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Different cortex activation between young and middle-aged people during different type problem-solving: An EEG&fNIRS study

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ABSTRACT

Problem-solving strategies vary depending on the type of problem and aging. This study investigated the hemodynamic response measured by the changes in the oxyhemoglobin concentration (HbO), alpha frequency power, and their interrelation during problem-solving in healthy young and middle-aged individuals, employing combined electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) recordings. The study included 39 young and 30 middle-aged subjects. The brain activation that occurred while answering different questions was recorded using combined EEG and fNIRS. During the EEG & fNIRS recording, four questions (arithmetic, general knowledge, insight, and basic operation) were used for problem-solving. Alpha power (8–13 Hz) and HbO changes were analyzed. The behavioral results indicated significant differences between age groups in various question types. While the middle-aged group performed better on the general knowledge questions, the older group performed better on the insight and four-process questions. The fNIRS results reveal significant differences in brain activation during problem-solving tasks, particularly in regions like DLPFC/TA, STG, pSSC/Wernicke, and STG/angular gyrus Wernicke's area. The young group with the highest HbO was recorded during arithmetic questions, general knowledge questions, and basic operation questions. In contrast, there was no significant highest HbO during insight questions. Similar findings were observed in the middle-aged group, with the highest HbO recorded during general knowledge questions. However, there was no significant HbO in other channels during the solving of other question types in this group. The alpha power varied across different electrodes for various question types in both young and middle-aged groups. The highest alpha frequency band power for different electrodes was recorded while solving general knowledge questions in the young group and insight questions in the middle-aged group. Finally, the EEG and fNIRS correlation results showed positive correlations between HbO and alpha frequency band power in specific brain regions while solving general knowledge questions, particularly in the middle-aged group.

The study reveals age-related differences in behavioral performance, brain activation patterns, and neural correlates during various cognitive tasks, showcasing distinct strengths between middle-aged and young individuals in specific question types.

1. Introduction

Problem-solving is an indispensable mental ability in daily human life. There are different brain mechanisms underlying the responses to other types of questions (Subramaniam et al., 2009). The answer to the general knowledge question is retrieved from memory; numerical ability is used in arithmetic problems, and basic operations are performed only in questions containing numbers and symbols (Fleck, 2008; Binder and

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Desai, 2011; Zhou et al., 2018). In insight questions, the answer appears in the participant's mind with the moment of aha, and the answering strategy cannot be explained (Tik et al., 2018).

Although there is no consensus on the areas of the brain that are activated when answering different types of questions, various studies have been conducted. In functional Magnetic Resonance Imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) studies, they have been reported that specific cortical and subcortical structures are activated while answering various types of questions, especially the Superior Temporal Gyrus (STG), Dorsolateral Prefrontal Cortex (DLPFC), and Wernicke regions (Ruocco et al., 2014; Ruh et al., 2012; Shen et al., 2017; Lin et al., 2021; Joyal and Fecteau, 2016; Racz et al., 2017; Ashlesh et al., 2020). However, studies have shown that the regions activated when answering specific types of questions are different from each other (Hu et al., 2019). It has been reported that the thalamus and basal ganglia are particularly influential, the frontoparietal network is dominant, and the superior temporal, inferior parietal, and perisylvian regions are involved in answering arithmetic questions. In basic operation questions containing only numbers and symbols, the ventral occipital and temporal regions are activated (Arsalidou and Taylor, 2011; Soltanlou et al., 2018; Artemenko, 2021; Skau et al., 2022). It has been shown that the hippocampus, Parahippocampal, Temporal, Ventral Parietal, DLPFC, and Ventrolateral Prefrontal cortex (VLPFC) regions are involved in answering general knowledge questions (Rissman and Wagner, 2012; Woodward et al., 2006; Kuhl and Chun, 2014; Jahani et al., 2017; Berglund-Barraza et al., 2019). During the response to insight questions, there was a notable surge in activation across diverse cortical brain regions, notably the DLPFC, Middle Temporal Gyrus, and Anterior Cingulate Cortex (Tik et al., 2018; Ohkuma et al., 2022). Additionally, there was a significant increase in activation observed in subcortical structures, particularly evident in the thalamus, Ventral Tegmental Area, Substantia Nigra, Striatum, and Hippocampus, as demonstrated by Tik (Tik et al., 2018).

EEG studies have emphasized that alpha activity is particularly effective in thinking type, creative thinking, generating new ideas, and problem-solving (Fink et al., 2009). The left temporal, right frontal, and right parietal regions' alpha power increases in arithmetic questions and basic-operation questions, and as the difficulty level of the question increases, frontal and parieto-occipital regions' alpha power increases more significantly (Anderson et al., 2011; Kong et al., 2005; Liang et al., 2018; Montefinese et al., 2017). Although there are conflicting results in studies conducted with insight questions, it has been shown that alpha power increases in the right parieto-occipital region (Santarnecchi et al., 2019). Studies emphasize that the amount and location of alpha power varies depending on the question type, question-solving process, and difficulty level of the question (Sandkühler and Bhattacharya, 2008; Lin et al., 2012).

In Sanes, 2013 evaluating mental functioning skills separately, it has been reported that individuals experience cognitive decline in their problem-solving skills with aging (Sanes and Jessell, 2013). Hemodynamic and electrophysiological responses of the brain also change with aging. Despite all these changes, healthy older adults often continue to provide correct answers to the questions posed to them. There are various theories, overactivation, de-differentiation, frontal compensation, and brain maintenance, about the mechanisms that accompany aging and cognitive decline. Overactivation occurs when older adults have higher activation in specific brain regions than younger adults when performing cognitive tasks (Grady, 2012). De-differentiation refers to changes in specific regions that perform cognitive functions or a decrease in the number of regions (Li et al., 2001). Conversely, frontal compensation is excessive activation in the frontal regions of the elderly while performing cognitive function. It is theorized that all of these mechanisms are compensation strategies used to achieve/maintain cognitive skills (Yeung and Chan, 2021). In the Compensation Related Utilization of Neural Circuits hypothesis, it is suggested that older adults show excessive activation, in the frontal regions. In contradistinction, young adults show more activation in the task-related focal regions in response to task demand. It is thought that access to the relevant region in line with the task demand is restricted by aging, and even if more activation is shown in different regions, performance is reduced in the task due to this limitation (Reuter-Lorenz and Cappell, 2008). In the Scaffolding Theory of Aging and Cognition model, it is reported that alternative neural networks are established despite the changes that occur in the brain with aging and that cognitive functions can remain active in this way (Park and Reuter-Lorenz, 2009). Although they seem different, these theories should not be evaluated separately but should be handled with a holistic approach (Bonilauri et al., 2020; McDonough et al., 2022). EEG studies investigating changes in the aging process draw attention to the slowing down of alpha peak frequency with aging. Changes in alpha peak frequency in response to task demands appear different in brain regions in young adults than in older adults. Interestingly, slower dynamics of oscillatory activity are associated with cognitive changes in healthy older adults, considered as a compensatory mechanism (Stacey et al., 2021; Scally et al., 2018).

For a comprehensive investigation of brain activation, unimodal approaches sensitive to neural activity or hemodynamic response alone are insufficient. EEG provides electrophysiological data with high temporal resolution, and fNIRS provides hemodynamic data at a higher spatial resolution, allowing researchers to obtain more comprehensive data on different aspects of cortical activity in the studies (Omurtag et al., 2017; Aghajani et al., 2017). Hemodynamic measurements complement EEG data by capturing the metabolic and vascular responses underlying neural activity, which provides a more integrated view of the brain's functional dynamics. For this reason, it is seen that EEG&fNIRS combined multimodal systems are emphasized in studies. Although there has been an increasing number of EEG&fNIRS studies in recent years, to the best of our knowledge, no prior studies investigated systematically the problem-solving processes and change with aging. We focus on the EEG alpha band due to its prominent role in the task types employed in this study and its tendency to correlate strongly with hemodynamic activity (Keles et al. 2016).

The primary purpose of this study was to investigate the hemodynamic response (measured by HbO), alpha frequency power, and the relationship between hemodynamic response and alpha frequency power, which occur when answering different types of questions in healthy young and healthy middle-aged individuals, and to reveal the possible change due to aging. In this study, we utilized the superior temporal resolution of EEG in conjunction with the superior spatial resolution of fNIRS. EEG facilitates the detection of rapid fluctuations in neural activity, thereby offering high temporal resolution for the assessment of brain electrical activity, including alpha frequency power. Conversely, fNIRS provides the capability to monitor hemodynamic responses, specifically the variations in oxygenated hemoglobin (HbO) levels, with enhanced spatial resolution. The integration of these two modalities enables a comprehensive investigation of the temporal dynamics of neural activity, as measured by EEG, alongside its metabolic and vascular responses, as assessed by fNIRS. This multimodal approach enhances our understanding of the differences between problem types and aging-related changes in response to different types of problem-solving.

2. Material & methods

The study was approved by the Istanbul Medipol University Ethics Committee (Ethical Report No: 10,840,098–604.01.01-E.1064). All participants were informed about the study protocol and a consent form was obtained from the participants accepting the purpose and the methods of the study.

2.1. Participants

39 young participants aged 20–30 years (22 females, mean age (SD):

25.23±2.58 years, mean years of education (SD): 17.92 (± 2.03)) and 30 middle-aged participants aged 50–60 years (17 females, mean age (SD): 52,86±3,35 years, mean years of education (SD): 15.43 (± 6.89)) were recruited to participate in this study. All participants were right-handed according to the Edinburg Handedness scale (Oldfield, 1971), had no neurological or psychological disorders, and had normal vision. Participants who had a personal or family history of neuropsychiatric disorders used medication and had <26 points on the Montreal Cognitive Assessment Test (MoCA) were excluded from the study (Ozdilek and Kenangil, 2014). The demographical information of the participants is shown in Supplementary Material 1. We have observed a significant difference between the groups in age and MoCA scores as expected (MoCA: Young Group mean score (SD): 28.84±1.48; Middle-Aged Group mean score (SD): 27.83±1.62, $t(59.53) = 2.64$, $p = 0.010$) (Supplementary Material 1).

2.2. Experimental design

This study was designed according to the same protocol as our previous study (Saricaoglu et al., 2022). The participants were seated in a chair next to a table with a computer screen. All tests were performed sitting in the same location.

During the EEG and fNIRS registrations, participants were presented with four different types of questions, 4 separate blocks in which each question type was presented, and 22 different questions (belonging to the same question type) in each block. The blocks and questions in each block were randomly presented to the participants. The experimental design was prepared and presented with the E-Prime software (Psychology Software Tools Inc., Pittsburgh, PA).

The questions were followed: arithmetic questions, general knowledge questions, insight questions, and basic operation questions (Fig. 1).

1. **Arithmetic problem-solving task:** The arithmetic subscale questions of the Wechsler Adult Intelligence Scale-Revised (WAIS-R) were used for assessing brain activity generated during solving arithmetic questions with an analytic strategy. The Arithmetic subtest assesses arithmetic reasoning and analytic strategy by having participants solve mental arithmetic problems. Participants were invited to reason arithmetically to answer these arithmetic questions. An example of an arithmetic question 'If 2 plums are 30 g, how many grams is a dozen plums?' was given (Fig. 1. a). Turkish Standardization of Wechsler Adult Intelligence Scale-Revised (WAIS-R) was used (Sezgin et al., 2014).
2. **General knowledge question-solving task:** The general knowledge subscale questions of WAIS-R were used for assessing brain activity generated during responding to general knowledge questions with a retrieval strategy. The general knowledge subscale assesses the degree of general information acquired from culture. Participants were

