

SPECIAL ISSUE ARTICLE

EDITORS' ENDEAVORS

The Impact of Cognitive Reserve on Lateralization of EEG Phase-Locking Responses During Working Memory Tasks

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ABSTRACT

Cognitive reserve (CR), shaped by the interaction of lifestyle and genetics, enhances the efficient use of neural resources, allowing individuals with higher reserve to require less neural activity to accomplish a task than those with lower reserve. Although not solely a mechanism for neural efficiency, hemispheric asymmetries contribute to it through the lateralization of cognitive processes across hemispheres. It is hypothesized that CR may influence the degree of asymmetry in neural activity during various cognitive processes. The aims of this study were to explore the effects of CR on verbal and visuospatial working memory performance and its relationship with the degree of asymmetry in 2–9 Hz phase-locking responses. The data were collected in two separate laboratories: one in Turkey and one in Germany. The sample included 33 Turkish and 18 German participants, all of whom completed verbal and visuospatial Sternberg tasks at two difficulty levels (one-item and three-item). The behavioral performance parameter was d' value, with EEG asymmetry calculated via the laterality coefficient (LC) formula. Under conditions of increased task difficulty, the LCs in the verbal task and CR scores had significant associations, especially in the parietal electrode pairs. Similarly, the LCs in the visuospatial task had significant associations with CR scores in the parietal and occipital electrode pairs. Furthermore, phase-locking responses were significantly higher in the right hemisphere across both tasks. These findings suggest that CR influences neural asymmetry, emphasizing the right hemisphere's role in CR and its potential as a therapeutic target.

1 | Introduction

With its intricate web of neural connections, the brain requires a substantial share of the body's energy, making the efficient use of these resources essential for survival. In this regard, the reserve and resilience framework offers a comprehensive account of the

mechanisms that optimize neural efficiency (Stern et al. 2023). Cognitive reserve (CR), a theoretical construct within this framework, is proposed to explain the discrepancy between pathology or decline and cognitive performance, suggesting that the flexible and efficient use of existing neural resources helps mitigate functional decline (Stern 2002). In essence, CR helps explain

Abbreviations: ANCOVA, analysis of covariance; CR, cognitive reserve; CRiq, Cognitive Reserve Index questionnaire; EHI, Edinburgh Handedness Inventory; ERO, event related oscillations; ERSP, event related spectral perturbation; ITC, inter-trial coherence; LC, laterality coefficient; NR, neural reserve; WFQ, Waterloo Footedness Questionnaire.

how some individuals can maintain cognitive function despite underlying pathology. It is suggested that CR is shaped by life experiences, with factors such as educational attainment, occupational complexity, and engagement in physical, social, and cognitive activities contributing to its development over time. Neural compensation and neural reserve (NR) are two mechanisms thought to underlie CR: neural compensation refers to the brain's ability to recruit additional networks when primary systems are compromised (Barulli and Stern 2013), whereas NR, observed in healthy individuals, reflects more efficient use of existing resources (Stern 2009). In this sense, NR can be viewed as an adaptive mechanism that contributes to survival by optimizing neural resource use and energy expenditure (Padamsey and Rochefort 2023).

Given its significance, the number of neuroimaging studies exploring potential markers of CR is rapidly growing. A functional MRI study (Stern et al. 2003) reported increased activation during encoding in frontoparietal, temporal, and subcortical regions. A later study (Stern et al. 2018) identified a pattern of brain activation across 12 tasks associated with CR in healthy people, particularly in regions involved in frontoparietal cognitive control. Adding to this evidence, another study (Dunst et al. 2014), consistent with the NR mechanism, found that individuals with greater CR required less brain activation to accomplish a given task. In addition, EEG research offers complementary insights into neural efficiency by revealing how CR influences the synchronization of neural populations and the consistency of brain responses across trials. To date, EEG studies on CR have primarily focused on event-related potentials (ERPs), while the use of time-frequency analyses in this context appears to be underexplored. ERP findings in the literature show that individuals with greater CR exhibit less variation in response to increasing task demands, such as reduced prolongation of P3b latency (Speer and Soldan 2015) and P300 amplitude modulation (Gutiérrez-Zamora Velasco et al. 2021).

Similar to the efficiency observed in individuals with high CR levels, asymmetric organization of the brain's structure, function, and connectivity may represent a mechanism for optimizing processing by reducing redundant bilateral neural activity (Vallortigara 2006; Güntürkün et al. 2020; Hartwigsen et al. 2021). Indeed, several lateralization studies have demonstrated that greater asymmetry is associated with better task performance (Güntürkün et al. 2000; Magat and Brown 2009; Mellet et al. 2014; Zich et al. 2017). Genetic (Jahanshad et al. 2010) and environmental factors (Raymond and Pontier 2004; De Kovel et al. 2019), as well as hormonal fluctuations (Hausmann 2005), have been shown to influence hemispheric asymmetry, which also changes markedly over the adult lifespan, as highlighted by the HAROLD (Hemispheric Asymmetry Reduction in Older Adults) (Cabeza 2002) and right hemi-aging models (Salthouse 1995; Hatta et al. 2015), underscoring the dynamic nature of brain lateralization. However, it is important to acknowledge that hemispheric asymmetries do not necessarily reflect enhanced neural efficiency or confer an advantage, as they can also be observed in pathological conditions, such as depression (Hecht 2010; Fitzgerald 2024), anxiety (Glier et al. 2022), autism spectrum disorder (Jouravlev et al. 2020), and attention deficit hyperactivity disorder (Hale et al. 2010). Thus, while hemispheric asymmetry may signal neural efficiency in certain

contexts, observations should be interpreted with this nuance in mind.

Among theories on the neural correlates of CR, Robertson's right-hemisphere account (Robertson 2013, 2014) is particularly notable: although developed outside the lateralization literature, it uniquely emphasizes hemispheric asymmetry in understanding CR. He links noradrenergic activity (NA) to the protective effects of CR, highlighting how factors like education, occupational complexity, and premorbid intelligence activate cognitive processes such as arousal, sustained attention, error monitoring, and working memory, all of which depend on the right frontoparietal network (Brosnan et al. 2022). Robertson posits that the repeated activation of these processes enhances NA, thereby protecting the brain through mechanisms like synaptogenesis, neurogenesis, and reduced oxidative stress. To test this theory, Brosnan and colleagues (Brosnan et al. 2018) conducted a study using transcranial direct current stimulation (tDCS) targeting the right prefrontal and parietal regions. They found that individuals with high CR showed a superiority for the left visual field in processing speed prior to the stimulation, which was attributed to the right hemisphere's involvement in CR. Furthermore, participants with low CR exhibited increased processing speed for left visual field stimuli after tDCS, which the authors interpreted as a temporary emergence of the processing speed asymmetry observed in those with high CR.

Drawing on Robertson's theory and broader literature (López et al. 2014; Speer and Soldan 2015; Nussbaumer et al. 2015), working memory, particularly the Sternberg paradigm (Sternberg 1969), provides a well-suited framework for probing neural efficiency under increasing cognitive demands, as it involves distinct stages of memory processing: encoding, maintenance, and recall, and offers a robust, experimentally controlled method for examining working memory performance under varying levels of cognitive demand. Studies often examine working memory using the P300 component and event-related delta, theta, and gamma oscillations. ERPs are thought to arise from the superposition of oscillations across multiple frequency bands (Başar et al. 2001), with the P300 component in particular reflecting the combined contributions of event-related delta, theta, and gamma oscillations (Güntekin and Başar 2016). Given that the P300 component has been studied both in working memory (Polich 2007; Guerrero et al. 2023; Ding et al. 2025) and CR research (Speer and Soldan 2015; Gu et al. 2018; Gutiérrez-Zamora Velasco et al. 2021), characterizing the time-frequency dynamics of this brain response under comparable experimental conditions may provide a complementary approach to existing literature and enrich our understanding of the neural mechanisms of CR. While ERPs are a powerful and well-established method, they reflect a mixture of phase-locked and non-phase-locked activity (Zervakis et al. 2011), with the latter often obscured during averaging. Time-frequency approaches make it possible to examine these oscillatory dynamics, thereby providing additional insight into the electrophysiological correlates of CR. Evidence suggests that delta, theta, and gamma oscillations significantly contribute to working memory processes. Specifically, event-related delta power has been shown to be influenced by the serial position of items, whereas theta power has been shown to decrease with chunking strategies (Aktürk

et al. 2022) and increase with greater memory load (Jensen and Tesche 2002), also playing a critical role in maintaining temporal order information (Hsieh and Ranganath 2014). Moreover, event-related gamma power has been shown to be involved in the maintenance of object representations in memory (Bertrand and Tallon-Baudry 2000), selective attention, and the encoding and recall of memory items (Jensen and Colgin 2007; McGill and Kieffaber 2024). In addition to these power-based findings, studies demonstrate increased event-related phase-locking values in delta (Fell and Axmacher 2011), theta (Klimesch et al. 2004; Güntekin et al. 2020; Shin and Kweon 2022), and gamma (Schack and Weiss 2005; Bosman et al. 2014) frequency bands during memory encoding, further supporting the involvement of these oscillations in the encoding stage.

Although CR and hemispheric asymmetry are extensively studied in distinct contexts, their interplay holds potential to offer further insights into their contribution to cognitive function. While the lateralization of verbal and visuospatial working memory has been well documented, relatively little is known about how CR modulates hemispheric asymmetry during these processes. In particular, it remains unclear whether individuals with higher CR, potentially reflecting more efficient neural resource use, exhibit distinct patterns of asymmetry. Consequently, investigating the effects of CR on the lateralization of EEG activity during working memory tasks, essentially examining CR through the lens of hemispheric asymmetry, offers a novel approach that may help identify electrophysiological markers of CR.

The present study aimed to explore the effects of CR on verbal and visuospatial working memory performance and examine its relationship with hemispheric asymmetry through power and phase-locking values of event-related EEG oscillations recorded during verbal and visuospatial Sternberg tasks (Sternberg 1969). Another objective of this study was to examine the proposed role of the right hemisphere in CR by comparing verbal and visuospatial processes, known to be left- and right-lateralized, respectively, in the majority of healthy people (Ocklenburg et al. 2024). To this end, participants' CR levels were assessed using the Cognitive Reserve Index Questionnaire (CRIq) (Nucci et al. 2012). Furthermore, the Sternberg paradigms were modified by adjusting the stimuli location (left and right hemifields) and display duration to ensure tachistoscopic presentation (Benschop 1998), which allowed us to control for and compare the visual field advantage of these tasks (Bourne 2006).

A total of eight hypotheses were formulated, with four addressing behavioral outcomes and four focusing on electrophysiological measures. First, regarding behavioral performance, (Hypothesis 1) all subjects were hypothesized to perform better at visuospatial Sternberg task trials in which the stimuli are presented in the left visual field compared to trials in which the stimuli are presented in the right visual field. Based on this reasoning, it was anticipated that (Hypothesis 2) all participants would perform better in verbal Sternberg task trials when stimuli were displayed in the right visual field compared to when they were shown in the left visual field. Additionally, (Hypothesis 3) a positive correlation was anticipated, with subjects with higher CR levels likely to provide more accurate responses in verbal and

visuospatial Sternberg tasks. Lastly, (Hypothesis 4) subjects with higher CR levels were expected to exhibit better performance in the visuospatial Sternberg task compared to the verbal Sternberg task, reflecting the proposed role of the right hemisphere in CR. Regarding electrophysiological data, (Hypothesis 5) participants with higher CR were anticipated to show smaller changes in event-related gamma oscillatory power in response to increasing task complexity across both tasks (i.e., with a larger number of items to retain). They were expected to demonstrate a more pronounced asymmetry in the one-item condition, which would be maintained as set sizes increased. Additionally, (Hypothesis 6) a positive correlation was expected between CR levels and the degree of right hemisphere lateralization during the visuospatial Sternberg task, with this lateralization being less pronounced in individuals with lower CR and diminishing as task complexity increased. (Hypothesis 7) The power and phase-locking values of EEG event-related gamma oscillations were hypothesized to be influenced by task complexity. Finally, (Hypothesis 8) the power and phase-locking values of EEG event-related gamma oscillations were anticipated to be affected by the visual field condition. Following the hypothesis-driven analyses, exploratory analyses were conducted to examine the impact of CR on the lateralization of phase-locking values of slower oscillations (1–15 Hz).

