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Research article

Differential posterior alpha-beta EEG responses during visual memory encoding in children born with low birth weight compared to children born with normal birth weight

Tuba Aktürk [a,b,*], Ömer Ceran [c], Simay Alptekin [d,e], Figen Eroğlu Ada [d], Ebru Yıldırım [a], Hakan Uzunlar [e], Pervin Çalışoğlu [e], Enver Atay [d], Bahar Güntekin [a,f]

[a] Neuroscience Research Center, Research Institute for Health Sciences and Technologies (SABITA), Istanbul Medipol University, Istanbul, Türkiye
[b] Section Brain Stimulation and Cognition, Department of Cognitive Neuroscience, Faculty of Psychology and Neuroscience, Maastricht University, Maastricht, Netherlands
[c] Department of Pediatrics, School of Medicine, Istanbul Medipol University, Istanbul, Türkiye
[d] Department of Psychology, Humanities and Social Sciences, Istanbul Medipol University, Istanbul, Türkiye
[e] Department of Neuroscience, Graduate School of Health Sciences, Istanbul Medipol University, Istanbul, Türkiye
[f] Department of Biophysics, School of Medicine, Istanbul Medipol University, Istanbul, Türkiye

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ABSTRACT

Children with low birth weight (LBW) often exhibit poorer social and cognitive abilities than their normal birth weight (NBW) peers. These difficulties may persist into young adulthood and are accompanied by altered resting-state electroneurophysiological patterns. Considering the results of these studies, understanding the neural substrates of birth weight becomes more important. Here, we used EEG event-related oscillations to unravel differences between children born with low and normal birth weights during a visual memory encoding to explore further the birth weight effect on the brain oscillatory responses of 6-to-7-year-old children. This study used an observational, cross-sectional, between-group design comparing LBW/preterm ($N = 15$) and NBW ($N = 17$) children. EEGs of the children were recorded during the encoding phase of visual memory task. Additionally, all children were administered two subtests from the WISC-IV IQ assessment: working memory (WM) and processing speed (PS). We employed time-frequency analysis to investigate event-related brain oscillatory pattern to distinguish differentiation between LBW/preterm and NBW. Consistent with previous studies, our behavioral results demonstrated that LBW/preterm group scored worse on WM and PS than their NBW peers. EEG results highlighted a topological differentiation between LBW/preterm and NBW groups, with greater posterior event-related alpha and especially beta responses in the LBW/preterm group during item encoding. Importantly, posterior beta oscillatory responses negatively correlated with the PS score in NBW children. Based on our results, the differences in cognitive abilities in the LBW/preterm group may be associated with posterior overactivity, characterized by increased event-related alpha and beta responses. This overactivity may reflect a greater reliance on perceptual processing strategies during memory encoding in early school-aged children born with low birth

* Corresponding author. Department of Cognitive Neuroscience, Faculty of Psychology and Neuroscience, Maastricht University, Maastricht, Netherlands.

E-mail address: t.akturk@maastrichtuniversity.nl (T. Aktürk).

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weight. This has potential implications for tailoring educational strategies to their unique neurodevelopmental profiles.

1. Introduction

The term "low birth weight" is used to describe infants who are born weighing less than 2500 g, as defined by the World Health Organization (WHO). Low birth weight often results from an infant being born prematurely, defined as a preterm birth occurring before 37 completed weeks of gestation. Based on the 2004 publication by the United Nations Children's Fund and the World Health Organization, 20.6 million live births were reported to have occurred with the complication of low birth weight [1]. As recorded by data from United Nations International Children's Emergency Fund (UNICEF), in 2020, approximately 19.8 million newborns, accounting for around 14.7 percent of all global births that year, were impacted by low birth weight [2].

Low birth weight is considered a risk factor for various conditions, including long-term neurological disabilities and impaired academic achievement [3]. Numerous studies have demonstrated that children born with low birth weight tend to show delayed development in several social and cognitive abilities (e.g., attention, working memory) compared to their peers with their normal birth weight [4–9]. Likewise, according to two separate meta-analyses, children born with low birth weight exhibit poorer academic performance and more attention problems [10] as well as deficits in executive functions such as inhibition, working memory, and cognitive flexibility [11], compared to normal birth weight peers, and these problems remained persistent during transition young adulthood. Narberhaus et al. (2008) also found that in adulthood, individuals born with low birth weight demonstrated weaker performance in various cognitive domains, such as verbal fluency, executive function, and memory, compared to those with a normal birth weight [12]. Hence, comprehending the impact of birth weight on cognitive functions is paramount, considering its substantial influence on child development, academic performance, and overall quality of life. Furthermore, investigating birth weight's effect on brain signals and its impact on children's cognition might add a new perspective to these pioneer behavioral studies. Understanding the neural substrates of birth weight becomes more important, especially considering the results of these studies, which indicate that birth weight can affect cognitive abilities, and this effect may even persist into adulthood.