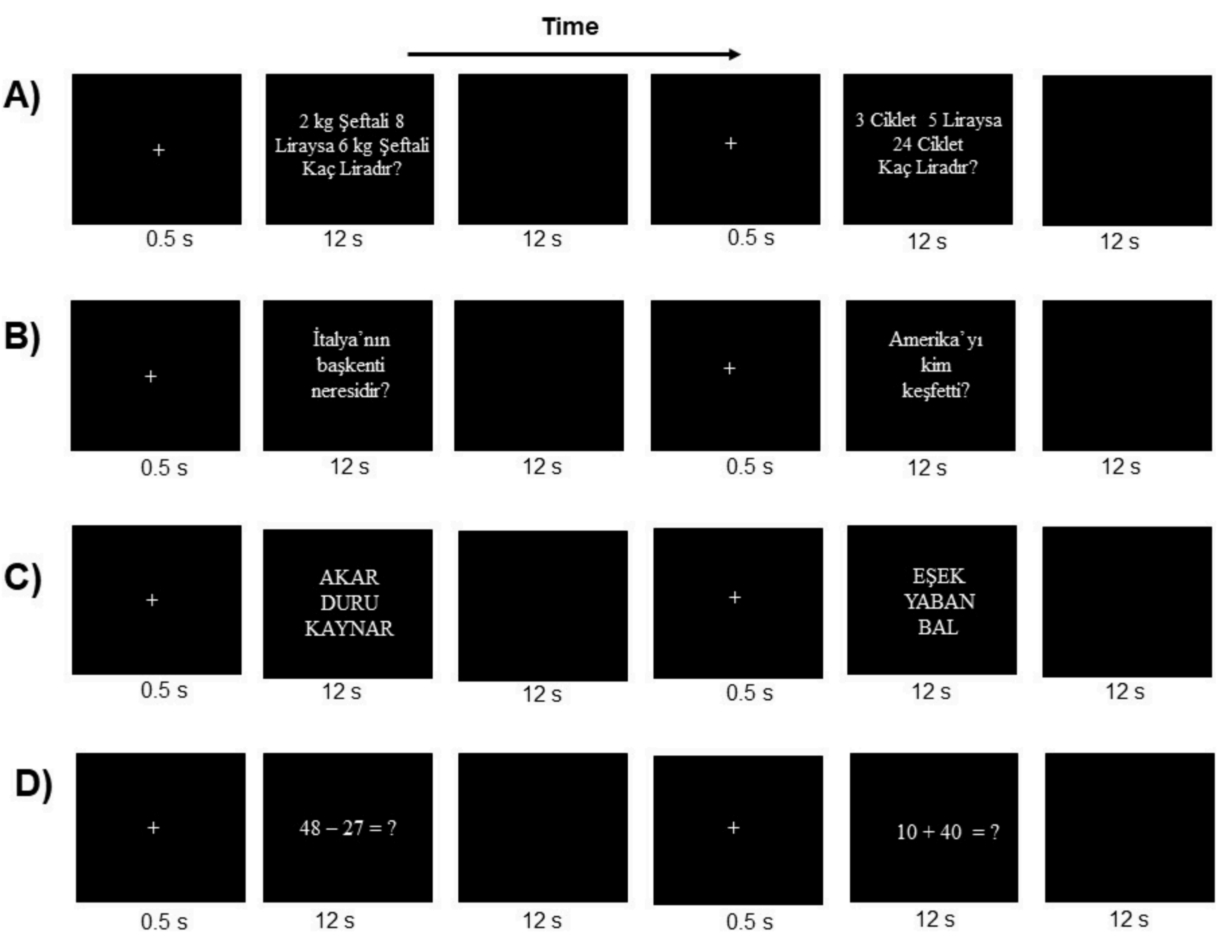

Fig. 1. Task Design (The representations of all question tasks during the fNIRS&EEG recordings. A. Arithmetic Questions Task ('2 kg şeftali 8 liraysa 6 kg şeftali kaç liradır?' means 'If 2 kg of peached are 8 lira, how much are 6 kg of peaches?' ('3 ciklet 5 liraysa 24 ciklet kaç liradır?' means 'If 3 gums are 5 lira, how much are 24 gums?') B. General Knowledge Question Task ('İtalya'nın başkenti neresidir?' means 'What is the capital of Italy?', 'Amerika'yı kim keşfetti?' means 'Who discovered America?'); C. Insight Questions Task ('Akar/Duru/Kaynar', 'Eşek/Yaban/Bal' same like Age/Mile/Sand' in Turkish) D. Basic Operation Questions Task. The questions presented in Turkish. The stimulus protocol was presented in the following order: A white cross pattern was presented for 0.5 ss as a fixation; Question stimuli were presented for a maximum of 12 ss (When the participant responded earlier, the interval between stimuli was exceeded); The time between stimuli (interstimulus interval) was 12 ss. s: seconds.)

invited to find the answer from their short-term or long-term memory to answer these questions. An example of a general knowledge question 'What is the capital of Spain?' was given (Fig. 1. b). The subtest general knowledge questions in the Turkish version were used (Sezgin et al., 2014).

3. **Insight question-solving task:** Questions from the Remote Associates Test (RAT) were used for assessing brain activity generated during responding to insight questions with insight. RAT test was used to measure insight problem-solving potential. RAT problems can be divided into two types forward and backward. In this study, we used forward RAT problems. In the forward RAT problems, the solution word was a suffix to all three words of a problem. For example; in the test, participants were given three words—CRAB, PINE, and SAUCE—and asked to come up with a new word that relates to all of them. The best answer to this particular query was APPLE (CRABAPPLE, PINEAPPLE, SAUCEAPPLE) (Fig. 1. c). Turkish Standardization of RAT was used (Özen et al., 2015).
4. **Basic Operation problem-solving task:** Addition and subtraction questions were used for assessing brain activity generated during responding to basic mathematical questions with an arithmetic strategy. The questions were presented with numbers and symbols without any verbal information. The literature suggests that the type of arithmetic operation, the number of steps involved, and the level of difficulty can influence the activation of different brain regions as well as the degree of activation. The tasks were designed using two-digit numbers of moderate difficulty, and the solutions also resulted in two-digit numbers. No carry-over operations were included. As an example '20 + 30 =?' was given (Fig. 1. d) (Liang et al., 2018; Liu, 2019).

To equalize the number of questions, 22 questions were randomly presented in each task. All questions were presented in Turkish in 3 lines, each question was presented on the screen in a way that corresponds to the same visual field (Fig. 1). The visual stimuli were shown in

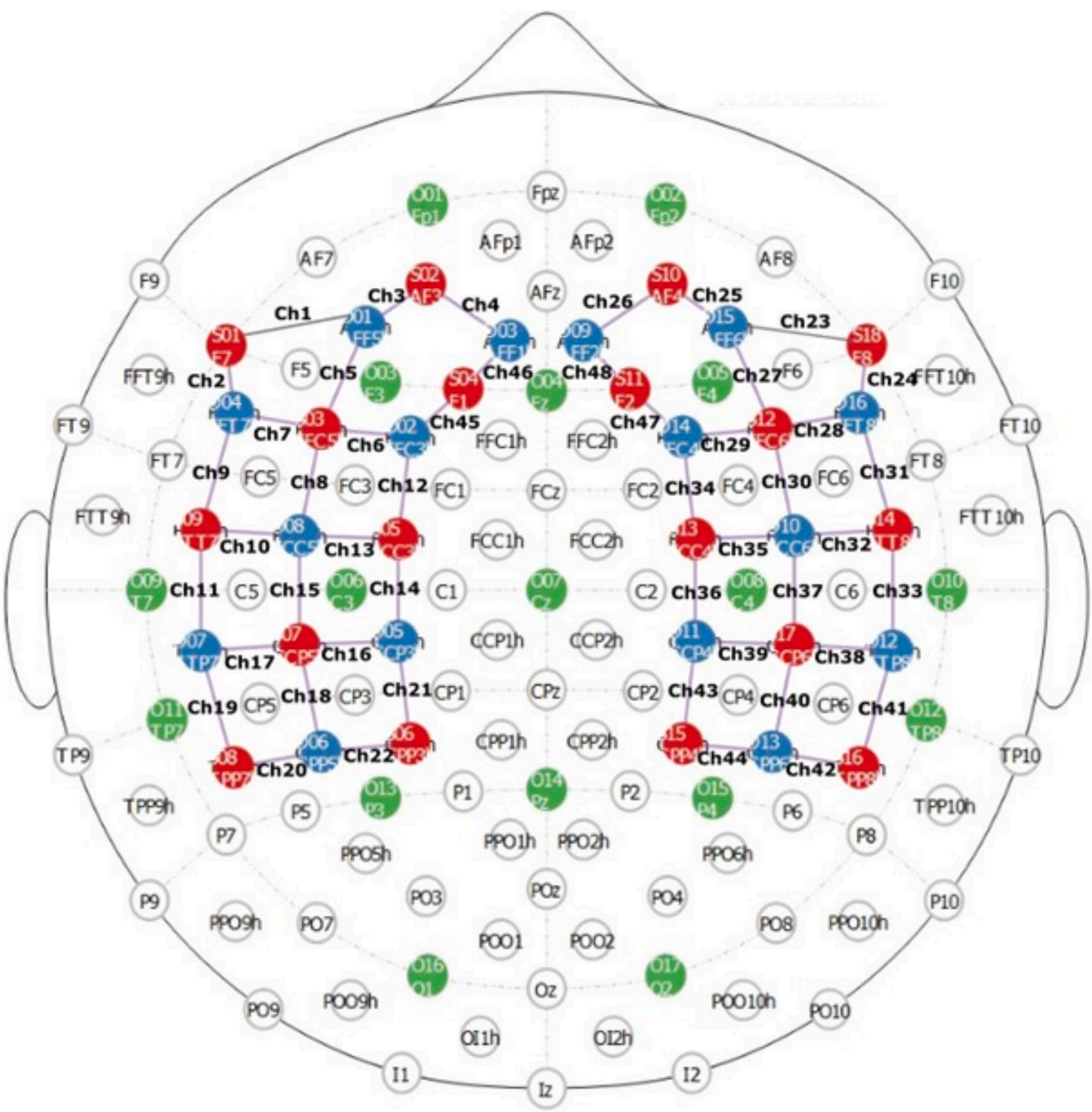

Fig. 2. EEG electrodes and fNIRS optodes placement in the cap. Red Circles: Source; Blue Circles: Detectors; Green Circles: EEG electrodes; Black lines: fNIRS channels.

full-screen mode on a 47.5 × 26.8 cm size monitor with a refresh rate of 60 Hz that was placed at a viewing distance of 90 cm.

The participants were asked to read the questions with their inner voice and to solve them mentally without using paper and pencil. When they found the answer, they were instructed to click on the keyboard and then say the answer aloud. If the participants did not click on the keyboard to answer, the question was considered unanswered. Each answer given by the participants was recorded and the number of correct answers, the number of wrong answers, and the number of blank questions were scored as 1 point for each question type. The score of each area was calculated over a maximum of 22 points. In addition, the response times to the questions were recorded in seconds. A response was expected within a minimum of 1 s and a maximum of 12 s.

The stimulus protocol was presented in the following order:

1. A white cross pattern was presented for 0.5 s as a fixation
2. Question stimuli were presented for a maximum of 12 s (When the participant responded earlier, the interval between stimuli was exceeded)
3. The time between stimuli (interstimulus interval) was 12 s (Fig. 1). The protocol design consisted of 88 random question definitions that required approximately 25 s to complete.

2.3. EEG&fNIRS data acquisition

In this study, we used located EEG and fNIRS measurements at standard 10–20 sites bilaterally covering the frontopolar, frontal, central, and temporal areas. EEG electrodes and fNIRS probes were mounted on an extended EEG cap (actiCAP 128, Brain Products GmbH, Germany). Fig. 2 shows the location of EEG electrodes and fNIRS probes.

The EEG system (Brain Product GmbH, Germany) was used with 18 measurement channels (Fp1, Fp2, F3, Fz, F4, C3, Cz, C4, T7, T8, Tp7, Tp8, P3, Pz, P4, O1, Oz, and O2). Two linked electrodes were placed on the earlobes as references. The ground electrode was placed behind the right earlobe. The electrooculogram was recorded at the lateral orbital rim of the left eye and the medial upper of the right eye. The electrodes used were standard Ag/AgCl ones and the EEG signals were sampled at feeg = 500 Hz. Brain Vision Recorder software (Brain Products GmbH, Germany) was used both to acquire the data and to check the quality of the signals before starting the experiments. The impedance of electrodes was kept below approximately 5 kΩ.

The fNIRS system (NIRx Medical Technologies LLC, Berlin, Germany) was recorded with 18 sources and 16 detectors combined in 48 channels of acquisition. fNIRS sources and detectors have been placed a maximum of 3.4 cm from each other, in order to ensure good-quality signals. The 48 NIRS channels were placed over frontal, temporal, and parietal lobe regions, including the DLPFC, frontopolar area (FA), frontal gyrus (FG), inferior prefrontal gyrus (IFG), superior temporal gyrus (STG), inferior temporal gyrus (ITG), temporopolar area (TA), pars triangularis Broca's area (BROCA), premotor/presupplementary area (preSMA), primer motor cortex (M1), postcentral gyrus (PCG), primary somatosensory cortex (pSSC), somatosensory association area (aSSC), supramarginal gyrus Wernicke's area, angular gyrus Wernicke's area, and superior parietal lobule (SPL) (Supplementary Material 2). The sampling frequency was 3.47 Hz, and the wavelengths used were 760 nm and 850 nm. NIRStar software (NIRx Medizintechnik GmbH, Germany) was used both to acquire the data and to check the quality of the signals before starting the experiments.

The participants sat in a dimly lit room during EEG and fNIRS recordings. They were instructed to sit comfortably in a chair and maintain a relaxed position.

2.4. EEG data analysis

Brain Vision Analyzer 2.2 Software (Brainproducts, Munich, Germany) was used for EEG data preprocessing. EEG recordings from the F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, T7, T8, TP7, and TP8 electrodes were analyzed. These electrodes were selected due to their proximity to the fNIRS channel locations (For instance, the C3 electrode is positioned centrally among fNIRS channels 13, 14, 15, and 16) (Fig. 2).

All analyses were calculated separately for four different types of questions given. Analyses were performed for correct answers only. Unanswered questions and incorrectly answered questions were excluded from the analyses. The preprocessing steps were as follows:

1. Segmentation 1: EEG analyses were performed for 2 s before the onset of the stimulus and 14 s into the onset of the stimulus to ensure consistency with the fNIRS data analysis, segmenting the data every 16 s following the presentation of the stimulus.
2. Segmentation 2: 16 s epochs were divided into 1 s epochs.
3. Artifact Rejection: For every 1 s epoch, manual artifact rejection was carried out to enhance data quality, with artifacts such as eye movement, blinking, and muscle movement being identified and removed offline by an expert EEG researcher without using any automated algorithms. This process was preferred as manual rejection has been shown to yield better results and preserve data integrity. Before Fast Fourier Transform (FFT) analysis, data was segmented into epochs and filtered to remove artifacts.
4. FFT: Subsequently, power spectrum analysis was performed using FFT (with 0.9 Hz maximum resolution; 10% Hanning window). FFT is an effective method for analyzing specific waveforms in EEG data due to its high-frequency resolution.
5. Average Power Calculation: The FFT power values of all epochs were averaged for each session. Based on the results of previous studies, the alpha frequency range of 8–13 Hz was determined. Alpha power was calculated separately for each 1-s epoch for the 2 s before the onset of the stimulus and the 14 s following the onset of the stimulus. This means that alpha power was computed for 1-s segments, capturing the relevant brain activity in the specified time frames. The average alpha power for these epochs was then calculated to allow for a better understanding of the general trends in the dataset. For EEG analysis, alpha frequency power was specifically calculated over the average response time for each question type, ensuring that the analysis was aligned with the corresponding stimulus presentations. This averaged alpha power was subsequently used in statistical analysis to assess the significance of the findings.