2 | Methods

The current study has been preregistered at the Open Science Framework (OSF) under the link https://osf.io/nxmp8/?view_only=466c8aea60b84c7ab68fa899d65b4c16.

2.1 | Participants

This study was conducted in collaboration with the researchers at Istanbul Medipol University, Turkey, and Medical School Hamburg, Germany, with data collection taking place at both centers. The sample size for the study was estimated using G*Power software, aiming for 0.8 statistical power to detect an effect size of 0.5 with a 0.05 alpha error probability. Based on the power analysis, the required sample size was 46. A total of 54 healthy participants were recruited, consisting of 36 Turkish (22 female, 14 male) and 18 German participants (14 female, 4 male), with an overall breakdown of 36 female and 18 male participants.

Participants gave informed consent after they had been briefed about the nature and aims of the study. They were treated following the Declaration of Helsinki. The study was approved by both the local ethics committee at Medical School Hamburg in Germany and Istanbul Medipol University Ethics Committee in Turkey (No: 10840098-604.01.01-E.18575).

2.2 | Exclusion Criteria and Questionnaires

All potential participants completed an online health pre-screening using the ICD-10 Symptom Rating (Tritt et al. 2008; Kizilhan et al. 2013), and only those with a total score below one were invited to the laboratory. Additionally, participants were

excluded if they chose to withdraw from the study, had vision problems affecting their ability to perceive stimuli, regularly used psychotropic medication, had a history of alcohol or substance abuse, a stroke or other central nervous system diseases with long-term effects, or a traumatic brain injury.

Prior to the EEG recording, all participants completed the Edinburgh Handedness Inventory (EHI) (Oldfield 1971; Atasavun Uysal et al. 2019) and the Waterloo Footedness Questionnaire (WFQ) (Elias et al. 1998; Ipek et al. 2021) to determine their lateralization quotients. Participants completed the CRiQ (Nucci et al. 2012), a semi-structured interview with three sections: Education, Work Activity, and Leisure. The education section records years of formal schooling and vocational training. The work activity section evaluates intellectual demands and responsibility in an individual's occupation, categorizing jobs into five levels from low-skilled manual work to highly intellectual occupations. The leisure section assesses engagement in activities outside work, categorized by frequency (e.g., weekly chores, monthly cinema visits, or annual travel). CRiQ scores were calculated using an open-access file by Nucci and colleagues, which adjusts for age effects, enabling cross-age group comparisons. Scores categorize CR levels as low (≤ 70), medium-low (71–84), medium (85–114), medium-high (115–130), and high (≥ 131). The validity and reliability of both the Turkish and German versions of all the questionnaires used in this study have been confirmed through previous studies (Oldfield 1971; Elias et al. 1998; Tritt et al. 2008; Nucci et al. 2012; Kizilhan et al. 2013; Atasavun Uysal et al. 2019; Ipek et al. 2021; Ozakbas et al. 2021).

2.3 | Experimental Procedure

The study used a repeated measures design (within-subjects), meaning that all participants completed every task in the study. The computer tasks were administered in a randomly assigned order to each participant prior to EEG recording. Regardless of the task, participants were administered the 1-item condition before the 3-item condition. The tasks in the study were developed by modifying certain aspects of the Sternberg paradigm (Sternberg 1969). The design and presentation of these tasks were executed using the open-access PsychoPy software package (Brooks 2019). By incorporating both verbal and visuospatial working memory tasks, the study aimed to compare participants' performance in tasks typically associated with the left hemisphere (verbal tasks) and the right hemisphere (visuospatial tasks) in relation to their level of CR. Furthermore, the EEG responses recorded during these tasks were analyzed to understand how brain activity varies with different types of memory tasks and CR levels.

The Sternberg paradigm structure primarily consists of the following four phases: presentation of memory set, delay period, presentation of probe stimulus, and response. In this study, the duration of the memory set presentation and the locations of the stimuli on the screen were controlled according to the hypotheses. One of the objectives of this study was to compare the lateralization processes of verbal and visuospatial working memory, so the stimuli in the memory set were tachistoscopically presented (160 ms) to ensure that visual input

was directed to only one hemisphere at a time. This approach allows for comparisons between conditions where the input reached either the dominant or nondominant hemisphere for the relevant cognitive process, and it is frequently used in visual hemifield studies. Another manipulation involved adjusting the location of the stimuli. To ensure the visual input reached only the nasal retina, the stimuli were precisely positioned 3° away from the fixation cross, either towards the left or right visual hemifield.

To maintain participants' focus on the center of the screen throughout the experiment, the fixation cross remained constant. Each trial began with a 160 ms stimulus presentation, followed by a 5000 ms delay period, after which the probe stimulus was shown for 5000 ms. In the verbal Sternberg task, participants pressed the up-arrow key if the probe stimulus was part of the memory set and the down-arrow key if it was not. Following the logic in Speer and Soldan's study (Speer and Soldan 2015), the memory set letters were presented in uppercase and the probe stimuli in lowercase to prevent participants from responding based on letter shape. In the visuospatial Sternberg task, participants were asked to remember the location of the stimuli and decide whether the probe stimulus appeared in the exact same position as in the memory set. After each response, the interval between stimuli randomly varied between 2 and 3 s, with only the fixation cross displayed during this time. Each paradigm's trials were repeated 60 times. Thirty of them were presented in the left visual hemifield and 30 in the right visual hemifield. Each side had 15 congruent (included in the memory set) and 15 incongruent (not included in the memory set) probe stimuli, presented in a random order. The tasks were administered at two difficulty levels: 1 and 3. An asterisk (*) was used as a placeholder during both the encoding phase (when the memory set was displayed) and the recall phase (when the probe stimulus appeared) to ensure visual consistency between the one-item and three-item memory set conditions. A visual representation of the verbal Sternberg task under the three-item condition is provided in Figure 1.

Task performances of participants were calculated using signal detection theory (Stanislaw and Todorov 1999). Specifically, the d' value was employed as a performance indicator. According to this theory, the d' value is defined as the discrimination parameter, reflecting an individual's ability to distinguish between signal and noise; in this study, it corresponded to discriminating between congruent and incongruent probe stimuli. The value was computed using the Z scores of hit and false alarm rates [$d' = Z(\text{hit rate}) - Z(\text{false alarm rate})$].

2.4 | EEG Recording

EEG recordings were conducted at two different centers. Both centers followed the same experimental protocols for stimulus presentation and task administration to ensure consistency across centers. Recording sessions in Turkey were conducted in a dimly lit Faraday cage to prevent potential interference from electromagnetic waves, and in Germany, recordings were conducted in a soundproof cabin. Participants were seated 57 cm away from the monitor, with their heads supported by

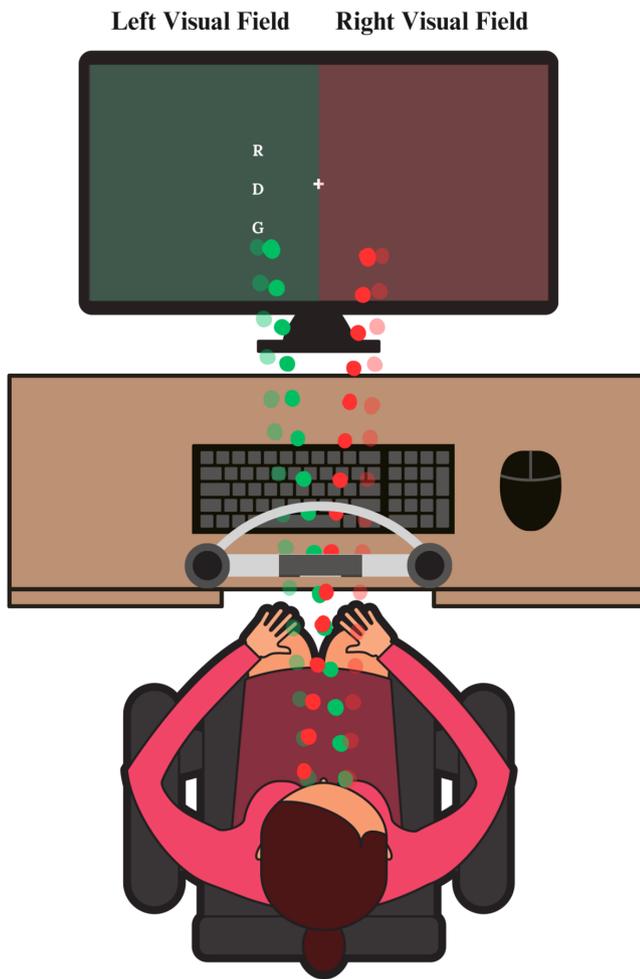


FIGURE 1 | Demonstration of a task condition. The figure depicts a left visual field trial of the verbal Sternberg task under three-item memory set condition.

a chin rest. The experiment consisted of two working memory tasks (verbal and visuospatial Sternberg paradigms) at two difficulty levels (1 and 3-item memory sets), spread across four sessions.

In Turkey, EEG signals were amplified using a BrainAmp MR Plus 32-channel DC system (Brain Products GmbH, Germany) and recorded with a sampling rate of 500 Hz. A 32-electrode elastic cap was used following the international 10–20 system (EasyCap GmbH, Germany). Electrodes were positioned at Fp1, Fp2, F7, F3, Fz, F4, F8, Ft7, Fc3, Fcz, Fc4, Ft8, Cz, C3, C4, T7, T8, Tp7, Cp3, Cpz, Cp4, Tp8, P3, Pz, P4, P7, P8, O1, Oz, and O2. Reference electrodes (Ag–AgCl) were placed on the right and left earlobes (A1 + A2), and the ground electrode was positioned beneath the right earlobe. Electrooculogram (EOG) electrodes were placed at the medial upper and lateral orbital rim of the left eye to record eye movements. In Germany, EEG signals were amplified using the actiCHamp system (Brain Products GmbH, Germany) and recorded with 32-channel, gel-based actiCAP active electrodes (EasyCap GmbH, Germany), following the international 10–20 system. Electrodes were placed at Fp1, Fp2, F7, F3, Fz, F4, F8, Ft9, Fc5, Fc1, Fc2, Fc6, Ft10, Cz, C3, C4, T7, T8, Tp9, Cp5, Cp1, Cp2, Cp6, Tp10, P3, Pz, P4, P7, P8, O1, Oz, and O2. The ground and reference electrodes were located on

the scalp. Impedance values were kept below 10 k Ω throughout the recordings.

2.5 | EEG Signal Analysis

All EEG analyses were conducted on data corresponding to the encoding phase of the task, defined as the initial memory set presentation, which occurred in either the left or right visual field. Event-related spectral perturbation (ERSP) and inter-trial coherence (ITC) analyses were performed after noise and artifacts were removed through a series of preprocessing steps using BrainVision Analyser 2.2 software. ERSP was used to assess stimuli-dependent spectral changes across trials, relative to baseline activity, reflecting event-related increases or decreases in neural synchronization. ITC analysis was used to assess the consistency of phase angles across trials, yielding a phase-locking value ranging from 0 to 1. This measure indicates how consistently the brain responds across trials, with higher values reflecting greater similarity in phase angles, essentially capturing the brain's ability to produce the same response to repeated stimuli. Phase-locking values obtained from ITC analyses provide a sensitive index of neural synchronization and may offer a more suitable measure for detecting individual variations related to NR. Based on the study's electrophysiological hypotheses, the initial analyses were centered on the gamma frequency band (25–48 Hz). Subsequent exploratory analyses in the 1–15 Hz range revealed compound responses spanning the delta, theta, and early alpha bands, with prominent activity particularly evident between 2 and 9 Hz. To further examine this pattern, time-frequency data were visually inspected for each participant individually. The consistency of these observations across participants informed the decision to focus on the 2–9 Hz range in the exploratory analyses, rather than adhering to traditional frequency band definitions, in order to more accurately capture the observed neural dynamics.

