differences in the dynamic interplay between these physiological measures, highlighting both similarities and distinct patterns in younger and older adults.

Temporal and Cross-Correlation Analysis Our cross-correlation analysis demonstrated that both age groups displayed fluctuations in the temporal relationship between alpha power and pupil diameter. Younger adults exhibited more positive correlations at specific time lags, particularly around 250-300 milliseconds, suggesting a quicker and stronger coupling between alpha power and pupil responses. In contrast, older adults showed more delayed and weaker correlations, which could be indicative of age-related reductions in the efficiency of neural networks involved in attentional and cognitive control [12]. These results are consistent with previous studies that have shown age-related changes in both EEG and pupillary responses. For instance, older adults tend to exhibit reduced alpha power and altered pupillary responses during cognitive tasks, reflecting changes in cortical excitability and autonomic regulation [12]. The studies have shown that increased cognitive demand in auditory tasks leads to higher alpha power in the parietal cortex, whereas visual tasks often result in decreased alpha power in visual areas. This suggests that both pupil size and alpha power respond to changes in cognitive demands, potentially driven by a common underlying neural process such as noradrenergic modulation [11] [25]. Our findings add to this body of knowledge by providing a detailed analysis of the temporal dynamics between these measures.

Age-Related Differences Both younger and older adults exhibited high pupil diameters at alpha power peaks, followed by a decrease. This trend aligns with the existing literature, suggesting a general coupling between alpha oscillations and pupil dynamics [20]. However, our study revealed that younger participants had higher and quicker pupil dilation peaks compared to older participants. The observed time lag of 1-2 seconds in pupil diameter decrease following an increase in alpha power was notably shorter in younger adults, indicating more rapid physiological responses. This finding may reflect age-related declines in neural processing speed and autonomic nervous system function [24]. These differences suggest that age-related changes in neural and autonomic regulation significantly influence these physiological measures. Younger individuals' greater variability might be attributed to their more adaptable neural responses to cognitive demands [11].

Implications for Cognitive Aging The differential patterns observed in our study underscore the importance of considering age-related changes in neurophysiological processes when studying cognitive aging. The quicker and stronger relationship between alpha power and pupil diameter in younger adults may reflect more efficient neural processing and autonomic regulation. In contrast, the delayed and weaker correlations in older adults suggest a decline in these functions, which could contribute to the broader cognitive declines associated with aging [16].

Future Research Directions While our study provides important insights, several research gaps remain. Future studies should investigate the underlying neurophysiological mechanisms contributing to the observed age-related differences in alpha power and pupil diameter relationships. This could involve exploring the role of specific neurotransmitter systems, such as the cholinergic system, which is known to influence both alpha oscillations and pupillary responses [22].

Moreover, larger and more diverse samples are needed to generalize these findings across different populations. Including participants from various age groups, cultural backgrounds, and with different health statuses can help to elucidate the broader applicability of our findings and enhance the understanding of how these neurophysiological processes operate in the general population.

Chapter 6

Conclusion

Our study explored the relationship between alpha power and pupil diameter in younger and older adults across passive, go/nogo, and simple reaction time (RT) tasks. Results showed that both age groups experienced a high pupil diameter at alpha power peaks, followed by a decrease. However, younger participants exhibited higher and quicker dilation peaks compared to older participants, with notable time lags between the groups across all tasks. Specifically, the pupil diameter decreases following an increase in alpha with a time lag of 1-2 seconds after the peak, with younger adults showing a quicker response.

When examining alpha power response to pupil diameter peaks, younger adults showed higher peaks but older showed more decreases in alpha power. The cross-correlation analysis revealed temporal relationships where both groups displayed fluctuations, but younger participants had more positive correlations at specific time lags, indicating a quicker and stronger relationship between alpha power and pupil diameter. In younger adults, a positive correlation occurred with a time lag of approximately 250-300 milliseconds, whereas older adults showed more delayed and weaker correlations.

Despite these findings, several research gaps remain. Future studies should investigate the underlying neurophysiological mechanisms that contribute to the observed age-related differences in alpha power and pupil diameter relationships. Additionally, examining the influence of other cognitive tasks and stressors could provide a more comprehensive understanding of these dynamics. Furthermore, larger and more diverse samples are needed to generalize these findings across different populations.

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