Furthermore, for the correlation analysis between fNIRS and EEG data, the average alpha frequency power was computed for the 2 s before the onset of the stimulus and the 14 s after the onset of the stimulus, aligning the timing of both modalities for a more comprehensive understanding of the neural responses to the stimuli.

2.5. fNIRS data analysis

The fNIRS data were preprocessed using MATLAB 2019b (MATLAB, 2019) and the MATLAB-based fNIRS processing package, Homer3.

1. The preprocessing began with converting the raw data into optical density (OD) values.
2. Correction and Detection of Motion Artifacts: To correct and detect motion artifacts, two functions from the Homer3 package were employed:
   - hmrR_MotionCorrectWavelet (iqr=1.50): This function is designed to correct motion artifacts using wavelet transformation. The interquartile range (IQR) value is set to 1.50, establishing a statistical threshold for identifying motion artifacts. This parameter minimizes the influence of outliers in the dataset. The wavelet transformation facilitates the separation of high-frequency components when analyzing time-ordered data.

- hmrR_MotionArtifactByChannel (tMotion = 0.5, tMask = 1.0, STDEVthresh = 20.0, AMPthresh = 5.0): This function utilizes several threshold values to identify motion artifacts:
- tMotion = 0.5: This parameter defines the time interval for motion detection, indicating the period in which motion is recognized.
- tMask = 1.0: This parameter specifies the duration for which the data will be masked following the detection of motion.
- STDEVthresh = 20.0: This standard deviation threshold identifies abnormal motion conditions, with a higher threshold ensuring the detection of significant motion artifacts within the dataset.
- AMPthresh = 5.0: This amplitude threshold mandates that the recorded signal exceeds a specified level during motion, thereby enhancing detection accuracy.
- Experimental Design and Timing: To improve the controllability of the experiment, motion artifacts occurring between 2 s before and 14 s after stimulus presentation were excluded from the analysis. This specific timeframe is critical for assessing participants' responses to stimuli, as any motion during this interval can negatively impact the accuracy and validity of the results.

3. Additionally, the signal was processed using a bandpass filter, with a low cutoff frequency of 0.5 Hz to remove high-frequency noise. The OD of the signal was then converted to concentration changes using the modified Beer-Lambert law, with a path length factor (ppf) of 1.0.
4. To calculate the hemodynamic response function (HRF), the hmrR_GLM function was employed with the following parameters:
   - trange = -2.0 14.0: This parameter specified the time range for the analysis, where the value -2.0 s indicated the period preceding the stimulus onset, and 14.0 s represented the duration following the stimulus onset. This range allows for the examination of the HRF both before and after the stimulus presentation.
   - glmSolveMethod = 1: This parameter indicates the method used to solve the generalized linear model (GLM). A value of 1 typically refers to the default method for estimating parameters within the GLM framework.
   - idxBasis = 1: This parameter specifies the basis function to be used in the analysis. A value of 1 usually corresponds to a predefined basis function (a gamma function) for modeling the HRF.
   - paramsBasis 1.0 1.0: These values define the parameters of the basis function. The first value typically corresponds to the peak time of the response, while the second value may relate to the standard deviation or width of the response.
   - rhoSD_ssThresh = 40.0: This parameter sets the maximum distance threshold for the standard deviation of the short-separation channels, with a value of 40.0 indicating that channels with a distance greater than this threshold will not be included in the analysis. This threshold helps ensure that only reliable signals are considered.
   - flagNuisanceRMethod = 2: This parameter indicates the method for handling nuisance regressors. A value of 2 generally means that the average signal from all long-distance channels will be used as a regressor to account for potential artifacts.
   - driftOrder = 3: This parameter specifies the order of polynomial drift correction to be applied to the data. A value of 3 indicates that a cubic polynomial will be used to model and remove any low-frequency drifts in the signal.
   - c_vector = 0: This parameter represents the contrast vector for hypothesis testing, with a value of 0 indicating no specific contrast is being applied.

   Overall, these parameters were chosen to optimize the estimation of the hemodynamic response, ensuring accurate modeling of brain activity in response to stimuli.
5. Hemodynamic response functions were created for 2 s before the onset of the stimulus and 14 s into the onset of the stimulus.

   Following preprocessing, it was noted that the hemodynamic response returned to baseline within 14 s post-stimulus. Although 14 s may seem short for fNIRS analysis, the preprocessing results indicate that this duration is sufficient for capturing task-related responses.
6. Since short channel separation was not used during data collection and recording, we applied a maximum distance threshold of 40 (rhoSD_ssThresh = 40) and calculated the average signal from all long-distance channels (flagNuisanceRMethod = 2) to be used as a regressor (Gagnon et al., 2011). While using the average signal from all channels may not completely eliminate the influences of skin blood flow and systemic effects, this approach was deemed necessary due to the absence of short separation channels. The rationale behind this choice is that averaging long-distance channels can help to mitigate noise and variability inherent in individual channel signals, thus providing a more stable estimate of the underlying brain activity.

fNIRS simultaneously provides the changes in the concentrations of both HbO and deoxyhemoglobin (HbR). Previous studies reported that the signal-to-noise ratio of HbO is better than that of HbR and the HbO signal is more sensitive for processing the task response (Cheng et al., 2015; Xu et al., 2019). In this research, the HbO data was analyzed.

In this research, the HbO data were analyzed, and as a result of the group preprocessing analysis, it was observed that the HbO peak occurred between 2 and 6 s post-stimulus. For the fNIRS analysis, the mean HbO value during this peak interval (2 to 6 s) was included in the statistical analysis. The decision to focus on the peak HbO time is justified by its demonstrated sensitivity in reflecting the neural activation associated with the task, allowing for a more precise assessment of brain activity in response to the stimuli.

For the correlation analysis between the fNIRS and EEG data, HbO was calculated by averaging a total of 16 s, which included 2 s before the stimulus and 14 s after it. This duration was selected to encompass the entire response period, as there is no specific temporal definition for the correlation analysis, allowing for a comprehensive assessment of the neural activity following the stimulus presentation.

2.6. Correlational analysis of EEG and fNIRS signal

Correlation analysis was employed to elucidate the relationships between the two distinct neuroimaging techniques, EEG and fNIRS. This approach was favored as it offers a more comprehensive understanding of brain functionality by determining whether a relationship exists between the EEG and fNIRS data. Additionally, correlation analysis provides an opportunity to evaluate the consistency and reliability of the data obtained from both methods. A strong correlation between the EEG and fNIRS data indicates that both techniques reflect similar cognitive processes, thereby enhancing the validity of the findings.

All analyses were calculated separately for four different types of questions given. EEG and fNIRS analyses were performed for correct answers only. Unanswered questions and incorrectly answered questions were excluded from the analyses.

In our study, the correlation between alpha power and hemodynamic responses (HbO and HbR) was analyzed. The relationship between alpha power and hemodynamic response in the whole response process was investigated from 2 s before the stimulus to 14 s after the stimulus. MATLAB 2019b (MATLAB, 2019) program was used for the correlational analysis.

The mean HbO was calculated within the 13 ROIs (Region of Interests) to enhance reliability and its correlation with the EEG channel located in each ROI region was examined. The ROIs and their associated EEG electrodes and fNIRS channels are summarized in Table 1.

2.7. Statistics

SPSS (Statistical Package for Social Science) 25.0 for Windows and Jamovi (The jamovi project, 2021) program were used for the statistical analysis. The normal distribution of the variables was tested by the

Table 1
The 13 determined ROI regions and their correlated fNIRS channels and EEG electrodes.

ROI Number	fNIRS Location (Channel Number)	EEG Electrode
ROI 1	Left DLPFC, and Premotor/PreSMA (CHs 1 to 7, 45, and 46)	F3
ROI 2	Right DLPFC, Premotor/PreSMA (CHs 23 to 29, 47, 48)	F4
ROI 3	DLPFC (CHs 4, 26, 45 to 48)	Fz
ROI 4	Left Premotor/PreSMA, Primary Somatosensorial cortex (CHs 13 to 16)	C3
ROI 5	Right Premotor/PreSMA, Primer Somatosensorial cortex (CHs 35 to 37, 39)	C4
ROI 6	Premotor/PreSMA, Primary Somatosensorial cortex, Wernicke (CHs 12, 14, 21, 34, 36, 43)	Cz
ROI 7	Left Wernicke (CHs 20, 22)	P3
ROI 8	Right Wernicke (CHs 42, 44)	P4
ROI 9	Wernicke, Somatosensorial Association (CHs 21, 22, 43, 44)	Pz
ROI 10	Left Superior Temporal Gyrus (CHs 10, 11, 17)	T7
ROI 11	Right Superior Temporal Gyrus (CHs 32, 33, 38)	T8
ROI 12	Left Wernicke, Temporal Gyrus (CHs 17, 19, 20)	TP7
ROI 13	Right Wernicke, Fusiform Gyrus (CHs 38, 41, 42)	TP8

ROI: Region of Interest; CHs: Channels

Kolmogorov-Smirnov Test. The nominal data of the independent variables were analyzed with the Chi-Square Test, and the numerical data of the independent variables were analyzed with the Independent Sample *t*-test.

Behavioral data collected during EEG&fNIRS recording determined for each question type as the score of correct answers, the score of incorrect answers, the score of unanswered questions, and the average response time (time in seconds until the participant clicks the keyboard). The Independent Samples T-test was performed for the statistical analysis of the behavioural data collected during fNIRS&EEG recording.

Time-dependent differences within groups were analyzed with Two-Way Repeated Measure ANOVA and Group*QuestionType interactions between groups were analyzed with MANOVA for EEG and fNIRS data. Following the analysis, Bonferroni correction was applied for the Post Hoc tests.

For the correlation analysis, bivariate linear correlation (Pearson correlation, 2-tailed) analysis was used between fNIRS and EEG data. The EEG and fNIRS data correlation results of the two groups were compared with the Independent Sample T-test. Bonferroni correction was applied for the tests. The significance value was accepted as $p<0.05$.

3. Results

3.1. Behavioral results

We have observed significant differences between the groups in the behavioral data collected during fNIRS and EEG recording (see Table 2). Results showed that there were no significant differences between the two groups for arithmetic questions' scores and the general knowledge questions' correct score was significantly higher in the middle-aged group than in the young group (General Knowledge Q. Correct: t (65.38) = -2.00, p= 0.049). The general knowledge questions' incorrect score was significantly higher in the young group than in the middle-aged group (General Knowledge Q.-Incorrect: t (65.99) = 2.73, p= 0.008). The insight questions' incorrect score was significantly higher in the young group than in the middle-aged group (Insight Q.-Incorrect: t (46.05) = -2.56, p= 0.014). The insight questions' response time was significantly higher in the middle-aged group than in the young group (Insight Q.-RT: t (44.52) = -2.45, p = 0.018). It was seen that the insight problem questions' correct score was significantly higher in the young group than in the middle-aged group (Insight Problem Q.Correct: t (40.89) = 3.66, p= 0.001). The basic operation questions' incorrect score, the basic operation questions' unanswered score, and the response time were significantly higher in the middle-aged group than in the young group (Basic Operation Q.-Incorrect: t (41.71) = -2.62, p= 0.012; Basic Operation Q.-Unanswered: t (31.00) = -3.28, p= 0.003; Basic Operation Q.-RT: t (51.76) = -3.46, p = 0.001).

Table 2
Comprassion between the groups in behavioral data.

	Young Group (n=39) (Mean±S.D.)	Middle-Aged Group (n=30) (Mean±S.D.)	P
Arithmetic Q.-Correct	14.34±4.28	13.63±3.31	0.445
Arithmetic Q.-Incorrect	2.63±1.88	3.40±2.60	0.180
Arithmetic Q.-Unanswered	4.68±3.54	5.00±3.93	0.732
Arithmetic Q.-RT (s)	9.14±1.51	9.64±1.61	0.203
General Knowledge Q.-Correct	16.07±3.13	17.50±2.71	**0.049***
General Knowledge Q.-Incorrect	3.57±1.86	2.46±1.47	**0.008***
General Knowledge Q.-Unanswered	2.36±2.62	2.03±1.97	0.550
General Knowledge Q.-RT (s)	4.42±1.22	4.60±1.80	0.646
Insight Q.-Correct	18.42±2.12	17.56±3.00	0.193
Insight Q.-Incorrect	0.92±1.21	1.96±1.95	**0.014***
Insight Q.-Unanswered	2.68±1.59	2.46±1.99	0.628
Insight Q.-RT (s)	3.63±0.80	4.31±1.35	**0.018***
Basic Operation Q.-Correct	21.28±1.03	19.80±2.02	**0.001***
Basic Operation Q.-Incorrect	0.68±1.01	1.70±1.91	**0.012***
Basic Operation Q.-Unanswered	0.02±0.16	0.50±0.77	**0.003***
Basic Operation Q.-RT (s)	3.24±1.04	4.31±1.41	**0.001***

n: Subject number; **S.D.:** Standard Deviation; **Q:** Question; **RT:** Reaction Time; **s:** seconds

3.2. fNIRS results

All channels were converted to standard Montreal Neurological Institute (MNI) coordinates using a probabilistic estimation method (Cutini et al., 2011). Anatomical labels were estimated based on the MNI coordinates of all channels.