The preprocessing steps applied to the data were as follows: (1) an IIR filter (0.1–60 Hz) and a 50 Hz Notch filter were applied to the raw EEG data; (2) artifacts caused by eye movements were identified using Independent Component Analysis (ICA) and removed from the filtered data; (3) for both working memory tasks, the data were segmented into 9-s trials, consisting of 2 s before and 7 s after stimulus presentation, divided by left and right visual field conditions; (4) the segmented data were then visually inspected, and epochs containing artifacts were manually removed. For the ERSP analysis in the gamma frequency band, the baseline was set between –300 and –100 ms (10 cycle Wavelet width, Frequency Step: 60, Logarithmic Steps), and decibel (dB) normalization was applied. For the ITC analyses, Wavelet transform (Continuous Wavelet transform, Gabor normalization) was applied to each epoch. The same parameters were used for the gamma band, while the frequency range for the exploratory analysis was set to 1–15 Hz (Morlet Parameter: 5, Frequency Step: 60).

2.6 | Statistical Analyses

For the statistical analyses, Repeated Measures ANCOVA, Pearson Correlation, Spearman Correlation, Friedman,

Durbin–Conover, and independent samples *t*-test were employed, with all analyses conducted using the Jamovi 2.3.28 software (The jamovi project, 2022). Seven repeated measures ANCOVAs were conducted: four hypothesis-driven (30–48 Hz power and 30–35 Hz phase-locking for each task) and three exploratory (2–9 Hz phase-locking for each task and a cross-task comparison testing the role of the right hemisphere in CR). In additional exploratory steps, age was included as a covariate in the 2–9 Hz phase-locking ANCOVAs to control for potential confounding effects, and an independent samples *t*-test was conducted to examine whether CRIq scores differed by gender. The significance level of $p < 0.05$ was adopted for all statistical analyses. Data from the following electrodes were analyzed: F3, F4, F7, F8, C3, C4, T7, T8, P3, P4, P7, P8, O1, and O2. These electrodes were selected to enable an exploratory assessment of EEG activity across multiple scalp regions. The time windows included in the analyses were 150–300 ms for 30–48 Hz power, 250–400 ms for 30–35 Hz phase-locking, and 0–300 ms for 2–9 Hz phase-locking values. The rationale for selecting these specific frequency ranges and time windows for the statistical analyses is detailed in Section 2.7 Adjustments to the Preregistered Methods and Analysis Plan. To briefly address this here, the selected ranges were informed by the data, based on consistent response patterns observed across participants. The within-group factors in the ANCOVA analysis models were task difficulty (1 item, 3 items), visual hemifield (left visual field, right visual field), location (F3–F4, F7–F8, C3–C4, T7–T8, P3–P4, P7–P8, O1–O2), and hemisphere (left, right). Greenhouse–Geisser sphericity correction was used, and Bonferroni-corrected *p* values were reported for post hoc analyses. CRIq, EHI, and WFQ scores were included as covariates. The relationship between EEG data and these scores was further assessed through Pearson correlation analysis if the covariates were significant. Behavioral performance was assessed by calculating *d'* values from participants' responses during the paradigms. Given the non-normal distribution of this value, the Friedman test, a non-parametric alternative to repeated measures ANCOVA, was used to analyze differences across conditions (task, task difficulty, and visual hemifield of stimulus presentation). When the Friedman test indicated significant differences ($p < 0.05$), the Durbin–Conover test was applied for post hoc pairwise comparisons, and the results were reported accordingly. As the *d'* values were not normally distributed, Spearman correlation analysis was used to examine the relationship between *d'* values and CR scores. In addition, EEG laterality coefficients (LCs) were calculated to obtain a numerical index of hemispheric asymmetry, allowing for a more accurate comparison of individuals in terms of lateralization. This coefficient quantifies the degree of hemispheric involvement in various cognitive functions (Vingerhoets et al. 2023). According to the formula $[(\text{Right Hemisphere} - \text{Left Hemisphere}) / (\text{Right Hemisphere} + \text{Left Hemisphere})]$ employed in this study, a positive value indicated right hemisphere dominance, while a negative value indicated left hemisphere dominance. In this study, LCs were used to examine the relationship between EEG lateralization and CR. Given that both CRIq scores and LCs were normally distributed, their association was tested using Pearson correlation analysis. The interquartile range (IQR) of the dataset was calculated, with Q1 representing the first quartile (25%), Q2 the second quartile (50%), and Q3 the third quartile (75%). The established criteria for extreme values were set as $Q1 - 3 \text{ IQR}$ or $Q3 + 3 \text{ IQR}$.

2.7 | Adjustments to the Preregistered Methods and Analysis Plan

There were several adjustments made to the methods and analysis plan after preregistration. These changes primarily involved modifications to the initially determined frequency ranges and time windows for gamma frequency band analyses, as well as revisions to the power analysis and resulting sample size.

In the preregistration of this study, it was specified that statistical analyses would be conducted within the following frequency bands: 25–30 Hz, 30–35 Hz, and 35–48 Hz, and across time windows of 0–200 ms, 200–400 ms, and 400–600 ms. However, after inspecting the results of the EEG signal analyses, it was observed that gamma-band responses were most prominent within narrower and slightly shifted time windows. As a result, the statistical analyses were conducted on the 150–300 ms window for 30–48 Hz power and the 250–400 ms window for 30–35 Hz phase-locking. This post hoc adjustment was made to more accurately capture the neural activity relevant to each analysis.

Initially, a target statistical power of 0.9 was set to detect an effect size of 0.5 with an alpha of 0.05, as calculated using G*Power, which resulted in a required sample size of 60. However, after considering study constraints (resources, time, and recruitment feasibility), it became clear that achieving 0.9 power was not practical. Therefore, the power was revised to 0.8, resulting in a smaller required sample size of 46. This adjustment was made to align the study with realistic limitations while maintaining sufficient power to detect meaningful effects.

These deviations are reported transparently here to ensure methodological rigor, and the adjustments do not compromise the integrity or validity of the findings.

3 | Results

3.1 | Final Sample

Fifty-four participants were initially recruited. Three were excluded based on predefined criteria: two due to substantial EEG noise artifacts and one for performing below chance level. This resulted in a final sample of 51 participants eligible for the EEG and CR analyses, specifically the repeated measures ANCOVA and Pearson correlation analyses. For analyses involving behavioral performance (see Section 3.2), four additional participants were excluded due to extreme values in behavioral data, yielding a behavioral performance subsample of 47 participants. Mean and standard deviation values of EHI and WFQ scores, along with demographic information, are presented in Table 1. Additionally, mean scores for the CRIq were analyzed separately for Turkish and German participants, and collectively (see Table 2).

Total CRIq scores differed significantly between the Turkish and German samples, with Turkish participants showing higher scores than German participants, $t_{49} = 5.35$, $p < 0.001$, Cohen's

TABLE 1 | The mean and standard deviation values of the Edinburgh Handedness Inventory and Waterloo Footedness Questionnaire scores, along with the demographic information of all participants.

	Total (N=51)	Turkish (N=33)	German (N=18)
Gender (female/male)	34F/17M	20F/13M	14F/4M
Age M ± SD	22.68 ± 3.10	23.81 ± 3.02*	20.61 ± 2.03*
Education (years) M ± SD	16.00 ± 2.91	17.34 ± 2.51*	13.55 ± 1.82*
EHI M ± SD	64.40 ± 43.72	60.13 ± 50.05	72.22 ± 28.39
WFQ M ± SD	8.8 ± 8.94	7.69 ± 10.20	10.77 ± 5.72

* $p < 0.01$.**TABLE 2** | The mean and standard deviation values of the Cognitive Reserve Index Questionnaire total scores and domain-specific scores.

Subjects	CRI—Education M ± SD	CRI—Working activity M ± SD	CRI—Leisure M ± SD	CRI—Total score M ± SD
Total (N=51)	97.76 ± 12.61	93.39 ± 2.88	90.41 ± 3.16	91.78 ± 6.90
Turkish (N=33)	103.12 ± 10.93	93.75 ± 3.34	91.09 ± 2.97	94.72 ± 6.03
German (N=18)	87.94 ± 9.21	92.72 ± 1.63	89.16 ± 3.20	86.38 ± 4.87

$d = 1.52$. As can be seen in Table 1, the Turkish sample had significantly higher mean age and years of education compared to the German sample. Given the strong influence of these demographic factors on CR indices, this difference in sample characteristics may plausibly account for the higher mean CRIQ scores in the Turkish group. To further explore other potential contributing factors, gender was also considered. As provided in Table 1, the German sample consisted predominantly of female participants (14 females, 4 males), resulting in a gender imbalance that could have influenced group-level comparisons. However, an exploratory independent samples t -test conducted on the full sample ($N = 51$) revealed no significant difference in CRIQ scores between males ($M = 92$, $SD = 7.38$) and females ($M = 91.67$, $SD = 6.75$), $t_{49} = -0.16$, $p = 0.876$, Cohen's $d = -0.05$, suggesting that gender composition was unlikely to account for the observed CRIQ differences between recording locations. It is worth noting that differences in education and age variables are not expected to affect the integrity of the current analyses, as participants were not compared based on nationality or recording location (Turkey and Germany). Instead, the full sample was treated collectively, with CRIQ scores used as a continuous variable to explore associations with neural measures. As such, while demographic differences between subsamples are acknowledged, they were not central to the primary analyses and were not intended as factors for group-level comparison.

To control for potential age-related confounding effects, exploratory repeated measures ANCOVA analyses were conducted on the EEG data for both tasks, with age included as a covariate in each model. The results are presented in Sections 3.5.1 and 3.5.2, where the respective EEG findings for these tasks are reported.

3.2 | Behavioral Performance

One of the aims of the study was to investigate the effects of CR on performance in Sternberg tasks assessing verbal and

visuospatial working memory. To this end, four hypotheses regarding participants' behavioral performance were formulated. To evaluate and compare task performance, d' values were calculated for each task. As this task performance parameter was not normally distributed, the Friedman test, the nonparametric alternative to repeated measures ANCOVA, was used to assess differences across conditions (task, task difficulty, and visual hemifield of stimulus presentation). When the Friedman test yielded a significant result ($p < 0.05$), post hoc pairwise comparisons were conducted using the Durbin–Conover test to identify the source of the effect. Similarly, due to the non-normal distribution of the data, the relationship between d' values and CRIQ scores was examined using Spearman correlation analysis.

To test Hypothesis 1, which predicted better performance in visuospatial Sternberg task trials with stimuli presented in the left visual field compared to the right, d' values were compared between visual fields separately for the one-item and three-item conditions using Friedman tests. For the one-item condition, the Friedman test revealed a significant difference between left and right visual field trials, $\chi^2_1 = 7.6809$, $p = 0.006$. The Durbin–Conover post hoc test confirmed this difference (statistic = 2.99, $p = 0.004$), with higher d' values observed for left visual field trials. For the three-item condition, no significant difference was found between visual hemifields, $\chi^2_1 = 1.0426$, $p = 0.307$. These results partially support Hypothesis 1, indicating a left visual field advantage in the visuospatial task in the one-item condition.