Electroencephalography (EEG) stands out as a feasible neuroimaging method for children to measure functional brain signals during cognitive tasks. EEG signals contain oscillatory components that reflect rhythmic patterns of neural activity. When these oscillations are time-locked to specific events (e.g., stimulus onset), they are referred to as event-related oscillations (EROs). In the event-related oscillations literature, despite numerous studies revealing the correlation between event-related theta, alpha, and beta oscillations and various critical cognitive functions, such as visual perception [13], attention [14], and memory [13,15,16], there remains a lack of research on the influence of birth weight on these cognitive domains. Some studies have focused on the overall EEG pattern (not with the event-related approach) in low birth weight infants, revealing an immature and disorganized electrophysiological pattern [17–20]. A few studies also demonstrate the effect of birth weight on resting state activity via brain oscillations [21–23]. Miskovic et al. (2009) compared adults with low birth weight to those with normal birth weight, revealing greater power in the low EEG frequency bands (delta and theta) and reduced power in the high EEG frequency bands (alpha and beta) specifically in the frontal regions of low birth weight adults compared to their normal birth weight counterparts. Doesburg et al. (2013) demonstrated that resting state alpha oscillations are slower over the prefrontal, temporal, and parietal areas in children born very preterm, and this slowing is linked to reduced visual-perceptual abilities [21]. Schmidt et al. (2010) showed higher right frontal alpha activity during the resting state in adults with low birth weight compared to those with normal birth weight [23]. All these studies indicated that the EEG method and, more specifically, brain oscillations are able to detect the birth weight effect in spontaneous brain activity. An important point to highlight is that none of those studies employed event-related EEG methodology. The event-related approach is a crucial method in exploring the neural correlates associated with specific cognitive ability, as it enables the analysis of the EEG response precisely when the stimuli are presented during the task in the scope of the measured cognitive ability.

As outlined earlier, previous findings suggest that children with low birth weight exhibit poorer cognitive functions compared to their normal birth weight peers, along with altered electroneurophysiological patterns. Building on this, our study employs event-related EEG methodology to explore further differences in event-related brain oscillations between children born with low and normal birth weights during the visual memory encoding. We expected that children with low birth weight will demonstrate impaired performance in the visual memory tasks, potentially leading to observable differences in event-related alpha, beta, and theta oscillations, given the critical roles of these frequencies in memory, attention, and visual perception as the task requires these cognitive components. Our primary goal was to ascertain whether and how event-related theta, alpha, and beta oscillations during the encoding phase of visual memory task reflect birth weight at the early school age of the children. To this end, we analyzed event-related brain oscillatory signals recorded during the encoding phase of visual memory task, in terms of phase and power for theta, alpha, and beta frequency bands to unravel the neural correlates of birth weight effects in children aged 6 to 7 years.

2. Material and methods

2.1. Participants

Study design and sample. This study used an observational, cross-sectional, between-group design comparing children born with low birth weight and/or preterm with children born with normal birth weight. A total of 38 children were assessed for eligibility, including 19 children born prematurely and/or with low birth weight (LBW/preterm) and 19 children with normal birth weight (NBW).

Four children from the LBW/preterm group and two children from the NBW group were excluded. Specifically, one child from each group was excluded for being younger than 72 months of age, which is below the age range required for standardized administration of the WISC-IV used in the study. Three children (two LBW/preterm and one NBW) were excluded due to noisy EEG data. In addition, one child from the LBW/preterm group did not wish to continue participation, and the study session was therefore terminated. As a result, the final sample consisted of 15 children with LBW/preterm (5 girls) and 17 children with NBW (10 girls). The participant flow diagram of the study is presented in Fig. 1.

Group definitions and recruitment. The LBW/preterm group consisted of 15 children who were born with a birth weight below 2500 g and/or before 37 weeks of gestation. Among these children, 12 were both low birth weight and preterm, 2 were preterm but had birth weights above 2500 g (3000 g and 3340 g), and 1 child was born with low birth weight but at term (37 weeks). The NBW group included children born at term (38-42 weeks) with birth weights above 2500 g.

Children in the LBW/preterm group were recruited through referral by a pediatric specialist (E.A.) from the Department of Pediatrics, School of Medicine, Istanbul Medipol University, Istanbul, Türkiye. Children in the NBW group were recruited mainly through general study advertisements. EEG recordings and intelligence test assessments for both groups were conducted in the laboratory setting at the Neuroscience Research Center, Research Institute for Health Sciences and Technologies (SABITA), Istanbul Medipol