3.2.1. Group*question type results

Group and question type main effects results were supplementary materials (Supplementary Material 3). These two significant main effects depend on the other within the subject factor reported below.

Group*Question Type statistically significant difference was found in **DLPFC/TA, STG, pSSC/Wernicke, STG/angular gyrus Wernicke's area** (Tables 3, 4). Please see Supplementary Material 3 for detailed results of ANOVAs.

3.2.2. Comparison of HbO during solving different question types in the young group

A significant difference was observed in the brain activations of the **STG** during problem-solving (Table 5). The highest HbO was recorded during solving arithmetic questions. While answering the arithmetic questions, there was no other channel where the HbO was highest.

Significant differences were observed in the brain activations of the in **DLPFC/TA, PreSMA/TA, STG/TA** during problem-solving (Table 5). The highest HbO was recorded during solving general knowledge questions. While answering the general knowledge questions, there was no other channel where the HbO was highest.

While solving the insight questions, there was no channel where the maximum HbO was significant ($p>0.05$).

Significant differences were observed in the brain activations of the

Table 3
Significant regions and electrodes in Group*QuestionType findings are summarized.

Brain Region (Channel No)/ Electrode	F	MSe	p	η2
DLPFC/TA (Ch 2)	3.15	22.5	.045	.035
STG (Ch 11)	6.67	35.6	.002	.064
pSSC/Wernicke (Ch 18)	3.47	12.3	.026	.039
STG/angular gyrus Wernicke's area (Ch 20)	3.69	17.7	.023	.023
FP1	4.30	6.24	.008	.021
FP2	5.04	7.56	.004	.025
F3	6.97	8.38	< 0.001	.029
F4	6.65	6.80	< 0.001	.023
C3	5.39	7.06	.002	.018
Cz	5.22	5.33	.002	.019
TP7	5.07	4.38	.003	.015
TP8	2.85	2.56	.042	.010
P3	6.77	8.74	< 0.001	.023
Pz	3.85	4.19	.015	.012
P4	7.97	10.84	< 0.001	.022
O1	7.68	12.68	< 0.001	.029
O2	10.7	18.35	< 0.001	.040

Ch: Channel

in **pSSC/Wernicke, STG/Wernicke, pSSC/PreSMA, pSSC/STG, pSSC, pSSC/angular gyrus Wernicke's area, aSSC/ angular gyrus Wernicke's area** during problem-solving (Table 5). The highest HbO was recorded during solving basic operation questions. While answering the basic operation questions, there was no other channel where the HbO was highest.

3.2.3. Comparison of HbO during solving different question types in the middle-aged group

A significant difference was observed in the brain activations of the **DLPFC/FA** during problem-solving in the middle-aged group (Table 5). The highest HbO was recorded during solving general knowledge questions.

There was no significant HbO in the channels during solving other questions in the middle-aged group (p>0.05).

3.2.4. Comparison of HbO during solving different question types between groups

Comparing the arithmetic question-solving activation between the two groups revealed there were significant differences in **aSSC/angular gyrus Wernicke's area** and **DLPFC/BROCA** (Table 6). The middle-aged group had higher activation values in these regions than the young group.

Comparing the general knowledge question-solving activation between the two groups revealed there were significant differences in **pSSC/STG, pSSC/ angular gyrus Wernicke's area, DLPFC/ITG,** and **DLPFC/BROCA** (Table 6). The young group had higher activation values in **pSSC/STG** and **DLPFC/ITG** than the middle-aged group. The middle-aged group had higher activation values in **pSSC/ angular gyrus Wernicke's area** and **DLPFC/BROCA** than the young group.

Comparing the insight question-solving activation between the two groups revealed there was no significant difference (p>0,005).

Comparing the basic operation question-solving activation between the two groups revealed there were statistical significances in **DLPFC/TA, STG, pSSC/ angular gyrus Wernicke's area, STG/ angular gyrus Wernicke's area,** and **DLPFC/FA** (Table 6). The middle-aged group had higher activation values in **DLPFC/TA** and **STG** than the young group. The young group had higher activation values in **pSSC/ angular gyrus Wernicke's area, STG/ angular gyrus Wernicke's area,** and **DLPFC/ FA** than the middle-aged group (Fig. 3).

3.3. EEG results

3.3.1. Group*question type results

Group and question type main effects results were supplementary materials (Supplementary Materials 3). These two significant main effects depend on the other within the subject factor reported below.

Group*Question Type statistically significant difference was found in **FP1, FP2, F3, Fz, F4, C3, Cz, TP7, TP8, P3, Pz, P4, O1,** and **O2** (Tables 3, 4). Please see Supplementary Material 3 for detailed results of ANOVAs.

3.3.2. Comparison of alpha frequency band power during solving different question types in the young group

A significant difference was observed in the alpha frequency band power of the **TP8** electrode during problem-solving (Table 7). The highest alpha frequency band power was recorded during solving

Table 5
Significant regions in comparison of HbO during solving different question types are summarized.

	Question Type with Max HbO	Brain Region (Channel No)	F	p	η2
Young Group	AQ	STG (Ch 11)	7.65	.004	.151
	GQ	DLPFC/TA (Ch 2)	3.50	.032	.075
		PreSMA/TA (Ch 7)	4.01	.023	.090
		STG/TA (Ch 9)	3.18	.049	.073
	IQ	-	-	>0.005	-
	BQ	pSSC/Wernicke (Ch 18)	4.73	.007	.087
		STG/Wernicke (Ch 20)	3.77	.021	.085
		pSSC/PreSMA (Ch 37)	4.13	.023	.099
		pSSC/STG (Ch 38)	4.47	.025	.108
		pSSC (Ch 39)	3.77	.021	.085
		pSSC/angular gyrus Wernicke's area (Ch 40)	4.49	.013	.113
		aSSC/ angular gyrus Wernicke's area (Ch 44)	3.64	.034	.089
Middle-Aged Group HbO	AQ	-	-	>0.005	-
	GQ	DLPFC/FA (Ch 25)	3.24	.049	.065
	IQ	-	-	>0.005	-
	BQ	-	-	>0.005	-

AQ: Arithmetic Questions; **GQ**: General Knowledge Questions; **IQ**: Insight Questions; **BQ**: Basic Operation Questions; **Ch**: Channel

Table 4
Group*questiontypes results.

	HbO Concentration				Alpha Power				
	STG	DLPFC/TA	pSSC/Wernicke	STG/angular gyrus Wernicke's area	FP1/ FP2	F3/ Fz/ F4	TP7/ TP8	Pz/ P4	O1/ O2
AQ	MAG>YG	MAG>YG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG
GQ	YG>MAG	MAG>YG	MAG>YG	MAG>YG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG
IQ	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG
BQ	YG>MAG	MAG>YG	MAG>YG	MAG>YG	YG>MAG	YG>MAG	YG>MAG	YG>MAG	YG>MAG

AQ: Arithmetic Questions; **GQ**: General Knowledge Questions; **IQ**: Insight Questions; **BQ**: Basic Operation Questions; **YG**: Young Group; **MAG**: Middle-Aged Group

Table 6
Comparison of alpha frequency band power during solving different question types in the young group.

Question Type	Brain Region (Channel Number)	Young Group (Mean±S.D.)	Middle-Aged Group (Mean±S.D.)	t (58)	p	Result
AQ	aSSC/angular gyrus Wernicke's area (Ch 44)	-0.37±2.52	1.35±3.54	-2.180	.033	MAD>YG
	DLPFC/BROCA (Ch 45)	-1.06±3.90	0.87±3.55	-2.009	.049	MAD>YG
GQ	pSSC/STG (Ch 17)	0.79±1.66	-0.17±1.95	2.068	.035	YG>MAD
	pSSC/ angular gyrus Wernicke's area (Ch 18)	0.00±1.99	1.11±2.01	-2.156	.035	MAD>YG
	DLPFC/ITG (Ch 23)	1.05±6.18	-1.38±2.53	2.007	.049	YG>MAD
	DLPFC/BROCA (Ch 45)	-0.60±2.41	1.05±2.33	-2.708	.009	MAD>YG
IQ	-	-	-	-	>0.005	-
BQ	DLPFC/TA (Ch 2)	-3.33±7.49	0.44±4.89	-2.313	.024	MAD>YG
	STG (Ch 11)	-5.42±9.86	-0.19±6.50	-2.425	.018	MAD>YG
	pSSC/ angular gyrus Wernicke's area (Ch 18)	2.28±3.96	-0.20±5.23	2.069	.043	YG>MAD
	STG/ angular gyrus Wernicke's area (Ch 20)	2.34±4.69	-0.75±5.79	2.278	.026	YG>MAD
	DLPFC/FA (Ch 25)	-0.51±4.62	-1.47±2.51	2.079	.042	YG>MAD

AQ: Arithmetic Questions; **GQ**: General Knowledge Questions; **IQ**: Insight Questions; **BQ**: Basic Operation Questions

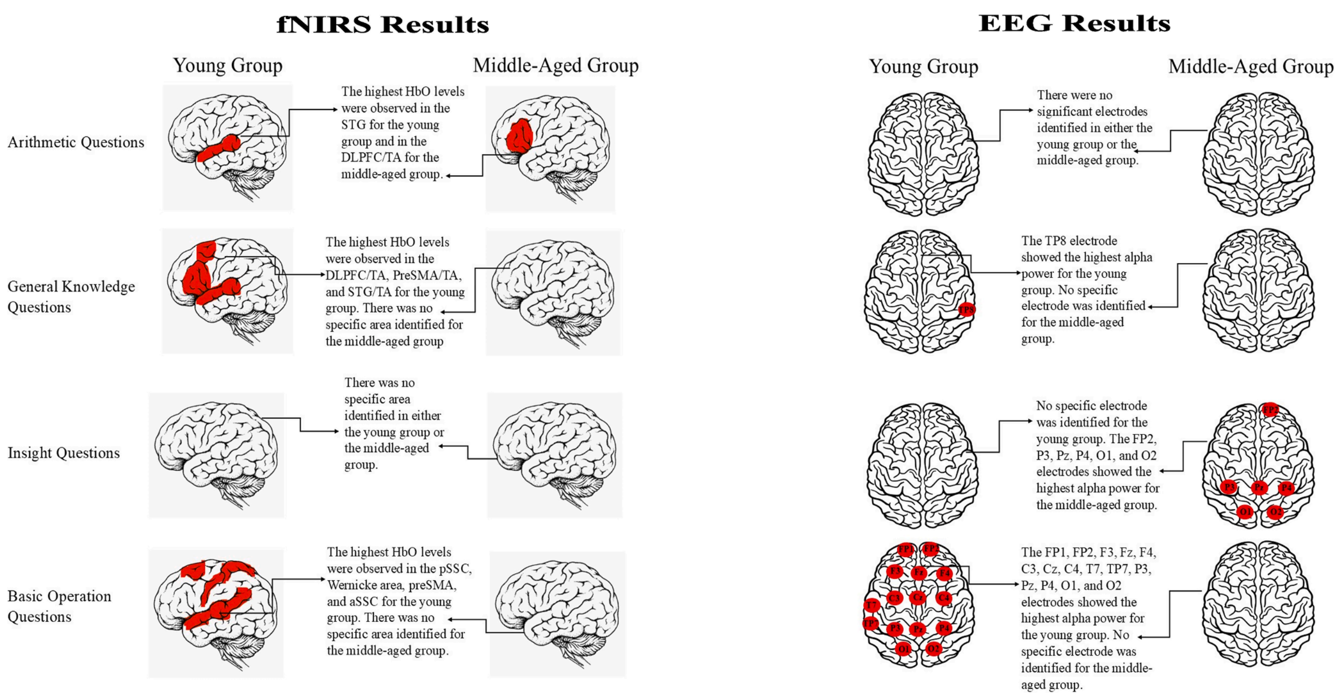

Fig. 3. Brain Regions with Significant Activation Identified via EEG and fNIRS. (The left side of the figure illustrates the fNIRS findings, highlighting the brain regions with the highest concentration of oxyhemoglobin during question answering. The right side presents the EEG findings, marking the electrodes associated with the highest alpha power observed during the same task. HbO: oxyhemoglobin concentration; STG: Superior Temporal Gyrus; DLPFC: Dorsolateral Prefrontal Cortex; TA: Temporopolar Area; PreSMA: Premotor/Presupplementary Area; pSSC: Primary Somatosensory Cortex; aSSC: Somatosensory Association Area).

general knowledge questions.

A significant difference was observed in the alpha frequency band power of the **FP1, FP2, F3, Fz, F4, C3, Cz, C4, T7, TP7, P3, Pz, P4, O1,** and **O2** electrodes during problem-solving (Table 7). The highest alpha frequency band power was recorded during solving basic operation questions.

There was no significant difference the alpha frequency band power in the electrodes during solving other questions in the young group ($p>0.05$).