Same analyses were conducted to test Hypothesis 2, which predicted better performance in verbal Sternberg task trials with stimuli presented in the right visual field compared to the left. Friedman tests revealed no significant differences between visual hemifields for either the one-item ($\chi^2_1 = 1.7234$, $p = 0.189$) or three-item ($\chi^2_1 = 1.7234$, $p = 0.189$) conditions.

To test Hypothesis 3, which anticipated a positive correlation between CRIQ scores and task performance, a Spearman

correlation analysis was conducted. There was no significant relationship between CRIq scores and d' values in the one- and three-item memory set conditions, regardless of visual hemifield of stimulus presentation or task (all $r_s(45) < 0.1056$, $p > 0.48$).

To test Hypothesis 4, which proposed that individuals with higher CR would perform relatively better in the visuospatial compared to the verbal Sternberg task, a repeated-measures ANCOVA was conducted with task (verbal, visuospatial), set size (one-item, three-item), and visual hemifield (left, right) as within-subject factors, and CRIq scores as a covariate. The task \times CRIq interaction was not significant ($F_{1, 45} = 0.0121$, $p = 0.913$), indicating that CR levels were not associated with differential task performance.

3.3 | Gamma Power

This section presents the results of the electrophysiological analyses focusing on power values of event-related gamma oscillations, conducted to test the corresponding hypotheses. To test Hypothesis 5, which proposed smaller task demand-related changes in gamma power due to higher CR levels across both tasks, repeated-measures ANCOVAs were conducted separately for each task. As mentioned before, the factors in the analysis models were task difficulty (1-item, 3-item), visual hemifield (left visual field, right visual field), location (F3-F4, F7-F8, C3-C4, T7-T8, P3-P4, P7-P8, O1-O2), and hemisphere (left, right). Greenhouse-Geisser sphericity correction was used. CRIq, EHI, and WFQ scores were included as covariates. The results did not provide evidence that gamma power (30–48 Hz; 150–300 ms) varied in relation to CR in either the verbal ($F_{1, 47} = 1.043$; $p = 0.312$; $\eta^2 = 0.0217$) or visuospatial Sternberg tasks ($F_{1, 47} = 0.516$; $p = 0.476$; $\eta^2 = 0.0109$). These analyses also tested the power-related aspect of Hypothesis 7, which predicted that these values would be influenced by task difficulty, as well as Hypothesis 8, which similarly predicted that event-related gamma power would vary depending on the visual hemifield in which the stimuli were presented. However, neither main effect reached statistical significance in either task (verbal task—task difficulty: $F_{1, 47} = 1.0844$; $p = 0.303$, $\eta^2 = 0.0226$, visual hemifield: $F_{1, 47} = 0.2630$; $p = 0.610$, $\eta^2 = 0.0056$; visuospatial task—task difficulty: $F_{1, 47} = 0.0160$; $p = 0.900$, $\eta^2 = 0.0003$, visual hemifield: $F_{1, 47} = 0.4671$; $p = 0.498$, $\eta^2 = 0.0098$), providing no support for these predictions.

In the verbal task, there was a significant main effect of location ($F_{2, 24, 105} = 3.588$; $p = 0.027$; $\eta^2 = 0.0709$), as well as a significant location \times CRIq interaction ($F_{2, 24, 105} = 3.843$; $p = 0.020$; $\eta^2 = 0.0756$). To explore the source of the significant main effect of location, a post hoc comparison using Bonferroni correction was conducted. Although uncorrected comparisons revealed greater power values in the P3–P4 electrode pair compared to F3–F4 ($p = 0.04$; adjusted $p_{\text{bonferroni}} = 0.916$), T7–T8 ($p = 0.04$; adjusted $p_{\text{bonferroni}} = 1.000$), P7–P8 ($p = 0.005$; adjusted $p_{\text{bonferroni}} = 0.105$), and O1–O2 ($p = 0.008$; adjusted $p_{\text{bonferroni}} = 0.162$), these differences were diminished after Bonferroni correction, suggesting that the difference may not be robust. To further examine the significant location \times CRIq

interaction, a Pearson correlation analyses between power values at each electrode and CRIq scores were conducted. No significant relationship was found between CRIq scores and event-related 30–48 Hz power values at any electrode site ($p > 0.05$).

In the visuospatial task, a significant main effect of location was found ($F_{3, 50, 165} = 3.255$; $p = 0.018$; $\eta^2 = 0.0648$), along with significant interactions for location \times CRIq ($F_{3, 50, 165} = 3.338$; $p = 0.016$; $\eta^2 = 0.0663$) and visual hemifield \times hemisphere ($F_{1, 47} = 4.156$; $p = 0.047$; $\eta^2 = 0.0812$). To examine the source of the significant main effect of location, a post hoc comparison using Bonferroni correction was conducted. However, none of the pairwise comparisons between locations reached significance, even prior to correction, indicating that the overall effect may reflect subtle, distributed differences rather than strong contrasts between specific pairs. To explore the location \times CRIq interaction further, Pearson correlation analyses were conducted between CRIq scores and 30–48 Hz power values at each electrode. These analyses revealed significant positive associations at P3 ($r_{49} = 0.30$, $p = 0.03$) and P8 ($r_{49} = 0.28$, $p = 0.049$) in the one-item left visual field condition, while no other electrode sites showed significant relationships. Post hoc tests exploring the visual hemifield \times hemisphere interaction yielded no significant results. Additionally, to test Hypothesis 6, which expected a positive correlation between CR and the degree of right-hemispheric lateralization during the visuospatial Sternberg task, Pearson correlation analyses were conducted between CRIq scores and LCs. The results partially supported the hypothesis, revealing a significant relationship with CRIq scores only for the LC of the P7–P8 electrode pair ($r_{49} = 0.39$, $p = 0.005$) in the one-item, right visual field condition.

3.4 | Gamma Phase-Locking

The phase-locking aspects of Hypothesis 7, which proposed that event-related gamma phase-locking values would be influenced by task difficulty, and Hypothesis 8, which proposed that these values would vary across visual hemifield conditions, were tested using separate repeated-measures ANCOVAs based on the same analysis models used for gamma power. Results of the repeated-measures ANCOVA conducted for the verbal Sternberg task revealed no significant main effects of task difficulty ($F_{1, 47} = 0.0369$; $p = 0.849$; $\eta^2 = 0.0008$) or visual hemifield ($F_{1, 47} = 0.1775$; $p = 0.675$; $\eta^2 = 0.0038$). For the visuospatial task, the results yielded no significant main effects of task difficulty ($F_{1, 47} = 1.2047$; $p = 0.278$; $\eta^2 = 0.0250$) or visual hemifield ($F_{1, 47} = 0.2999$; $p = 0.587$; $\eta^2 = 0.0063$).

Additionally, there was no evidence of gamma phase-locking values (250–400 ms for 30–35 Hz) varying in relation to CRIq scores in either the verbal ($F_{1, 47} = 0.8214$; $p = 0.369$; $\eta^2 = 0.0172$) or visuospatial ($F_{1, 47} = 0.0220$; $p = 0.883$; $\eta^2 = 0.0005$) Sternberg tasks. None of the main effects or interactions reached statistical significance. To test Hypothesis 6 with gamma phase-locking values, Pearson correlation analyses between CRIq and LCs of the 30–35 Hz phase-locking values were conducted. Contrary to the prediction in this hypothesis, no evidence was found for a relationship between CR and the degree of right-hemispheric lateralization during the visuospatial Sternberg task.

3.5 | Exploratory Analysis—2–9 Hz Phase-Locking

Exploratory EEG signal analyses were initially conducted in the 1–15 Hz range; however, following visual inspection of the data, prominent brain responses in the 2–9 Hz (0–300 ms) range were identified, leading to the selection of this frequency band for the subsequent statistical analyses. For the event-related phase-locking values, task difficulty, visual hemifield, location, and hemisphere factors were included as within-group factors, while the scores from the CRIq, EHI, and WFQ scales served as covariates in the Repeated Measures ANCOVAs. These analyses were conducted for verbal and visuospatial Sternberg tasks separately. As indicated in the Methods section (2.5. EEG Signal Analysis), all EEG results reported in this study correspond to the encoding phase of the task. The 0 ms point in the analysis window marked the presentation of the memory set, which appeared in either the left or right visual field. This clarification is particularly relevant at this stage, as EEG figures illustrating 2–9 Hz phase-locking responses in the verbal and visuospatial tasks will be presented in the respective sections for the verbal and visuospatial Sternberg tasks.

3.5.1 | Phase-Locking Results in the Verbal Sternberg Task

The results of this exploratory analysis indicated a significant main effect of hemisphere ($F_{1,47} = 5.446$; $p = 0.024$; $\eta^2 = 0.1038$). The main effects of task difficulty, visual hemifield, and location factors did not reach statistical significance. Additionally, a significant interaction was observed between visual hemifield and hemisphere ($F_{1,47} = 11.574$; $p = 0.001$; $\eta^2 = 0.1976$). Additionally, the CRIq ($F_{1,47} = 5.745$; $p = 0.021$; $\eta^2 = 0.1089$) and EHI ($F_{1,47} = 6.205$; $p = 0.016$; $\eta^2 = 0.1166$) scores were found to significantly influence the phase-locked responses in the 2–9 Hz band, whereas the effect of WFQ scores was not significant.

Significant main effects and interactions were examined with post hoc tests with Bonferroni correction. Post hoc comparisons following the significant main effect of hemisphere revealed that 2–9 Hz phase-locking responses were significantly higher in the right hemisphere ($M = -0.0128$, $SE = 0.0040$; $t_{47} = -3.2091$, $p_{\text{bonferroni}} = 0.002$). The results of the post hoc comparisons for the visual hemifield * hemisphere interaction indicated that the 2–9 Hz phase-locking responses in the right hemisphere were significantly greater compared to the left hemisphere during the verbal Sternberg tasks (one- and three-item) in the left visual field condition ($M = -0.0338$, $SE = 0.0065$; $t_{47} = -5.2349$, $p < 0.001$). When comparing the visual hemifield in which the stimuli were presented, it was found that the phase-locking values in the left hemisphere under the right visual field condition were significantly higher than those recorded in the left hemisphere under the left visual field condition ($M = -0.0318$, $SE = 0.0069$; $t_{47} = -4.6195$, $p_{\text{bonferroni}} < 0.001$). Furthermore, the phase-locking values recorded from the right hemisphere in the right visual field condition were significantly greater than those recorded from the left hemisphere in the left visual field condition ($M = -0.0235$, $SE = 0.0070$; $t_{47} = -3.3670$, $p_{\text{bonferroni}} = 0.009$).

Following the observation of significant effects of CRIq and EHI scores on the 2–9 Hz phase-locking responses, correlation

analyses were conducted to explore the relationships between these variables and the LCs for each electrode pair. None of the LCs for the electrode pairs demonstrated a significant relationship with EHI scores. On the other hand, significant relationships between CRIq scores and LCs were observed, all of which occurred in the left visual field condition. For the one-item condition, LCs of the following electrode pairs demonstrated significant correlations: F3–F4 ($r_{49} = 0.38$, $p = 0.005$), C3–C4 ($r_{49} = 0.40$, $p = 0.003$), P3–P4 ($r_{49} = 0.44$, $p = 0.001$), P7–P8 ($r_{49} = 0.41$, $p = 0.003$), T7–T8 ($r_{49} = 0.45$, $p < 0.001$). For the three-item condition, LCs of the P3–P4 ($r_{49} = 0.37$, $p = 0.008$) and P7–P8 ($r_{49} = 0.39$, $p = 0.005$) electrode pairs were significantly correlated with CRIq scores. The scatterplots corresponding to these significant relationships are displayed in Figure 2. Grand average time-frequency visualizations of electrode pairs showing significant associations with CRIq, generated separately for the Turkish and German samples, are presented in Figure 3. These figures are shown separately for each site to aid interpretation and are intended solely for visual representation, as the separation was not meant for statistical analyses, as further discussed below.

As provided in Table 2, CRIq scores differed significantly between the two recording sites, with Turkish participants showing higher average CRIq scores ($M = 94.72$) than German participants ($M = 86.38$; $p < 0.001$). Notably, when all 51 participants were included in a single grand average, the 2–9 Hz phase-locking responses appeared less pronounced, likely reflecting meaningful variability in phase-locking responses as a function of CR.

To avoid misrepresentation and support clearer interpretation, grand average time-frequency plots were generated separately for the Turkish and German samples. Although recording protocols were carefully standardized across sites, this approach also helps account for any potential site-related variability. While CRIq scores differed between groups at the group level, both samples included participants with relatively high and low CRIq scores when the data were median split (median = 91). Accordingly, CRIq was treated as a continuous variable in all statistical analyses. As mentioned in Section 3.13.1, to control for potential age-related confounding effects, exploratory repeated measures ANCOVA analyses were conducted. The results confirmed that the 2–9 Hz phase-locking values did not vary with age in the verbal Sternberg task ($F_{1,46} = 0.360$; $p = 0.552$; $\eta^2 = 0.0078$).

3.5.2 | Phase-Locking Results in the Visuospatial Sternberg Task

The results of this exploratory analysis revealed that no main effects reached statistical significance. However, significant interactions were found, including visual hemifield * hemisphere ($F_{1,47} = 7.588$; $p = 0.008$; $\eta^2 = 0.0013$), task difficulty * location * hemisphere ($F_{5,10,240} = 2.652$; $p = 0.023$; $\eta^2 = 0.0534$), and visual hemifield * location * hemisphere ($F_{2,77,130} = 3.863$; $p = 0.013$; $\eta^2 = 0.0759$). Additionally, the visual hemifield * hemisphere * CRIq ($F_{1,47} = 10.441$; $p = 0.002$; $\eta^2 = 0.1818$) interaction also reached significance. On the other hand, it was found that the CRIq ($F_{1,47} = 2.4268$; $p = 0.126$; $\eta^2 = 0.0491$), EHI ($F_{1,47} = 0.8176$; $p = 0.370$; $\eta^2 = 0.0171$), and WFQ ($F_{1,47} = 0.0768$; $p = 0.783$;

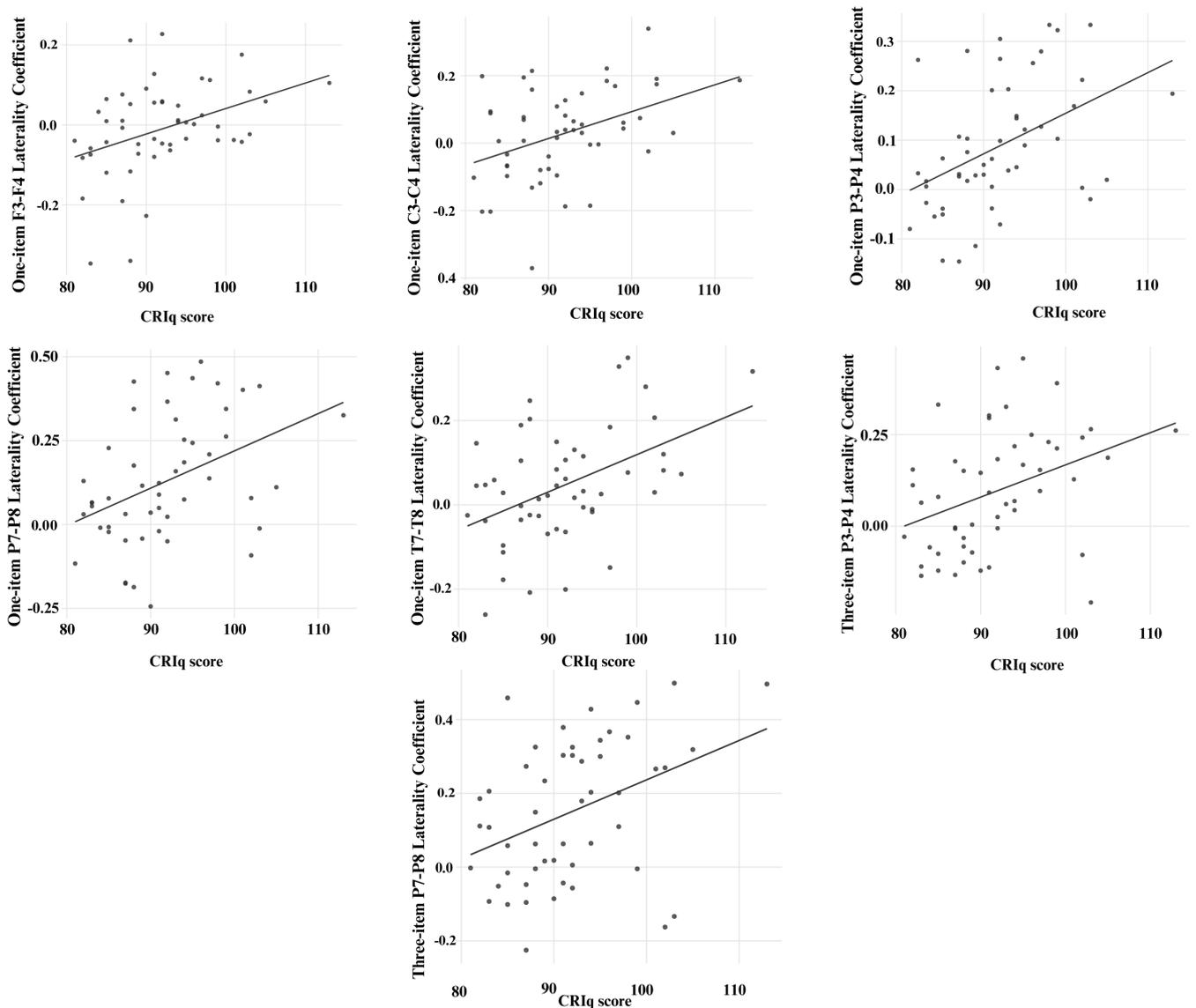


FIGURE 2 | Scatterplots of significant CRIq-LC relationships for the verbal Sternberg task across all participants. All plots correspond to LCs in the left visual field conditions. The X-axis in these plots represents CRIq scores, while the Y-axis represents the LCs of electrode pairs. Information regarding the electrode pair and task difficulty conditions for the specific LCs is provided in each plot.

$\eta^2=0.0016$) scores included as covariates did not have a significant effect on the event-related phase-locking responses in the 2–9 Hz band.

Significant interactions were examined using post hoc tests, with Bonferroni-corrected p -values reported. Post hoc comparisons were conducted for the interactions of visual hemifield * hemisphere, task difficulty * location * hemisphere, and visual hemifield * location * hemisphere. Post hoc comparisons of the visual hemifield * hemisphere interaction revealed that in the left visual field condition, 2–9 Hz phase-locking values in the right hemisphere were significantly ($M=-0.0411$, $SE=0.0059$; $t_{47}=-7.0210$, $p_{\text{bonferroni}} < 0.001$) higher than in the left hemisphere. The comparison of the left and right visual field conditions showed that 2–9 Hz phase-locking values recorded from the left hemisphere were significantly higher under the right visual field condition ($M=-0.0238$, $SE=0.0067$; $t_{47}=-3.5730$, $p_{\text{bonferroni}}=0.005$); while for the right hemisphere, these values were higher under the left visual field condition

($M=0.0306$, $SE=0.0068$; $t_{47}=4.4804$, $p_{\text{bonferroni}} < 0.001$). Post hoc examination of the task difficulty * location * hemisphere interaction demonstrated that in the one-item visuospatial Sternberg task, phase-locking responses recorded from the P7 electrode were found to be significantly higher than those recorded from the F3 ($M=-0.0525$, $SE=0.0104$; $t_{47}=-5.0260$, $p_{\text{bonferroni}}=0.003$), C3 ($M=-0.0577$, $SE=0.0099$; $t_{47}=-5.8248$, $p_{\text{bonferroni}} < 0.001$) and T7 ($M=-0.0604$, $SE=0.0079$; $t_{47}=-7.6090$, $p_{\text{bonferroni}} < 0.001$) electrodes. In the same condition, 2–9 Hz phase-locking responses recorded from the P8 electrode were significantly higher than those recorded from the F4 ($M=-0.0847$, $SE=0.0129$; $t_{47}=-6.5576$, $p_{\text{bonferroni}} < 0.001$), F8 ($M=-0.0781$, $SE=0.0130$; $t_{47}=-6.0228$, $p_{\text{bonferroni}} < 0.001$), C4 ($M=-0.0799$, $SE=0.0118$; $t_{47}=-6.7821$, $p_{\text{bonferroni}} < 0.001$), T8 ($M=-0.0739$, $SE=0.0093$; $t_{47}=-7.9558$, $p_{\text{bonferroni}} < 0.001$), and P4 ($M=-0.0398$, $SE=0.0081$; $t_{47}=-4.9482$, $p_{\text{bonferroni}} < 0.001$) electrodes. Furthermore, in the three-item condition, phase-locking responses recorded from the P7 electrode were found to be significantly higher than those recorded from the