3.3.3. *Comparison of alpha frequency band power during solving different question types in the middle-aged group*

A significant difference was observed in the alpha frequency band power of the **FP2, P3, Pz, P4, O1,** and **O2** electrodes during problem-solving (Table 7). The highest alpha frequency band power was recorded during solving insight questions.

There was no significant difference the alpha frequency band power in the electrodes during solving other questions in the middle-aged group ($p>0.05$).

3.3.4. *Comparison of alpha frequency band power during solving different question types between groups*

Comparing the arithmetic question-solving alpha frequency band power between the two groups revealed there was a significant difference in **TP7** electrode (Table 8). The young group had higher alpha frequency band power in left temporoparietal area than the middle-aged group.

Comparing the general knowledge question-solving alpha frequency band power between the two groups revealed there was no significant difference ($p>0,005$).

Comparing the insight question-solving alpha frequency band power between the two groups revealed there were significant differences in **C4** and **TP8** electrodes (Table 8). The young group had higher alpha frequency band power in right central and right temporopairetal area than the middle-aged group.

Comparing the basic operation question-solving alpha frequency band power between the two groups revealed there were significant differences in **FP1, FP2, F3, Fz, F4, C3, Cz, C4, TP7, TP8, P3, Pz, P4, O1,** and **O2** electrodes (Table 8). The young group had higher alpha

Table 7
Significant electrodes in comparison of alpha frequency band power during solving different question types are summarized.

	Question Type with Max Alpha Frequency Band Power	EEG Electrode	F	p	η2
Young Group	AQ	-	-	>0.005	-
	GQ	TP8	4.47	.006	.029
	IQ	-	-	>0.005	-
	BQ	FP1	9.66	< 0.001	.098
		FP2	7.91	< 0.001	.087
		F3	10.9	< 0.001	.105
		Fz	5.82	.002	.064
		F4	7.99	< 0.001	.069
		C3	9.97	< 0.001	.074
		Cz	7.25	< 0.001	.071
		C4	5.82	.002	.035
		T7	6.75	< 0.001	.050
		TP7	11.1	< 0.001	.071
		P3	12.2	< 0.001	.094
		Pz	6.58	< 0.001	.051
		P4	10.9	< 0.001	.067
		O1	10.5	< 0.001	.093
		O2	17.1	< 0.001	.127
Middle-Aged Group	AQ	-	-	>0.005	-
	GQ	-	-	>0.005	-
	IQ	FP2	4.21	.011	.031
		P3	3.40	.029	.017
		Pz	3.38	.032	.013
		P4	3.90	.017	.014
		O1	3.57	.021	.020
		O2	4.23	.009	.031
	BQ	-	-	>0.005	-

AQ: Arithmetic Questions; **GQ**: General Knowledge Questions; **IQ**: Insight Questions; **BQ**: Basic Operation Questions

frequency band power in all these areas than the middle-aged group (Figure 3).

3.4. EEG and fNIRS correlation results

3.4.1. Findings of positive correlation between HbO and alpha frequency band power

For Arithmetic Questions: There were no significant positive correlations in both the young group and the middle-aged group (Table 9, Figs. 4 and 5).

For General Knowledge Questions: There was no significant positive correlation in the young group. There were significant positive correlations in the middle-aged group. The significant correlations were between alpha power at **C3** electrode and **Premotor/PreSMA/Somatosensory cortex**; between alpha power at the **C4** electrode and **Premotor/PreSMA/Somatosensory cortex**, and alpha power at the **T7** electrode and the **Superior Temporal gyrus** (p=0.0291, p=0.0270, and p=0.0119, respectively) (Table 9, Figs. 4 and 5).

For Insight Questions: There was a significant positive correlation in the young group. The significant correlation was between the alpha power of the **Cz** electrode and the **Premotor/PreSMA/Somatosensory cortex** and **Wernicke regions** (p=0.0085). There was no significant positive difference in the middle-aged group (Table 9, Figs. 4 and 5).

For Basic Operation Questions: There was a significant positive correlation in the young group. The significant correlations were between the alpha power of the **C3, Cz, C4,** and **Pz** electrodes and the **Premotor/PreSMA/Somatosensory cortex** and **Wernicke regions** (p=0.0069; p=0.0020; p=0.0349; p=0.0098). There was no significant positive correlation in the middle-aged group (Table 9, Figs. 4 and 5).

Table 8
Comparison of alpha frequency band power during solving different question types between groups.

Question Type	EEG Electrode	Young Group (Mean ±S.D.)	Middle-Aged Group (Mean±S.D.)	t (67)	p	Result
AQ	TP7	2.46 ±1.39	1.75 ±1.48	2.050	.044	YG>MAD
GQ	-	-	-	-	-	-
IQ	C4	3.37 ±2.41	2.19 ±2.00	2.170	.034	YG>MAD
	TP8	2.44 ±1.82	1.59 ±1.64	2.016	.048	YG>MAD
BQ	FP1	3.76 ±2.07	2.47 ±1.62	2.799	.007	YG>MAD
	FP2	3.89 ±2.25	2.41 ±1.59	3.059	.003	YG>MAD
	F3	3.85 ±2.16	2.26 ±1.66	3.342	.001	YG>MAD
	Fz	3.77 ±1.99	2.67 ±1.69	2.428	.018	YG>MAD
	F4	3.60 ±2.12	2.40 ±1.74	2.521	.014	YG>MAD
	C3	4.28 ±2.42	2.68 ±1.93	2.966	.004	YG>MAD
	Cz	3.72 ±1.87	2.47 ±1.79	2.804	.007	YG>MAD
	C4	3.85 ±1.93	2.19 ±1.81	3.634	< 0.001	YG>MAD
	TP7	3.27 ±2.03	1.91 ±1.61	3.016	.004	YG>MAD
	TP8	2.74 ±1.95	1.51 ±1.35	2.967	.004	YG>MAD
	P3	4.67 ±2.31	2.93 ±1.95	2.079	.042	YG>MAD
	Pz	4.00 ±2.06	2.63 ±1.70	2.942	.004	YG>MAD
	P4	4.75 ±2.63	2.76 ±1.91	3.501	< 0.001	YG>MAD
	O1	4.60 ±2.74	2.51 ±1.77	3.619	< 0.001	YG>MAD
	O2	4.95 ±2.87	2.67 ±1.72	3.847	< 0.001	YG>MAD

AQ: Arithmetic Questions; **GQ**: General Knowledge Questions; **IQ**: Insight Questions; **BQ**: Basic Operation Questions

3.4.2. Findings of negative correlation between HbO and alpha frequency band power

For Arithmetic Questions: There were no significant negative correlations in both the young group and the middle-aged group (Table 9, Figs. 6 and 7).

For General Knowledge Questions: There were significant negative correlations in the young group. The significant negative correlations were between the alpha power of the **Fz** electrode and the **DLPFC**; and between the alpha power of the **TP8** electrode and the **Wernicke** (p=0.00176, p=0.0172, respectively). There was a significant negative correlation in the middle-aged group. The significant negative correlations were between the alpha power of the **P3** electrode and the **Wernicke** (p=0.0020) (Table 9, Figs. 6 and 7).

For Insight Questions: There was a significant negative correlation in the young group. The significant correlation was between the alpha

Table 9
Summary of the correlation findings.

Question Type	Group	p	Alpha Power in the Electrode	HbO in the Location	Correlation Type with Correct Answer Scores and Explanation
AQ	Young Group	>0.05	-	-	No significant correlations
	Middle-Aged Group	>0.05	-	-	No significant correlations
GQ	Young Group	0.00176	Fz ↑	DLPFC ↓	There was a significant negative correlation between alpha power in Fz and HbO in left DLPFC for general knowledge questions
		0.0172	TP8 ↑	Wernicke ↓	There was a significant negative correlation between alpha power in TP8 and HbO in left Wernicke for general knowledge questions
	Middle-Aged Group	0.0291	C3 ↑	Premotor/PreSMA/ Somatosensory cortex ↑	There was a significant positive correlation between alpha power in C3 and HbO in left Premotor/PreSMA/Somatosensory cortex for general knowledge questions
		0.0270	C4 ↑	Premotor/PreSMA/ Somatosensory cortex ↑	There was a significant positive correlation between alpha power in C4 and HbO in right Premotor/PreSMA/Somatosensory cortex for general knowledge questions
		0.0119	T7 ↑	STG ↑	There was a significant positive correlation between alpha power in T7 and HbO in left STG for general knowledge questions
		0.0020	P3 ↑	Wernicke ↓	There was a significant negative correlation between alpha power in P3 and HbO in left Wernicke for general knowledge questions
IQ	Young Group	0.0085	Cz ↑	Premotor/PreSMA/ Somatosensory cortex ↑	There was a significant positive correlation between alpha power in Cz and HbO in Premotor/PreSMA/Somatosensory cortex for insight questions
		0.0052	T8 ↑	STG ↓	There was a significant negative correlation between alpha power in T8 and HbO in right STG for insight questions
	Middle-Aged Group	0.0156	TP8 ↑	Wernicke ↓	There was a significant negative correlation between alpha power in TP8 and HbO in right Wernicke for insight questions
		0.0437	P3 ↑	Wernicke ↓	There was a significant negative correlation between alpha power in P3 and HbO in left Wernicke for insight questions
BQ	Young Group	0.0187	F3 ↑	DLPFC ↓	There was a significant negative correlation between alpha power in F3 and HbO in left DLPFC for basic operation questions
		0.0069	C3 ↑	Premotor/PreSMA/ Somatosensory cortex ↑	There was a significant positive correlation between alpha power in C3 and HbO in left Premotor/PreSMA/Somatosensory cortex for basic operation questions
		0.0020	Cz ↑	Premotor/PreSMA/ Somatosensory cortex and Wernicke ↑	There was a significant positive correlation between alpha power in Cz and HbO in Premotor/PreSMA/Somatosensory cortex for basic operation questions
		0.0349	C4 ↑	Premotor/PreSMA/ Somatosensory cortex and Wernicke ↑	There was a significant positive correlation between alpha power in C4 and HbO in right Premotor/PreSMA/Somatosensory cortex for basic operation questions
		0.0092	TP8 ↑	Wernicke ↓	There was a significant negative correlation between alpha power in TP8 and HbO in right Wernicke for basic operation questions
		0.0098	Pz ↑	Premotor/PreSMA/ Somatosensory cortex and Wernicke ↑	There was a significant positive correlation between alpha power in Pz and HbO in Premotor/PreSMA/Somatosensory cortex for basic operation questions
	Middle-Aged Group	0.0225	TP7 ↑	Wernicke ↓	There was a significant negative correlation between alpha power in TP7 and HbO in left Wernicke for basic operation questions
		0.0088	P3 ↑	Wernicke ↓	There was a significant negative correlation between alpha power in P3 and HbO in left Wernicke for basic operation questions

AQ: Arithmetic Questions; **GQ**: General Knowledge Questions; **IQ**: Insight Questions; **BQ**: Basic Operation Questions

power of the **T8** electrode and the **Superior Temporal Gyrus** (p=0.0052). There were significant negative correlations in the middle-aged group. The significant correlations were between the alpha power of the **P3** electrode and the **Wernicke**; and between the alpha power of the **TP8** electrode and the **Wernicke** (p=0.0437 and p=0.0156, respectively) (Table 9, Figs. 6 and 7).

For Basic Operation Questions: There were significant negative correlations in the young group. The significant negative correlations were between the alpha power of the **F3** electrode and the **DLPFC**; and between the alpha power of the **TP8** electrode and the **Wernicke** (p=0.0187, p=0.0092, respectively). There were significant negative correlations in the middle-aged group. The significant negative correlations were between the alpha power of the **P3** and **TP7** electrodes and the **Wernicke** (p=0.0088 and p=0.0225, respectively) (Table 9, Figs. 6 and 7).

3.4.3. Comprasion findings of HbO and alpha frequency band power correlations between two groups

For Arithmetic Questions: There was no significant difference between the two groups for the correlation between alpha power and HbO (p>0.05).

For General Knowledge Questions: There was a significant difference between the two groups for the correlation between the alpha power of **P3** and HbO in the **left Wernicke**. The correlation power of the young group was higher than that of the middle-aged group (ROI 7: Young Group:0.01±0.35, Middle-Aged Group:-0.17±0.29, t(67) = 2.32, p = 0.023).

For Insight Questions: There was a significant difference between the two groups for correlation between alpha power of **T8** and HbO in **right Superior Temporal Gyrus**. The correlation power of the middle-aged group was higher than that of the young group (ROI 11: Young Group: -0.12±0.28, Middle-Aged Group: 0.02±0.22, t (67) = -2.39, p = 0.019).

For Basic Operation Questions: There was a significant difference between the two groups for the correlation between the alpha power of **P3** and HbO in the **left Wernicke**, and between the alpha power of **P4** and alpha power in the **right Wernicke**. The correlation power of the young group was higher than that of the middle-aged group (ROI 7: Young Group: 0.08±0.37, Middle-Aged Group:-0.13±0.29, t(67) = 2.63, p = 0.011; ROI 9: Young Group: 0.13±0.34, Middle-Aged Group: -0.06 ±0.28, t(67) = 2.64, p = 0.010).