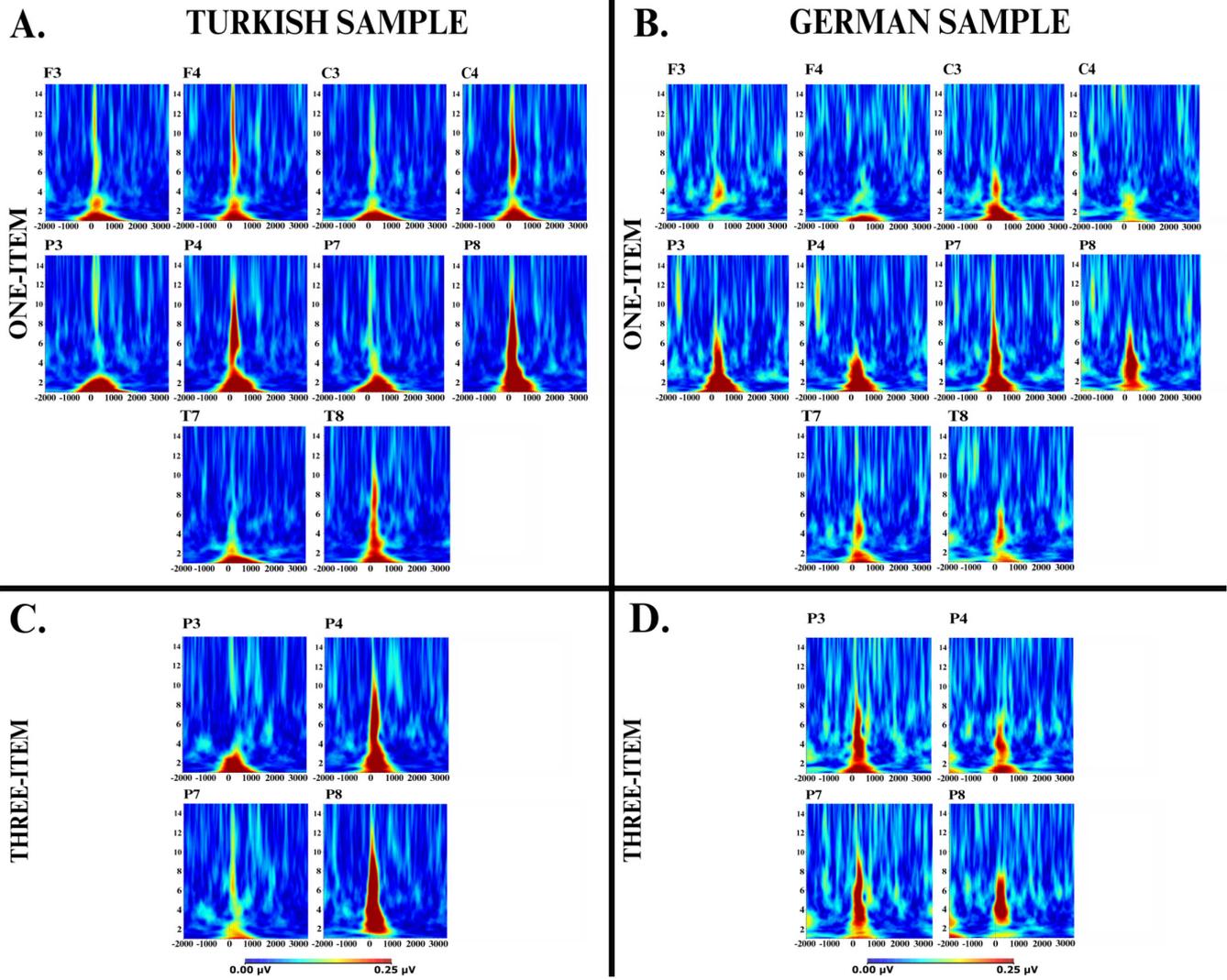


FIGURE 3 | Grand average visualizations of the ITC analysis (1–15 Hz; –2000 to 3000 ms) for electrode pairs of LCs significantly correlated with CRIq scores. (A) The phase-locking responses for the Turkish sample in the one-item verbal Sternberg task, left visual field condition, for electrode pairs that exhibited significant correlations with CRIq scores. (B) The same condition and electrode pairs for the German sample are displayed. (C) The phase-locking responses for the Turkish sample in the three-item verbal Sternberg task, left visual field condition, with the corresponding electrode pairs correlated with CRIq scores. (D) The same condition and electrode pairs for the German sample are presented.

F3 ($M = -0.0599$, $SE = 0.0117$; $t_{47} = -5.1121$, $p_{\text{bonferroni}} = 0.002$), C3 ($M = -0.0486$, $SE = 0.0108$; $t_{47} = -4.4999$, $p_{\text{bonferroni}} = 0.017$), and T7 ($M = -0.0599$, $SE = 0.0094$; $t_{47} = -6.3797$, $p_{\text{bonferroni}} < 0.001$) electrodes. Similarly, it was observed that the values recorded from the P8 electrode under the same condition were significantly higher than those recorded from the F4 ($M = -0.1001$, $SE = 0.0150$; $t_{47} = -6.6550$, $p_{\text{bonferroni}} < 0.001$), F8 ($M = -0.0904$, $SE = 0.0155$; $t_{47} = -5.8264$, $p_{\text{bonferroni}} < 0.001$), C4 ($M = -0.0768$, $SE = 0.0142$; $t_{47} = -5.4063$, $p_{\text{bonferroni}} < 0.001$), and T8 ($M = -0.0901$, $SE = 0.0127$; $t_{47} = -7.0892$, $p_{\text{bonferroni}} < 0.001$) electrodes.

Comparisons of the visual hemifield * location * hemisphere interaction demonstrated that in the one-item and three-item conditions of the visuospatial Sternberg tasks with stimulus presentation in the left visual field, phase-locking values were significantly higher at several electrode sites in the right hemisphere compared to their left hemisphere counterparts. Specifically, significantly higher phase-locking values were observed

at T8 electrode compared to T7 ($M = -0.0368$, $SE = 0.0084$; $t_{47} = -4.3961$, $p_{\text{bonferroni}} = 0.024$); at P4 electrode compared to P3 ($M = -0.0563$, $SE = 0.0093$; $t_{47} = -6.0726$, $p_{\text{bonferroni}} < 0.001$); at P8 electrode compared to P7 ($M = -0.1156$, $SE = 0.0159$; $t_{47} = -7.2562$, $p_{\text{bonferroni}} < 0.001$); and finally, at O2 electrode compared to O1 ($M = -0.0500$, $SE = 0.0088$; $t_{47} = -5.6938$, $p_{\text{bonferroni}} < 0.001$). On the other hand, in conditions with stimulus presentation in the right visual field, the initial significant hemispheric differences observed in electrode comparisons were no longer evident after Bonferroni correction.

Given that post hoc comparisons could not be conducted for the visual hemifield * hemisphere * CRIq interaction due to the continuous nature of CRIq scores, Pearson correlation analyses between CRIq scores and LCs were conducted to further explore the source of this significant interaction. There were significant relationships between CRIq and LCs. For the one-item condition, significant correlations between CRIq scores and LCs were observed for the following electrode pairs: P3–P4 ($r_{49} = 0.32$,

$p=0.020$) in the left visual field, and O1–O2 ($r_{49}=-0.43$, $p=0.002$) and P3–P4 ($r_{49}=0.41$, $p=0.003$) in the right visual field. For the three-item condition, significant correlations were observed for the following electrode pairs: P7–P8 ($r_{49}=0.33$, $p=0.020$) in the left visual field, and P3–P4 ($r_{49}=-0.34$, $p=0.016$) and O1–O2 ($r_{49}=-0.29$, $p=0.039$) in the right visual field. The scatterplots corresponding to the significant relationships between CRIq and LCs are displayed in Figure 4. Grand average time-frequency visualizations for the visuospatial task are shown in Figure 5, presented separately for the Turkish and German samples, following the same format described and used earlier. The exploratory repeated measures ANCOVA conducted to control for age-related confounding effects confirmed that, similar to the verbal Sternberg task, 2–9 Hz phase-locking values in the visuospatial task did not vary with age ($F_{1,46}=1.118$; $p=0.296$; $\eta^2=0.0237$).

3.6 | Comparison of Hemispheric Dominance Across Tasks

To compare hemispheric dominance in verbal and visuospatial tasks, an exploratory repeated measures ANCOVA analysis was conducted, including phase-locking responses recorded during both tasks. The factors of task, task difficulty, visual hemifield, location, and hemisphere were included as within-subjects factors, while the scores from the CRIq, EHI, and WFQ were included as covariates.

The results revealed no significant main effects. Interactions between task difficulty * hemisphere ($F_{1,47}=13.898$; $p<0.001$; $\eta^2=0.2282$) and visual hemifield * hemisphere ($F_{1,47}=11.788$; $p=0.001$; $\eta^2=0.2005$) were significant. The CRIq scores, included as a covariate, had a significant effect on phase-locking responses in the 2–9 Hz band ($F_{1,47}=4.676$; $p=0.036$; $\eta^2=0.0905$). On the other hand, the effects of EHI and WFQ scores did not reach significance. Post hoc comparisons for task difficulty * hemisphere interaction revealed that phase-locking values recorded during one- and three-item tasks significantly differed between hemispheres, as demonstrated in Figure 6, which displays the estimated marginal means plot of this comparison. For one-item tasks, values recorded from the right hemisphere were significantly higher than those from the left hemisphere ($M=-0.0137$, $SE=0.0042$; $t_{47}=-3.2305$, $p_{\text{bonferroni}}=0.014$). Similarly, in three-item tasks, values from the right hemisphere were also significantly higher than those from the left hemisphere ($M=-0.0128$, $SE=0.0040$; $t_{47}=-3.2091$, $p_{\text{bonferroni}}=0.014$). Post hoc Bonferroni comparisons conducted to further examine the visual hemifield * hemisphere interaction indicated that, in the left visual field conditions of both tasks, 2–9 Hz phase-locking values recorded from the right hemisphere were significantly higher than the left hemisphere ($M=-0.0372$, $SE=0.0054$; $t_{47}=-6.9151$, $p_{\text{bonferroni}}<0.001$). Moreover, phase-locking values in the 2–9 Hz range were significantly higher in both the left ($M=-0.0278$, $SE=0.0058$; $t_{47}=-4.7938$, $p_{\text{bonferroni}}<0.001$) and right hemispheres ($M=-0.0170$, $SE=0.0052$; $t_{47}=-3.2869$, $p_{\text{bonferroni}}=0.012$) when stimuli were presented in

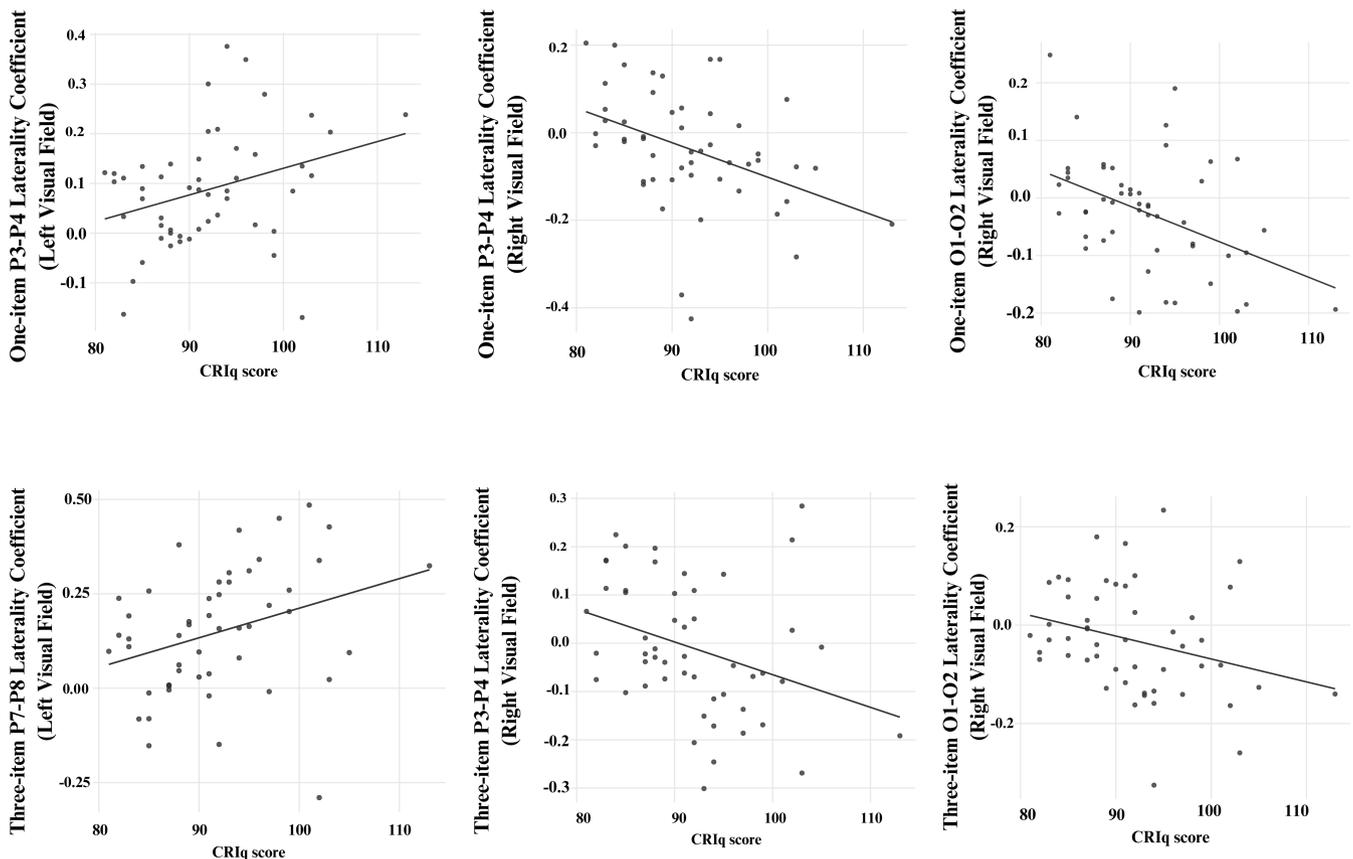


FIGURE 4 | Scatterplots of significant correlational relationships between CRIq and LCs for the visuospatial Sternberg task across all participants. The X-axis in these plots represents CRIq scores, while the Y-axis represents the LCs of electrode pairs. Information regarding the electrode pair, task difficulty, and visual hemifield conditions for the specific LCs is provided in each plot.

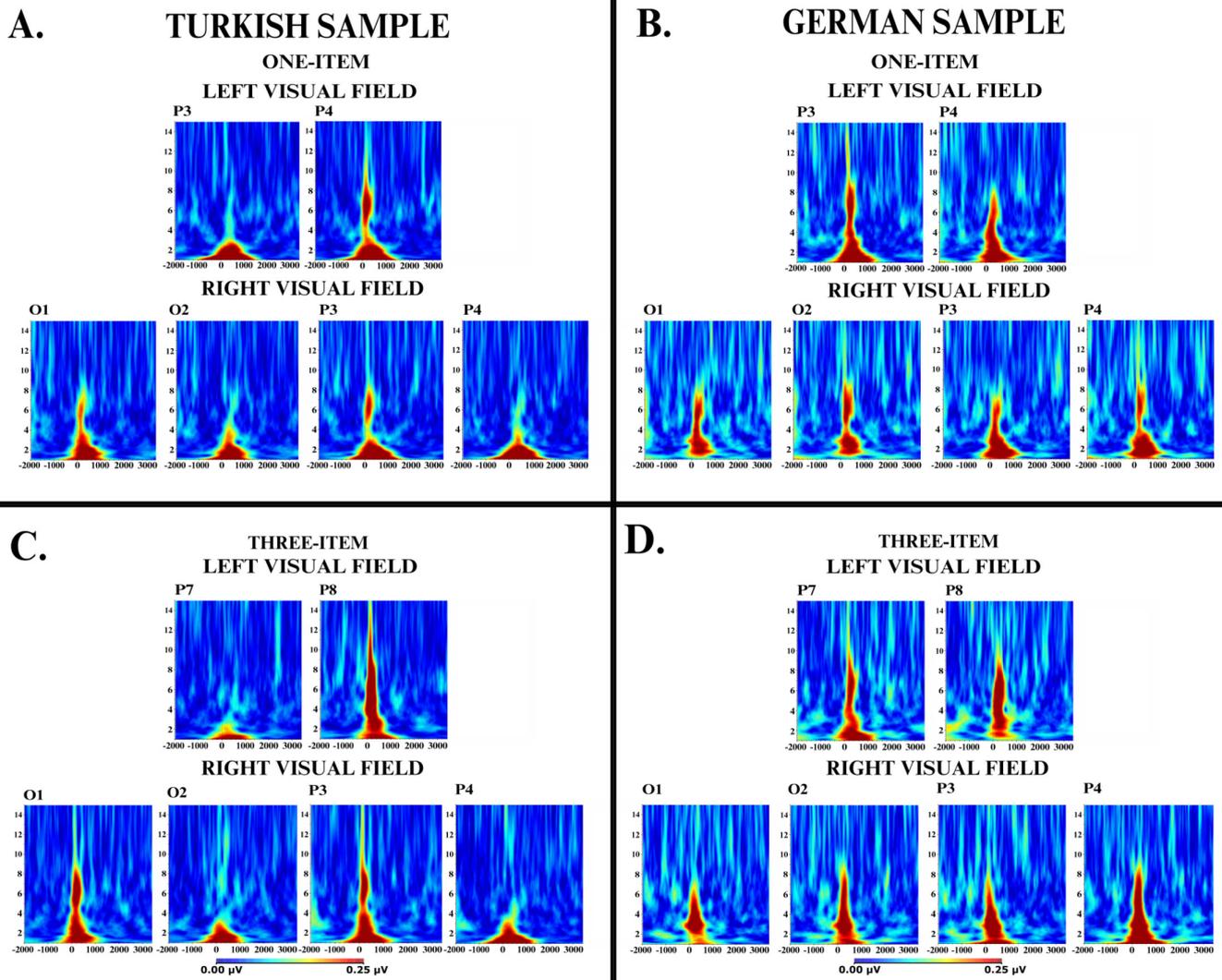


FIGURE 5 | Grand average plots of the ITC analysis (1–15 Hz; –2000 to 3000 ms) for electrode pairs of LCs significantly correlated with CRIQ scores, separated by visual field conditions. (A) Phase-locking responses for the Turkish sample in the one-item visuospatial Sternberg task. (B) Phase-locking responses for the German sample in the same task with significantly correlated electrode pairs. (C) Phase-locking responses for the Turkish sample in the three-item visuospatial Sternberg task. (D) Grand average visualizations for the same task and electrode pairs in the German sample.

the right visual field, compared to values recorded from the left hemisphere during left visual field trials. Lastly, a comparison of visual fields for the 2–9 Hz values recorded from the right hemisphere revealed that right hemisphere values were higher in the left visual field condition ($M = 0.0202$, $SE = 0.0062$; $t_{47} = 3.2659$, $p_{\text{bonferroni}} = 0.012$).

4 | Discussion

The primary objective of this study was to investigate how CR influences verbal and visuospatial Sternberg task performance and its relationship with the degree of lateralization in EEG responses recorded during these tasks. The behavioral hypotheses primarily predicted that a visual field advantage would be observed in these tasks and that higher CR would be associated with better task performance. Hypothesis 1 was partially supported, as the d' value for the one-item visuospatial Sternberg task in the left visual field condition was higher than that for

the one-item verbal Sternberg task. Contrary to the prediction of Hypothesis 2, the verbal Sternberg task did not show a right visual field advantage. Additionally, there was no evidence of a relationship between CR and behavioral performance (d' values), meaning Hypothesis 3 was not supported. Furthermore, the proposed relationship between CR and visuospatial task performance (higher CR leading to better task performance) in Hypothesis 4 was not supported. The electrophysiological hypotheses were regarding the effects of CR on power and phase-locking values of event-related gamma oscillations, as well as the correlational relationship between hemispheric asymmetry in these responses and CR. Hypothesis 5, predicting that higher CR would result in smaller changes in event-related gamma power with increasing task demands, was not supported. Hypothesis 6, predicting a positive correlation between CR and right hemispheric lateralization during the visuospatial Sternberg task, was partially supported by the correlation between CRIQ scores and LC of the P7–P8 electrode pair in the one-item right visual field condition. Hypothesis 7 and Hypothesis 8, which predicted

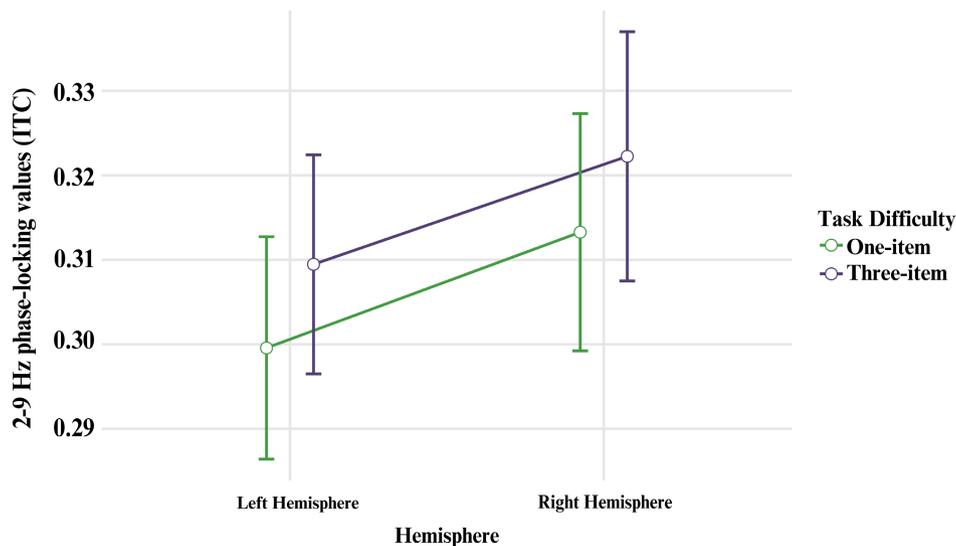


FIGURE 6 | Estimated Marginal Means plot showing the interaction between task difficulty and hemisphere. This plot presents the estimated marginal means of phase-locking values in the 2–9 Hz frequency range recorded during the one- and three-item conditions across both the verbal and visuospatial tasks. The green line indicates phase-locking values for the one-item condition, while the purple line shows values for the three-item condition. Values represent collective phase-locking responses for each task difficulty condition.

that gamma power and phase-locking values would be affected by task difficulty and visual hemifield of stimulus presentation, respectively, were not supported for the power or phase-locking results of either task.

The same approach was used in exploratory analyses to assess CR's impact on 2–9 Hz phase-locking responses and their association with hemispheric asymmetry. CRIq score was a significant covariate in the verbal task, suggesting a direct relationship with performance. In the visuospatial task, although CR was not significant as a covariate, significant interactions indicated that its effect on performance may depend on other factors. Significant correlations observed between LCs from both tasks and CRIq scores support the proposed link between lateralization and CR. Additionally, to explore the proposed role of the right hemisphere in CR, 2–9 Hz phase-locking responses were compared across verbal and visuospatial working memory tasks, which were specifically selected due to their established lateralization patterns in the left and right hemispheres, respectively. This comparison revealed that 2–9 Hz phase-locking values recorded from the right hemisphere were significantly higher in both task conditions.

The behavioral findings of this study revealed that d' values demonstrated a visual field advantage only in the one-item condition of the visuospatial task. Since both the verbal and visuospatial tasks engage cognitive processes with well-established lateralization patterns, it was expected that behavioral performance would potentially benefit from stimulus presentation in the contralateral visual field. These expectations formed the basis for Hypotheses 1 and 2. While Hypothesis 1 was partly supported by the observed visual field advantage in the visuospatial task, Hypothesis 2 was not supported, as the verbal task did not demonstrate a similar effect. The lack of a strong visual field effect could be due to various factors, including the complexity of the tasks. It is possible that the tasks did not induce enough cognitive load to activate the mechanisms that would

benefit from these visual field advantages. Moreover, no significant relationship was found between CRIq scores and behavioral performance (d' values), resulting in Hypothesis 3 not being confirmed. Possible explanations for the absence of a significant relationship include the following: (1) Lifelong experiences, which are core components of CR, accumulate over time. Therefore, a questionnaire or composite measure specifically designed to capture CR in early adulthood, the primary age group in this study, may provide a more accurate evaluation of CR. The CRIq was used in this study to ensure the use of a standardized measure, making the results easier to compare and contribute to the accumulation of consistent data across studies. Despite this, the CRIq may lack the sensitivity needed to detect subtle differences in reserve levels among the healthy young participants, potentially because the questionnaire's year-based scoring approach limits score variation in younger individuals, even with the application of an age-correction formula. In similar efforts, a study aimed at developing a questionnaire to assess CR in adolescents referred to this measure as “cognitive reserve potential,” highlighting the need for age-specific proxies to more accurately measure CR in younger populations (Conte et al. 2023). A review of CR measurement across studies (Nogueira et al. 2022) suggests that an ideal evaluation of CR should be more comprehensive, incorporating abilities such as verbal fluency, along with questionnaires on education, work, and lifestyle. In addition, the sample primarily consisted of students of similar ages who were from the main universities involved in data collection. Consequently, this may have limited the diversity of lifestyle factors among participants, potentially leading to more similar levels of CR. To gain a more nuanced understanding of the effects of CR on behavioral performance, it would be beneficial to incorporate participants with a broader range of ages and lifestyle backgrounds, as this may lead to more accurate results. (2) The difficulty levels (one-item, three-item) set in the verbal and visuospatial Sternberg tasks may not have imposed a sufficient cognitive load to assess the effects of increasing task demands adequately. In the preparation of the tasks, memory sets of one,

three, and five items were pilot-tested to ensure their feasibility. Conventional Sternberg paradigms generally display memory sets for at least 2.5 s and can include set sizes of up to seven items. In this study, stimuli were shown for just 160 ms, resulting in below-chance performance (less than 50%) in the five-item condition, which was therefore removed from the study. This may have resulted from the difference in encoding time. Furthermore, in existing literature, task difficulty is not solely manipulated by varying the number of items (e.g., one, four, or seven) but also by whether the stimuli are identical (e.g., 4,4,4,4) or distinct (e.g., 5,4,2,9) despite having the same number of items (Gutiérrez-Zamora Velasco et al. 2021). Finally, no significant relationship was found to support Hypothesis 4's prediction that individuals with higher CR would perform better on the visuospatial task. In addition to task-related factors, this may be due to the possibility that CR is more strongly reflected through neural efficiency mechanisms, rather than raw behavioral output.