In summary, the primary findings revealed the following outcomes:

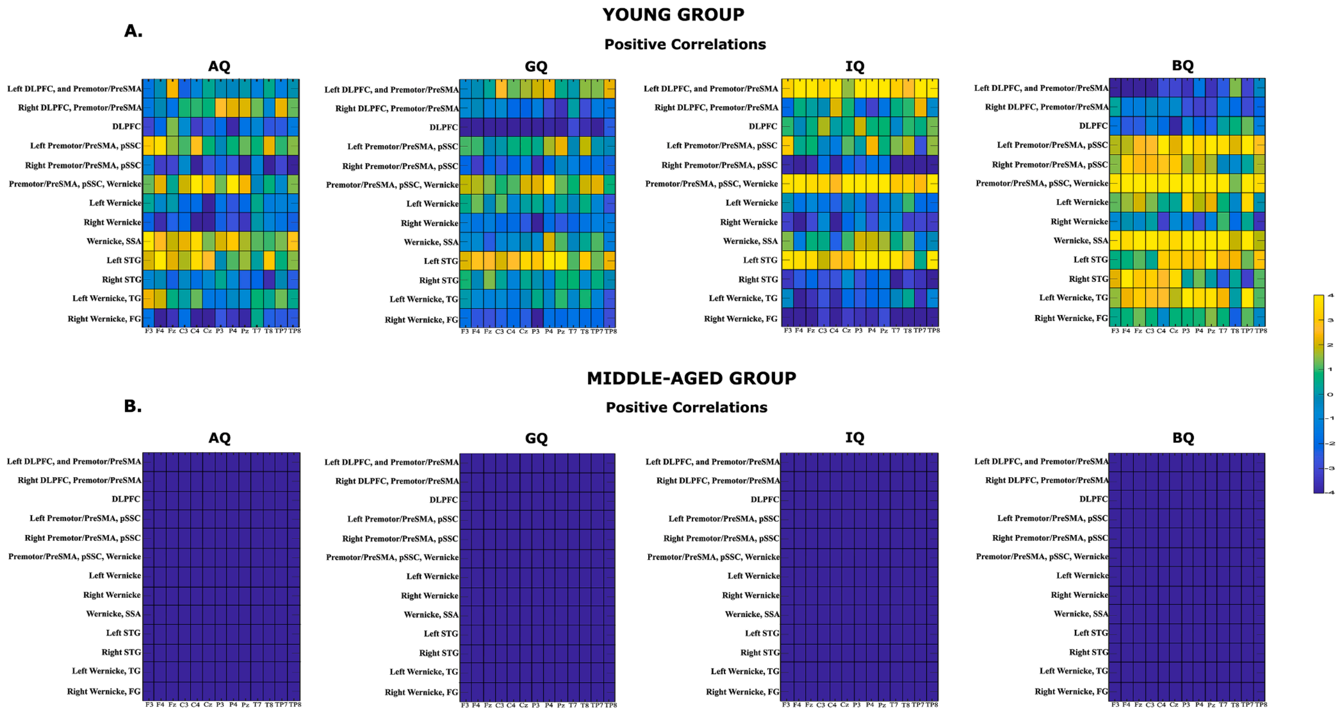

Fig. 4. Findings of Positive Correlation Between HbO and Alpha Frequency Band Power. (This figure illustrates the relationships between EEG electrode names, presented along the x-axis, and the corresponding regions associated with fNIRS channels, indicated along the y-axis. The intersections of the x and y axes represent the degree of positive correlation between HbO and alpha frequency band power, providing insights into brain activity during various cognitive tasks. The figure encompasses all observed positive correlations, including those that are not statistically significant. The color coding conveys the significance levels of the positive correlations: blue indicates a low significance level ($p > 0.05$), while yellow and green signify higher significance levels ($p < 0.05$). In this context, blue areas highlight positive correlations that did not reach statistical significance, whereas yellow and green areas denote statistically significant positive correlations that may warrant further investigation.) (AQ: Arithmetic Questions; GQ: General Knowledge Questions; IQ: Insight Questions; BQ: Basic Operation Questions).

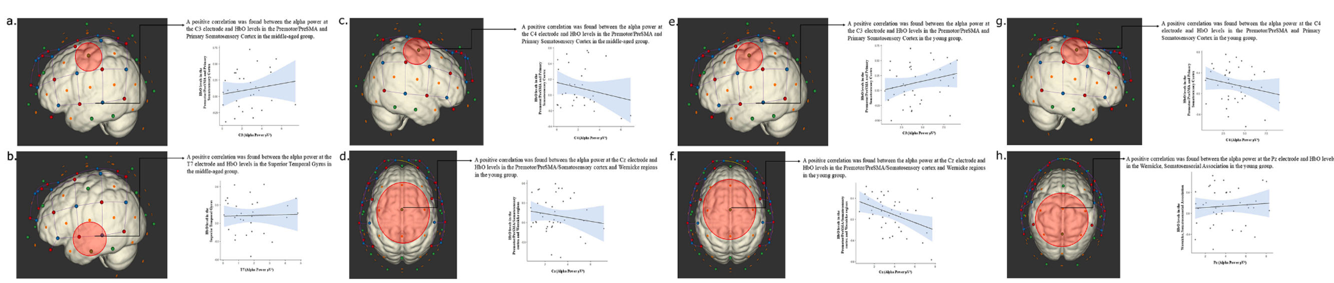

Fig. 5. The scatter plots of the positive correlation analysis results, accompanied by a brain region visualization (a. The scatter plots of the positive correlation between alpha power at the C3 electrode and HbO levels in the Premotor/PreSMA and Primary Somatosensory Cortex while answering general knowledge questions in the middle-aged group, accompanied by a brain region visualization. b. The scatter plots of the positive correlation between alpha power at the T7 electrode and HbO levels in the Superior Temporal Gyrus while answering general knowledge questions in the middle-aged group, accompanied by a brain region visualization. c. The scatter plots of the positive correlation between alpha power at the C4 electrode and HbO levels in the Premotor/PreSMA and Primary Somatosensory Cortex while answering general knowledge questions in the middle-aged group, accompanied by a brain region visualization. d. The scatter plots of the positive correlation between alpha power at the Cz electrode and HbO levels in the Premotor/PreSMA/Somatosensory cortex and Wernicke regions while answering insight questions in the young group, accompanied by a brain region visualization. e. The scatter plots of the positive correlation between alpha power at the C3 electrode and HbO levels in the Premotor/PreSMA and Primary Somatosensory Cortex while answering basic-operation questions in the young group, accompanied by a brain region visualization. f. The scatter plots of the positive correlation between alpha power at the Cz electrode and HbO levels in the Premotor/PreSMA/Somatosensory cortex and Wernicke regions while answering basic-operation questions in the young group, accompanied by a brain region visualization. g. The scatter plots of the positive correlation between alpha power at the C4 electrode and HbO levels in the Premotor/PreSMA and Primary Somatosensory Cortex while answering basic-operation questions in the young group, accompanied by a brain region visualization. h. The scatter plots of the positive correlation between alpha power at the Pz electrode and HbO levels in the Wernicke, Somatosensorial Association while answering basic-operation questions in the young group, accompanied by a brain region visualization. The shaded area denotes the standard error. Dots represent the observed scores. The X-axis represents the alpha power, while the Y-axis represents the HbO levels.).

The behavioral results indicate significant differences between age groups in various question types. Specifically, middle-aged individuals outperformed young individuals in general knowledge questions, while young individuals performed better in insight problem questions and basic operation questions. Additionally, differences in response time and incorrect scores were observed between the two age groups.

The fNIRS results reveal significant differences in brain activation during problem-solving tasks, particularly in regions DLPFC/TA, STG, pSSC/Wernicke, and STG/angular gyrus Wernicke's area. These differences were observed in both young and middle-aged groups, suggesting

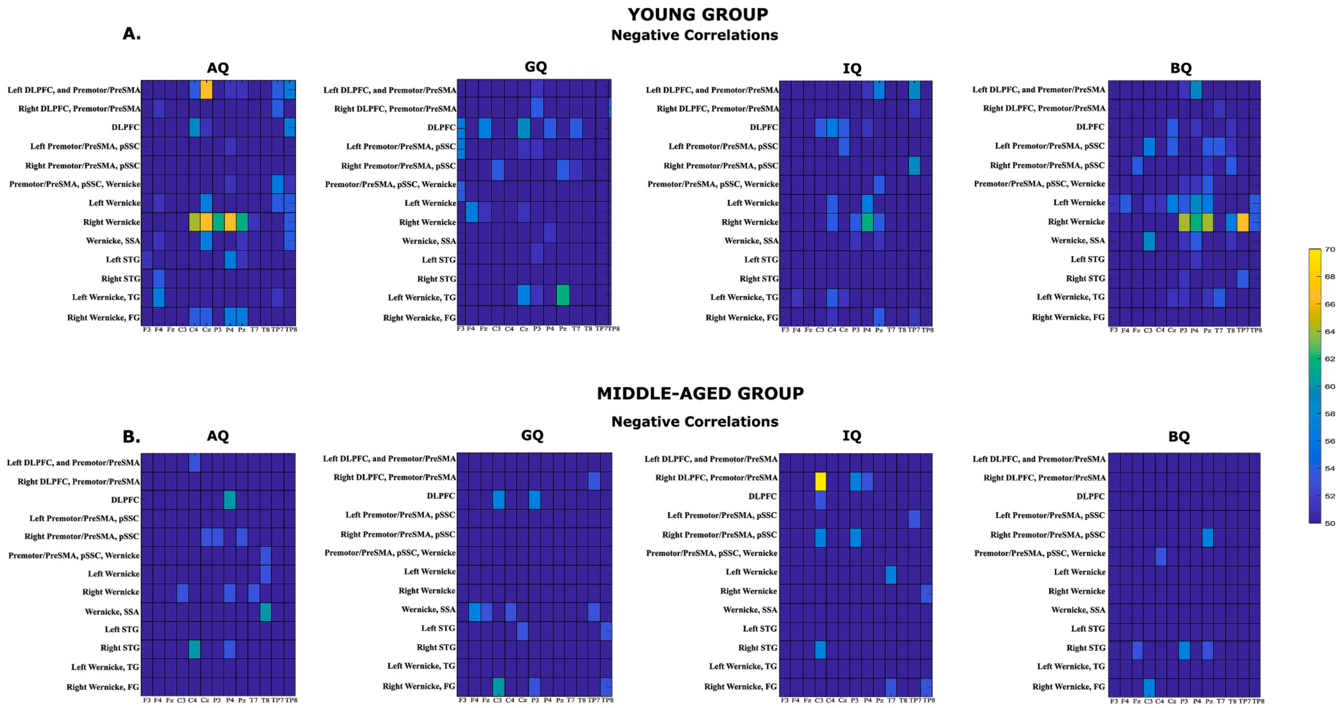

Fig. 6. Findings of Negative Correlation Between HbO and Alpha Frequency Band Power. (This figure illustrates the relationships between EEG electrode names, presented along the x-axis, and the corresponding regions associated with fNIRS channels, indicated along the y-axis. The intersections of the x and y axes represent the degree of negative correlation between HbO and alpha frequency band power, providing insights into brain activity during various cognitive tasks. The figure encompasses all observed negative correlations, including those that are not statistically significant. The color coding conveys the significance levels of the negative correlations: blue indicates a low significance level ($p > 0.05$), while yellow and green signify higher significance levels ($p < 0.05$). In this context, blue areas highlight negative correlations that did not reach statistical significance, whereas yellow and green areas denote statistically significant negative correlations that may warrant further investigation.) (AQ: Arithmetic Questions; GQ: General Knowledge Questions; IQ: Insight Questions; BQ: Basic Operation Questions).

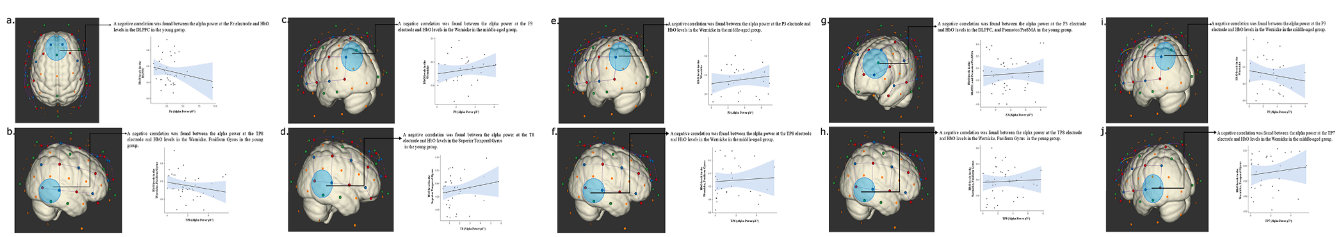

Fig. 7. The scatter plots of the negative correlation analysis results, accompanied by a brain region visualization (a. The scatter plots of the negative correlation between alpha power at the Fz electrode and HbO levels in the DLPFC while answering general knowledge questions in the young group, accompanied by a brain region visualization. b. The scatter plots of the negative correlation between alpha power at the TP8 electrode and HbO levels in the Wernicke, Fusiform Gyrus while answering general knowledge questions in the young group, accompanied by a brain region visualization. c. The scatter plots of the negative correlation between alpha power at the P3 electrode and HbO levels in the Wernicke while answering general knowledge questions in the middle-aged group, accompanied by a brain region visualization. d. The scatter plots of the negative correlation between alpha power at the T8 electrode and HbO levels in the Superior Temporal Gyrus while answering insight questions in the young group, accompanied by a brain region visualization. e. The scatter plots of the negative correlation between alpha power at the P3 electrode and HbO levels in the Wernicke while answering insight questions in the middle-aged group, accompanied by a brain region visualization. f. The scatter plots of the negative correlation between alpha power at the TP8 electrode and HbO levels in the Wernicke while answering insight questions in the middle-aged group, accompanied by a brain region visualization. g. The scatter plots of the negative correlation between alpha power at the F3 electrode and HbO levels in the DLPFC, and Premotor/PreSMA while answering basic-operation questions in the young group, accompanied by a brain region visualization. h. The scatter plots of the negative correlation between alpha power at the TP8 electrode and HbO levels in the Wernicke, Fusiform Gyrus while answering basic-operation questions in the young group, accompanied by a brain region visualization. i. The scatter plots of the negative correlation between alpha power at the P3 electrode and HbO levels in the Wernicke while answering basic-operation questions in the middle-aged group, accompanied by a brain region visualization. j. The scatter plots of the negative correlation between alpha power at the TP7 electrode and HbO levels in the Wernicke while answering basic-operation questions in the middle-aged group, accompanied by a brain region visualization. The shaded area denotes the standard error. Dots represent the observed scores. The X-axis represents the alpha power, while the Y-axis represents the HbO levels.).

distinct neural patterns associated with different question types. The comparison of HbO during problem-solving in the young group indicates specific brain activation patterns for different question types. Notably, the highest HbO was recorded during arithmetic, general knowledge, and basic operation questions. In contrast, no significant channel showed maximum HbO during insight questions. Similar findings were observed in the middle-aged group, with the highest HbO recorded during general knowledge questions. However, there was no significant HbO in other channels during the solving of various question types in this group.