In terms of the electrophysiological data, the hypothesis-driven power and phase-locking analyses in the gamma band (30–48 Hz and 30–35 Hz respectively) revealed no evidence that these values varied in relation to CR in either the verbal or visuospatial Sternberg tasks. Accordingly, the prediction in Hypothesis 5 that higher CR would lead to smaller changes in gamma power values in response to increasing task demands was not supported. Gamma power and phase-locking values did not demonstrate significant change depending on the task difficulty or visual hemifield of stimulus presentation, as expected in Hypotheses 7 and 8. The significant main effect of location in both tasks, along with other interactions, disappeared after Bonferroni correction. The conservative nature of the Bonferroni correction suggests that these results should be interpreted with caution rather than dismissed. In the visuospatial task, a significant relationship was found between CRIq and the LC of the P7–P8 electrode pair in the one-item, right visual field condition, partially supporting Hypothesis 6. This result may suggest that CR-related neural mechanisms emerge in response to increased task demands. Although observed during a lower item load condition, since visual information from the right visual field is primarily projected to the left hemisphere, this visual field condition may impose additional demands on a right-lateralized task. This finding may suggest that with higher CR, there is a tendency toward enhanced right hemispheric lateralization in gamma power responses during this task condition. The gamma frequency range was specifically selected due to extensive evidence of its role in working memory processes (Lisman and Idiart 1995; Howard 2003; Axmacher et al. 2010; Lisman 2010). Given its very fast and low-amplitude nature (Herrmann et al. 2010), this paradigm may have been insufficient to detect asymmetry in this frequency band. The brief duration of our stimulus presentation may have been too short to effectively capture the dynamics of gamma power and phase-locking responses. Analyses capable of detecting more subtle changes in network activity might offer a more thorough examination of the gamma band, allowing for a more accurate assessment.

The results of the exploratory 2–9 Hz phase-locking analyses for the verbal Sternberg task revealed a significant main effect of hemisphere, showing right hemisphere dominance across all task conditions (task difficulty and visual field), along with a

significant visual hemifield * hemisphere interaction. Specific visual field comparisons showed that values recorded from the left hemisphere were higher in the right visual field condition compared to the left visual field. Additionally, the comparison of ipsilateral visual field conditions (right visual field for the right hemisphere and left visual field for the left hemisphere) revealed higher values in the right hemisphere. Ipsilateral stimulus presentation typically yields lower values in the corresponding hemisphere. Since this was a verbal task, greater engagement of the left hemisphere would normally be expected, regardless of hemifield. The observation of higher right-hemisphere values in the right visual field condition may therefore suggest an adaptive shift in hemispheric engagement, potentially reflecting increased task demands associated with the verbal task. However, these results should be regarded carefully, as this apparent shift in hemispheric engagement may be influenced by individual variation and may not be directly related to task demands. Significant associations between the LCs and CRIq scores were specifically found in left visual field conditions, particularly in the parietal electrode pairs, indicating that these relationships emerged when the primarily engaged hemisphere was the non-dominant one for this task. As a result, this may have created a task load that allowed for a more evident observation of the neural efficiency mechanism. In terms of LCs, positive values and increases in that direction suggest a dominance of the right hemisphere. Consequently, the significant positive correlations observed between these coefficients and CR scores imply that as CR increases, so does the dominance of the right hemisphere in the 2–9 Hz phase-locking values. While the current finding concerns lateralization during the encoding phase, it may be considered within a broader framework of CR-related neural efficiency. Although not directly comparable, previous research has shown that individuals with higher CR exhibit smaller changes in P3b amplitude and phase latency during the delay and probe phases of the verbal Sternberg task (Speer and Soldan 2015). Taken together, these findings may suggest that neural reserve-related mechanisms can vary depending on the neural measure and the specific stage of cognitive processing. Since it has been observed that as the difficulty level of working memory tasks increases, phase-locking values in the delta (Siegel et al. 2009; Fell and Axmacher 2011), theta (Herweg et al. 2020), and alpha (Kwon et al. 2015) frequency bands also rise, accompanied by reports of improved overall task performance, these interpretations are consistent with existing literature.

Continuing with the results from the visuospatial Sternberg task, visual hemifield * hemisphere comparisons confirmed the expected pattern, with higher right hemisphere values in the left visual field condition and higher left hemisphere values in the right visual field condition. It was observed that 2–9 Hz phase-locking values in the parietal region were higher than those in the frontal, central, and temporal regions for both one-item and three-item memory sets. There were significant negative correlations between the LCs in the parietal and occipital regions for the right visual field condition and CRIq scores. Since a negative correlation indicates that higher CRIq scores are associated with lower LCs, this suggests that individuals with higher CR tend to exhibit decreasing LCs, which may reflect greater left hemispheric engagement. Greater left hemisphere involvement is expected in the right visual field condition, as visual information from the right visual field

is primarily processed by the left hemisphere. Additionally, significant correlations between parietal electrode pairs and CRIq were observed in the left visual field condition. Following the reasoning discussed above, the ipsilateral visual field presentation in both tasks (left visual field for the verbal task and right visual field for the visuospatial task) may be considered to induce task load (Bourne 2006). The consistent correlation between parietal electrode pairs and CRIq in these conditions may suggest the potential involvement of neural reserve-related effects, pointing to the possibility that CR may modulate hemispheric engagement under increased task demands. The fact that this pronounced asymmetry in the parietal region was also evident during the verbal working memory task may point to an active neural network involved in cognitive processes related to working memory (Zurowski et al. 2002; Ravizza et al. 2005; Emch et al. 2019). Also, these results may contribute to supporting evidence regarding the existence of a right-lateralized frontoparietal attention network associated with CR (Brosnan et al. 2018; Brosnan et al. 2022).

The comparison of verbal and visuospatial tasks revealed that 2–9 Hz phase-locking values in the right hemisphere were significantly higher across all conditions in both tasks. Numerous studies confirm that verbal and visuospatial processes are lateralized to the left and right hemispheres, respectively (Nagel et al. 2013; Güntürkün et al. 2020; Williams et al. 2023), making the observed overall right hemisphere dominance distinct from expectations. As previously discussed, this right hemisphere dominance, which correlates with CRIq and is particularly evident in the parietal electrode pairs, may reflect the influence of NR on hemispheric engagement patterns, an underlying neural mechanism of CR.

Upon visualizing the 2–9 Hz phase-locking responses, it became evident that including all 51 participants in the grand average diminished coherence, likely due to variability in CR levels. Given that 2–9 Hz phase-locking was influenced by CR and mean CRIq scores differed significantly between Turkish and German samples, averaging across the entire group risked obscuring the asymmetric pattern. To address this, grand averages were generated separately for each sample to preserve the integrity of the findings. Considering the significant age difference across recording locations, it was essential to confirm that the increasing asymmetry in 2–9 Hz phase-locking values with higher CR levels was not influenced by age (Szaflarski et al. 2006). This potential confounding effect was controlled by including age as a factor in the exploratory repeated measures ANCOVA analyses for both tasks, leading to the conclusion that age did not meaningfully explain this difference. While cultural differences could also be considered, the study tasks were designed to minimize cultural influences, using common letters of the alphabet and universally recognized shapes as memory items. It is important to note that while the German sample did not exhibit the pronounced EEG lateralization patterns observed in the Turkish sample, they showed substantial 2–9 Hz phase-locking responses, particularly in the parietal electrodes of both tasks (as shown in Figures 3 and 5), with both hemispheres similarly engaged. Although their CRIq scores were significantly lower than those of the Turkish sample, this difference may stem from other factors, and thus, their brain response patterns warrant further investigation.

This study had several limitations, the first being the sensitivity of the CRIq as a measure of CR in young adults. To improve the accuracy of future assessments and better capture subtle variations among young adults, it may be beneficial to include additional proxy variables, such as verbal fluency and IQ scores, which are commonly used in the literature, to calculate a composite score. The second limitation can be described as the homogeneity of the sample, as most participants were university students with similar lifestyles. This similarity may have restricted lifestyle diversity and consequently reduced the variance in CR scores. A third limitation of the study is the significant difference in age and years of education between the Turkish and German samples, which also corresponded with differences in CRIq scores. Although these variables were statistically accounted for, future studies could benefit from matching samples more closely across demographic and CR-related variables to reduce potential confounding effects related to cultural or site-specific factors. More broadly, the cross-sectional design and focus on healthy young adults may limit the extent to which these findings can be generalized to models of CR typically studied in aging or clinical populations. However, we suggest that examining early interindividual variability in CR-related factors and their associations with neural efficiency may offer insight into how CR mechanisms are expressed earlier in life. The fourth limitation involves the Sternberg tasks used in this study. It was concluded that the difficulty levels of these tasks may not have generated sufficient task load to observe the effects of the neural efficiency mechanism adequately. Future studies could address this limitation by incorporating verbal and visuospatial Sternberg tasks with a four-item memory set, in addition to the one- and three-item memory sets.

The findings of this study are expected to contribute to the ongoing efforts to identify electrophysiological markers of CR. It could offer an objective and cost-effective method for accurately measuring CR in individuals. This advancement has the potential to greatly enhance research in this field by enabling the objective assessment of premorbid CR and monitoring changes that occur in the presence of pathology.

5 | Conclusion

The present study examined the relationship between CR and the lateralization of event-related 30–48 Hz power and phase-locking responses in the 30–35 Hz and 2–9 Hz ranges, recorded during verbal and visuospatial working memory tasks, through a set of preregistered hypotheses and exploratory analyses. Although the gamma band did not yield significant results to sufficiently support the hypotheses, 2–9 Hz phase-locking responses showed significant differences across task conditions, and the degree of lateralization in these responses was significantly related to CRIq scores, predominantly in the parietal electrode pairs. A comparison across tasks revealed right hemisphere dominance. While the results provide valuable insights, future research should address limitations such as the sensitivity of CR in detecting individual variation, homogeneity of the sample in terms of lifestyle, demographic differences across subsamples, and the need for sufficient task load. Overall, these findings are expected to contribute to identifying neural correlates of CR in healthy young individuals, offering potential

pathways for future interventions aimed at enhancing the efficiency and capacity of neural networks in relation to CR.

Author Contributions

Rümeysa Duygun: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review and editing. **Petunia Reinke:** conceptualization, data curation, investigation, methodology, writing – review and editing. **Sebastian Ocklenburg:** conceptualization, investigation, methodology, project administration, resources, supervision, writing – review and editing. **Bahar Güntekin:** conceptualization, investigation, methodology, project administration, resources, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The dataset used in this study is openly available on the Open Science Framework (OSF) at (https://osf.io/nxmp8/?view_only=466c8aea60b84c7ab68fa899d65b4c16), ensuring transparency and accessibility for further research.

Peer Review

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