The EEG results indicate significant differences in alpha frequency band power during problem-solving tasks. The alpha power varied across different electrodes for various question types in both young and middle-aged groups. The highest alpha frequency band power was recorded during the solving of general knowledge questions in the young group and insight questions in the middle-aged group. Comparisons between the two age groups revealed significant differences in alpha frequency band power during the solving of arithmetic, basic operation, and insight questions. These differences were observed in multiple electrodes, suggesting distinct neural processes associated with different question types in young and middle-aged individuals.

Finally, the EEG and fNIRS correlation results showed significant positive correlations between HbO and alpha frequency band power in specific brain regions during the solving of general knowledge questions, particularly in the middle-aged group. No significant correlations were observed for arithmetic questions.

4. Discussion

The results of this study indicated age-related differences in behavioral performance, brain activation patterns, and neural correlates during various cognitive tasks. It was observed that different cortical activation patterns emerge between young and middle-aged individuals, that there are changes in question answering success with aging, and that different theories related to aging may emerge alone or together depending on the type of question in this study rather than only one emerging in older individuals.

4.1. Arithmetic questions and EEG&fNIRS investigations

When the results of the answers to arithmetic questions were compared, the young group gave more correct answers than the middle-aged group. Similarly, studies have shown that individuals' arithmetic skills decrease with aging and that older individuals give more wrong answers (Rozencwajg et al., 2010).

Mathematical operations are based on the left hemisphere's dominant fronto-parietal network (Artemenko, 2021). The triple code model explains the process of answering mathematical questions. The first of the triple codes is the code for the numbers and symbols in the question; the second is for the quantitative quantities to which the numerical symbols correspond; the third is the code for verbal information that may be included in the question. The processing of these three codes takes place in different brain regions. When it comes to processing numerical symbols, bilateral activation of the inferior ventral occipito-temporal region in the brain, activation of the inferior parietal region for quantitative quantity data, and activation of the left perisylvian region for processing the verbal code are mentioned (Arsalidou and Taylor, 2011). It was reported that the DLPFC is especially important in following numerical operations through the attention function, performing the operations, performing the operations by the relevant rules, and monitoring the correct progress of the process, and serves as a center throughout the arithmetic operation process (Ruh et al., 2012). Question Type* Group results showed that HbO in STG/ang Wernicke and Pssc/Wernicke regions and alpha activity power in frontal, temporal, temporoparietal, and occipital regions were higher in the young group than in the middle-aged group (Tables 3, 4). In the middle-aged group, there was higher oxyhemoglobin than in the young group in the DLPFC/TA and STG regions. In the results comparing the two groups, it was seen that significantly stronger activation occurs in the aSSC/Wernicke and DLPFC/Broca regions in the middle-aged group than in the young group. When the question types were compared within the groups, it was observed that while there was significant activation in the STG in the young group while answering arithmetic questions, there was no significant activation in any region in the middle-aged group. In neuroimaging studies conducted with mathematical operations, STG is considered the center of arithmetic problem-solving skills (Suárez-Pellicioni and Booth, 2022; Zhou et al., 2018). In answering arithmetic questions, the findings indicate that it is consistent with de-differentiation theory. At the same time, activation occurs in the task-related region in the young group, and task-specific activation disappears with aging. These findings also showed that with aging, regions responsible for attention, comprehension, and language functions such as DLPFC, Broka, and Wernicke perform the task by exhibiting higher activation, and a neural compensation occurs (Fox et al., 2006; Li et al., 2001; Bartley et al., 2018; Nasios et al., 2019).

In the EEG findings, it was seen that the alpha activation power of the young group was significantly higher in the left temporoparietal location than in the middle-aged group (Tables 3, 4). This suggested that the mathematical processing area is more active in answering questions in the young group, while attention and interpretation processes are more dominant in the middle-aged group. Previous investigations on the learning process of arithmetic operations have asserted that children exhibit elevated alpha activation in frontal regions. As these individuals acquaint themselves with arithmetic operations, a subsequent decline in alpha activation within the frontal region is documented, accompanied by a concomitant rise in activation within the parietal region. This observed fronto-parietal shift in brain activation during arithmetic processing signifies the engagement of the frontal cortex in attentional and learning processes, juxtaposed with an augmented functional specialization of arithmetic processing within the parietal cortex (Artemenko, 2021). Contrastingly, the current findings indicated a potential reversal of this trend throughout aging. As individuals transition from youth to middle age, heightened activation in the frontal region is observed, ostensibly attributable to increased processing challenges. This observed pattern aligns with the tenets of the frontal compensation theory.

On the other hand, no significant correlation was evident in the alpha power and HbO correlation findings during the arithmetic question-answering process.

4.2. General knowledge questions and EEG&fNIRS investigations

When the results of the general knowledge questions were compared, it was seen that the middle-aged group had a significantly higher score for correct answers and a lower score for incorrect answers.

General knowledge questions can be answered by retrieving previously acquired knowledge (Sezgin et al., 2014). For this reason, answering general knowledge questions is based on memory and limbic systems, especially semantic memory. It was reported that semantic information is encoded and recalled by the activation of many regions in the brain in an information-specific manner, depending on a combination of neural activity distributed in cortical regions (Renoult et al., 2019). Moreover, it has been shown that the concepts to which the information is related are encoded together with sensory, motor, and other modalities, and activation occurs in different neural regions where the relevant modalities are located during information retrieval (Rissman and Wagner, 2012). Studies show that the hippocampus, parahippocampal, temporal, parietal, and frontal regions are involved in all these processes (Renoult et al., 2019). The hippocampus had connectivity with the temporal and parietal regions, and the temporal region plays a role together with the hippocampus in encoding semantic information and concepts that may be related to knowledge (Woodward et al., 2006). Question Type* Group results showed that the HbO was higher in the young group than the middle-aged group in the STG and that the HbO was higher in the DLPFC/TA, pSSC/Wernicke and STG/angular Wernicke regions in the older group. As a result of the comparison of the two groups, higher activation in pSSC/STG and DLPFC/ITG was revealed in the young group than in the middle-aged group; in the middle-aged group, higher activation was observed in the pSSC/angular Wernicke and DLPFC/Broca regions. When the question types were compared within the groups, it was observed that there was significant activation in the DLPFC/TA, preSMA/TA, and STG/TA regions in the young group and the DLPFC/FA region in the middle-aged group, while answering general knowledge questions. Previous studies have shown that DLPFC is an effective region in all processes, from encoding, selection, and recall of semantic information, and that it is activated in the selection, manipulation, and monitoring of information (Daw et al., 2006; Fox et al., 2006; Koechlin et al., 1999). This is consistent with ourfindings which indicated that the DLPFC and temporal region are essential in both groups. Our results also showed that the temporal area is more strongly active in young people, and Wernicke and Brocka are more effective in the middle-aged group. Our findings indicate that there may be a differentiation in regions with aging.

According to the EEG findings, alpha power was observed to be higher in the frontal, temporoparietal, parietal, and occipital regions (FP1, FP2, F3, Fz, F4, TP7, TP8, Pz, P4, O1, and O2) in the middle-aged group compared to the young group. Additionally, in the comparison between question types, it was observed that there was a significantly higher alpha power in the Fz region in the young group. Still, this difference was not significant in the middle-aged group. While frontal alpha power is associated with cognitive tasks and decision-making, parieto-occipital alpha is associated with signal perception and sensory coding (Kolev et al., 2002). Although it had been stated in the literature that alpha power changes from posterior to anterior during the aging process, we have found that task-related frontal alpha activity may remain high in young people. In addition our results suggest that higher alpha power occurs in multiple regions to increase functionality, consistent with the theory of neural inefficiency associated with aging. The higher alpha power as a compensatory mechanism may be responsible for the sustained performance we have found in the older group.

In the correlation findings, it was seen that there is a positive significant correlation between alpha activation at C3 and C4 electrodes and premotor/pre-SMA/Somatosensory cortex and Wernicke region and between alpha activation at T7 electrodes and STG. In the young group, between Fz and DLPFC, between the TP8 electrode and Wernicke area; in the middle-aged group, there was a negative correlation between the P3 electrode and Wernicke. Correlation findings supported the idea that the alpha power correlation in the region with Wernicke and STG has a significant impact on answering general knowledge questions. It also indicates that regional differentiation occurs with aging.

4.3. Insight questions and EEG&fNIRS investigations

When the results of the answers to the insight questions are compared, it is seen that the number of wrong answers and the average answer time are significantly higher in the middle-aged group than in the younger group. In a study investigating the effect of aging with various puzzle questions and insight questions, it is reported that, similar to our findings, the answering time increases as you get older and older individuals give more wrong answers (Nef et al., 2020).

The moment of insight is a type of question defined as "a big speculative leap", where the process of answering insight questions suddenly and unpredictably results in an answer that flashes in the mind, but no conscious explanation of the process can be made. Neuroimaging studies conducted with insight questions report increased activation in the Prefrontal, Temporal, Parietal and Occipital lobes (Luo and Knöblich, 2007; Luo and Niki, 2003; Luo et al., 2004a, 2004b). It is reported that the Posterior Cingulate cortex and Superior Temporal gyrus are more active during preparation for solving insight questions (Kounios and Beeman, 2014). It has been shown that activity in the temporal cortex is an effective region in understanding the question when faced with an insight question, producing new close or distant semantically related words based on the question, and integrating the answer into the question (Binder and Desai, 2011). Also, the STG is especially effective in establishing semantic relationships, encoding and recalling information, and structuring the answer based on the information given in the question (Tik et al., 2018). On the other hand, the DLPFC is involved in target selection, and the Middle Temporal gyrus is involved in the representation and association of abstract semantic information (Tik et al., 2018; Feil et al., 2010). A 7 Tesla fMRI study comparing correctly answered insight questions with unanswered insight questions shows that there is a significant increase in activation in the DLPFC, Middle Temporal gyrus, and Anterior Cingulate cortex. It is reported that the Thalamic pathways, Ventral Tegmental area, Substantia Nigra, as well as Striatum and Hippocampus are active. The study indicates that a wide cortical and subcortical network activation will occur when answering insight questions (Tik et al., 2018). However, there are no previous fNIRS studies with insight questions. Question Type* Group results show that the oxyhemoglobin density in the STG, pSSC/Wernicke, STG/angular Wernicke and DLPFC/TA regions is significantly higher in the young group than in the middle-aged group. While significant activation occurred in similar regions in the young group, consistent with the literature, it was observed that there was no significant activation specific to the question type or region in the middle-aged group.

In EEG studies, it was first discovered by Jung-Beeman and his colleagues that there was a significant increase in alpha power when answering insight questions and that alpha could be associated with creativity/groundbreaking ideas, and the findings were also supported in other studies (Jung-Beeman et al., 2004; Stevens and Zabelina, 2019). Specifically, in the process of answering questions through insight, before the answer reaches consciousness, there is a significant increase in alpha power in the occipital region, and immediately afterwards there is a significant increase in alpha power in the temporal region (Rothmaler et al., 2017). A number of other studies also show increased alpha power in the parietal region. The parietal region is the region where sensory information is processed and sensory information integration is carried out (Gebuis et al., 2014). Thus, increased alpha power in the parietal region is associated with internally directed creative processes. Similarly, it can be seen that the alpha power of F3, TPz, TP8, Pz, P4, O1 and O2 electrodes is higher in the young group than in the old group, and the alpha power in Fz and F4 electrodes is higher in the middle-aged group than in the young group. Here, it can be seen that with aging, the difference in the dominant hemisphere may actually occur due to a decrease in the number of activated regions.

In young people, there is a positive correlation between the Cz electrode and the premotor/preSMA/Somatosensory cortex, and a negative correlation between T8 and STG; In the middle-aged group, there is a negative correlation between P3 and TP8 electrodes and Wernicke's area. Similar to the literature, our findings show significant activation in the DLPFC/TA, STG, Pssc/Wernicke and STF/Angular Wernicke regions, especially in temporal, parietal and occipital alpha power. Additionally, there appears to be a change from the temporal region to the temporoparietal region with aging.

4.4. Basic operation questions and EEG&fNIRS investigations

When the answers to the basic operation questions were compared, it was seen that the young group was more successful in all evaluation parameters. It has been reported that arithmetic processing skills decrease with aging (Rozencwajg et al., 2010).

The parietal region is seen as an influential region, especially in arithmetic questions consisting of numbers and symbols. It was reported that it is the region responsible for information about numerical symbols and maybe the region where simple arithmetic operations and memorized operations are stored (Arsalidou and Taylor, 2011; Schwartz et al., 2020). The function of the somatosensory cortex is not limited only to sensory input processing but is an effective region in establishing connections between concepts and matching sensory information with semantic information (Kuhl and Chun, 2014; Bartley et al., 2018; Acuna et al., 2002; Zhou et al., 2018). These findings indicated that SSC is effective in converting and processing symbolic information into semantic information in basic operation questions consisting of numbers and symbols. Studies have reported that bilateral activation of the inferior ventral occipitotemporal region, another region effective in processing numbers and symbols and solving problems, occurs

(Arsalidou and Taylor, 2011). Similarly, in the study, a significant result was observed in the temporal region. It was reported that the Wernicke area, which has a significant impact on language processing and understanding, is the active region in solving questions involving numbers and symbols (Bartley et al., 2018; Newman et al., 2011). This points to Wernicke's importance in making sense of questions that contain only numbers and symbols, such as basic operation questions. Question Type* Group results showed that HbO in STG and alpha power in frontal, temporoparietal, parietal, and occipital locations in the young group are significantly higher than in the middle-aged group. In the middle-aged group, the HbO in the DLPFC/TA, Pssc/Wernicke, and STG/ang Wernicke regions appears higher than in the young group. In the results comparing the two groups, there was significantly higher activation in the right DLPFC/FA, left pSSC/angular Wernicke, and left STG/angular Wernicke regions in the young group than in the middle-aged group and the left STG and left DLPFC/TA, there was a significantly higher activation in the middle-aged group than in the young group. It was seen that there is a high activation and alpha power, which is higher in the young group than in the middle-aged group in all locations. Although it was reported that the left hemisphere is dominant in studies on mathematical operations, the opposite findings are also the case (Santarnecchi et al., 2019). Although there are few studies on lateralization, studies report that the left region will be more active in right-hand dominant individuals, and the right region will be more active in left-hand dominant individuals (Artemenko et al., 2020). However, since the individuals in the study were right-hand dominant, this suggests that this difference is not due to lateralization but rather an age-related change in the regions of the brain that show dominant activation, even if the right hand is looking. In addition, this indicates that when faced with complex questions, the response is made by a network in which both hemispheres and more than one region are activated in the brain, rather than a specific hemisphere or a region. In the EEG data, alpha power was higher in the young group at almost all electrodes. It was reported that alpha power is inversely proportional to mental effort and directly proportional to mental fatigue (Jausovec and Jausovec, 2000; Li et al., 2020). The fact that the young group answered the basic operation questions faster and with higher success in the behavioral data can be interpreted as less mental effort or more tired young people.

In correlation findings, in the process of answering the basic operation questions' process, there was a positive correlation between C3, Cz, C4 and Pz electrodes and premotor/preSMA/Somatosensory cortex and Wernicke region in the young group, and a negative correlation between F3 electrode and DLPFC and TP8 electrode and Wernicke region; in the middle-aged group, there was a negative significant correlation between P3 and TP7 electrodes and Wernicke's area. These findings indicated that Wernicke, the Parietal lobule, and SSC have a significant impact on answering the basic operation questions. However, more studies are needed to interpret negative and positive correlations. This situation can be interpreted as positive correlations disappearing with aging, negative compensations similar to the negative correlation in young people continuing to compensate, and new negative correlations and compensation situations coming into play.

4.5. Question answering processes

When faced with any problem, the first step, regardless of the question type, is to understand the problem itself, the situation implied by the question, or the rule sets related to the context of the problem, start the answering process, and take the necessary actions until the answer is reached. Studies indicate that a central neural network in the brain is primarily involved in the problem-answering process (Bartley et al., 2018). It is thought that this central network emerges by being activated in the inter- and intra-hemispheric regions of the brain. Still, this network cannot be reduced to a fixed, simple, one-to-one activated region and exists as an extensive network distributed throughout the brain (Cocchi et al., 2013). The ongoing processes related to problem-solving are also dynamic; a transition is made from the central neural network to a specific neural network depending on the type of question, its difficulty, and the semantic and symbolic information contained in the question. Here, a neural network that can be called multiple demands comes into play (Duncan, 2010). Presumably, the central neural network, after defining the fundamental data about the question, prepares the ground for activating specific regions by the question type and transfers information. The complex answering process is reduced to sub-parts, and successive task steps are transferred to the relevant areas of the brain to perform the necessary cognitive operations (Bartley et al., 2018). Although primary regions such as DLPFC, Temporal region, and language regions are activated and form the primary network to perform many skills, especially attention, working memory, and memory involved in a question, unique, specific, and different activations and correlations occur in local regions specific to the question type. In all these processes, alpha activation increases significantly in the relevant regions and plays a vital role in the response process. It is reported that with the aging process, there is a change in the regions activated during the task, a decrease in the number of regions, more activation in some regions, and frontal compensation occurs (Grady, 2012; Li et al., 2001; Yeung and Chan, 2021). All of these mechanisms are compensatory strategies used to maintain cognitive skills. In line with the task demand, compensation strategies come into play, alternative neural networks are established, and the activation degrees of the regions change, thus ensuring that the cognitive task is continued successfully.

An advantage of multimodal recordings is exemplified by our findings regarding inter-area differences in alpha-HbO correlation. Table 9 suggests that two groups of electrodes (Fz, P3 v C3, C4, Cz, Pz) both showed increased alpha power, however the correlations with local oxygenation were opposite. The first group (DLPFC and Wernicke's areas) showed increased alpha accompanied by lower HbO across age and task conditions. The resulting negative correlation is consistent with the findings of Keles et al. (2016). The fact that the cited results were obtained during resting-state may suggest that the negative correlation we have found may be associated with underlying baseline processes rather than task performance. By contrast task-evoked activation of bilateral somatosensory areas (C3, C4, Cz, Pz) show positive correlation between alpha power and the local oxygenation across different ages and tasks. This may be associated with enhanced alpha oscillations helping to improve cognitive performance as well as working and episodic memory functions, through inhibition of interfering and task irrelevant processing systems (Hanslmayr et al., 2005; Klimesch et al., 1999; Zoefel et al., 2011; Hsueh et al., 2016). These studies suggest that neurofeedback enhancement of alpha power in electrodes C3, Cz, and C4 training improved episodic and working memory.

This study reveals that problem-solving strategies differ according to the type of problem and that the strategies used change with aging. In terms of education, it suggests that educators should adapt their teaching methods to the problem-solving strategies of individuals in different age groups. While more analytical and systematic approaches can be emphasized for young individuals, it may be beneficial to teach more flexible and adaptive strategies to individuals in the middle age group. Teaching specific strategies for different types of problems will help students solve problems more effectively. In addition, continuing education programs should be developed to adapt to the cognitive abilities and strategies that change with age. This will provide an approach that will support individuals' lifelong learning processes.

In terms of clinical, the findings of the study point to the importance of individualized intervention plans. Individualized intervention plans can be created to develop problem-solving strategies for elderly individuals. This provides more effective treatment and rehabilitation processes in clinical practices.

Although there have been an increasing number of EEG&fNIRS studies in recent years, to the best of our knowledge, our study is the first to reveal problem-solving processes for four types of questions and the change with aging with EEG&fNIRS correlation findings. Previous studies utilizing EEG-fNIRS and EEG-fMRI methodologies have consistently shown that the relationship between alpha oscillations and hemodynamic responses, such as HbO or BOLD signals, is dynamic, varying over time and across brain regions. Under resting-state conditions, this relationship tends to be more stable and predominantly negative (Laufs et al., 2006, 2003). In contrast, during task performance, it exhibits greater variability, encompassing both positive and negative correlations. For instance, an EEG-fMRI study highlighted the context-dependent and dynamic nature of alpha-BOLD relationships, providing valuable insights into the neurophysiological mechanisms underlying brain function (Ingram et al., 2024). These findings suggest that task-related correlations, whether positive or negative, may reflect the redistribution of neural resources and region-specific activation levels. Alpha oscillations appear to serve distinct functional roles depending on the task type and the brain region involved, showcasing the brain's remarkable adaptability to fluctuating cognitive demands. Moreover, the variability in alpha-BOLD correlations underscores the brain's capacity for dynamic reorganization, aligning with the concept of a flexible and efficient neural processing system. Our findings demonstrated that the middle-aged group outperformed the younger group in answering general knowledge questions. Positive correlations were observed in three brain regions, while one region exhibited a negative correlation. Similar trends were observed for insight and arithmetic problems, except that no significant correlations were identified during arithmetic problem-solving. In the middle-aged group, positive correlations were detected between: Alpha power in the central regions and HbO levels in the premotor, pre-SMA, and somatosensory cortices, Alpha power in the left temporal region, and HbO levels in the superior temporal gyrus. Conversely, a negative correlation was identified between alpha power in the left parietal region and HbO levels in Wernicke's area. The superior task performance observed in the middle-aged group suggests that positive correlations may play a pivotal role in supporting cognitive activity. The negative correlation, however, indicates that the functional role of alpha oscillations may vary depending on the brain region and specific task demands, reflecting their potential inhibitory or regulatory functions. In the young group, negative correlations for general knowledge questions were observed between: Frontal alpha power and HbO levels in the DLPFC, Temporoparietal alpha power, and HbO levels in Wernicke's area. Despite achieving good scores in general knowledge questions, the younger group exhibited lower overall performance compared to the middle-aged group. These findings suggest that the observed positive and negative correlations may be associated with task-specific and age-dependent neural resource allocation. The results of this study align with the variability reported in the literature, emphasizing the necessity for further research to elucidate the functional significance of positive and negative EEG-fNIRS correlations. Given the limited number of studies in this domain, there is a critical need for expanded research efforts to explore these relationships across diverse tasks, brain regions, and age groups. Such investigations hold promise for advancing our understanding of the dynamic interplay between neural oscillations and hemodynamic responses, thereby contributing to a more comprehensive understanding of brain-behavior relationships.

There are some limitations in our study. First, although we recorded fNIRS to scan the frontal, temporal, and superior parietal regions, it does not reveal activation over the inferior parietal and occipital regions. Furthermore since the spatial resolution of fNIRS is limited to the upper layers of cortex, no information can be obtained about subcortical structures. More fNIRS and/or fMRI studies combined with EEG are needed to cover all brain regions. The study focused on healthy individuals aged 20–30 (young group) and 50–60 (middle-aged group) to minimize the confounding effects of age-related changes in brain activity and circulation. While age-related alterations in frequency bands and cerebral blood flow are important, including older individuals could introduce general aging effects that might not directly relate to the cognitive processing differences being studied (Jabès et al., 2021; Al Zoubi et al., 2018; Zappasodi et al., 2015; Prakash et al., 2009). Future research should include a broader age range, particularly older populations, to further investigate age-related cognitive changes. Significant differences were observed between age and question types in our study, but the continuity of our findings should be ensured with similar studies or alternative comparative analyses. This study constitutes the first example in the existing literature. For this reason, it was not possible to make similar or alternative comparisons. It is clear that along with the analysis of the basic structure, further studies will also need comparative analyses. In this study, correlation analysis was conducted. However, there is a need for further research that employs more advanced analytical techniques, such as causality, connectivity, and coherence. Standardization of analytical methods in studies utilizing combined EEG and fNIRS methodologies is essential. Specifically, the implications of positive, negative, or absent correlations should be examined in detail concerning their physiological or cognitive functional significance.

5. Conclusion

In conclusion, our study has important theoretical implications. Our findings support the idea that, along with a central neural network for the realization of problem-solving skills, specific regions are activated in response to the problem depending on the type of question. It is observed that there is a decrease in the number of brain regions activated with healthy aging, but individuals can perform cognitive functions with differentiation and compensation strategies. It is seen that the DLPFC, Wernicke, and STG regions and alpha activation in the electrodes corresponding to these regions play an essential role in the problem-solving process, and specific regions are activated in different question types. It indicates that there is differentiation in the regions activated with aging and that differentiation occurs in neural networks with a comprehensive, holistic compensation rather than a specific compensation. This distinction may also apply to other age groups and pathologies associated with cognitive decline or disorders occurring during the aging process. Moreover, this study can be generalized to other cognitive functions, primarily memory and executive functions, foundational to problem-solving strategies.

Ethics statement

The study was approved by the Istanbul Medipol University Ethics Committee (Ethical Report No: 10840098–604.01.01-E.1064).

Data and code availability statement

We are glad for submitting our article as a potential publication to the "Neuroimage" journal. The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Mevhibe Saricaoglu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Meryem Ayşe Yücel:** Writing – original draft, Visualization, Formal analysis, Data curation. **Miray Budak:** Writing – review & editing, Formal analysis. **Ahmet Omurtag:** Writing – review & editing, Formal analysis. **Lutfu Hanoglu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us and the content has not been published or submitted for publication elsewhere except as a brief abstract in the proceedings of a scientific meeting or symposium. The authors have no conflicts of interest or any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2025.121062.

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