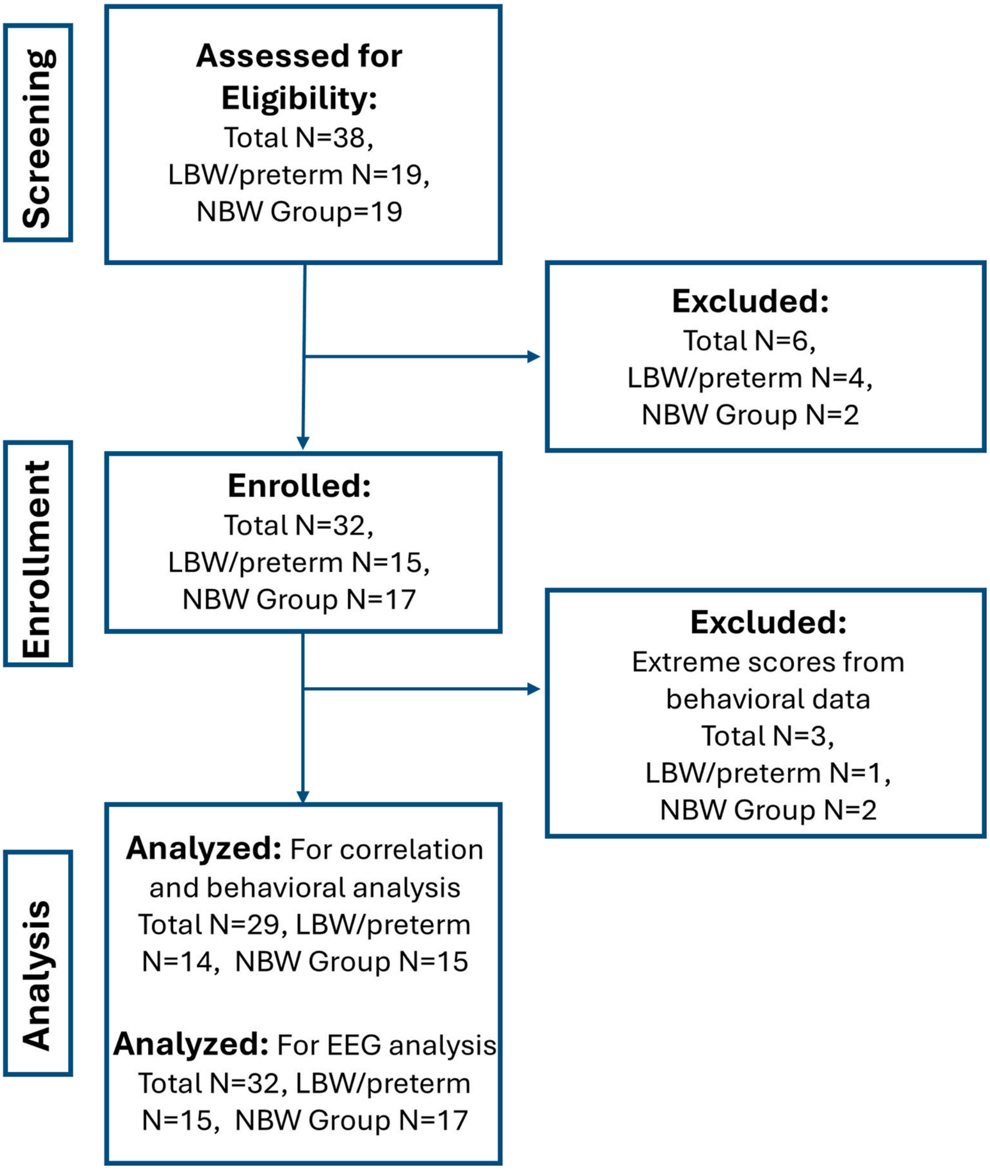

Fig. 1. Participant flow diagram. The diagram illustrates participant inclusion, exclusion, and final group allocation throughout the study.

University, Istanbul, Türkiye. Participants were recruited between November 2018 and August 2020.

Inclusion and exclusion criteria. Children were eligible for inclusion if they were between 72 and 95 months of age, had normal or corrected-to-normal vision, and, based on parent report, had no history of learning, speech, hearing, behavioral, or intellectual difficulties, neurodevelopmental disorders (e.g., autism spectrum disorder or attention-deficit/hyperactivity disorder), major neurological illness, epilepsy, genetic syndromes, or brain injury. In addition, children in the LBW/preterm group had to be born with a birth weight below 2500 g and/or before the 37th gestational week, whereas children in the NBW group had to be born at term (38-42 weeks) with a birth weight above 2500 g.

Participant characteristics. The education level of the children ranged from kindergarten to 3rd grade. All children were between 72 and 95 months of age. There were no significant group differences in sex, age, or education (all *ps* $> .05$). Demographics of the groups are given in Table 1.

Socio-demographic information was also collected via parent report. This included parental education, number of siblings, and monthly household income. Education and number of siblings information was provided by 30 out of 32 participants (15 LBW/preterm, 15 NBW) while income information was provided by 27 participants in total (13 LBW/preterm, 14 NBW).

Parental education was categorized into three levels based on total years of formal education: Low (≤8 years), Medium (9–12 years), and High (≥13 years). A chi-square test revealed no significant difference between the LBW/preterm and NBW groups in maternal education level ($\chi^2(2) = 1.42, p = .492$) or paternal education level ($\chi^2(2) = 0.92, p = .632$). Family income was reported on a 5-point scale representing total monthly household income, with no significant group difference observed ($\chi^2(3) = 6.26, p = .100$). The number of siblings did not differ significantly between groups either ($p = .630$).

Sample size. No a priori power analysis was conducted prior to data collection. The sample size was determined based on participant availability and feasibility within the study period, particularly given the specific population under investigation. The final sample consisted of 32 children, which is comparable to sample sizes in previous developmental EEG studies (e.g., Köster et al., 2017; Xie et al., 2018). To estimate the sensitivity of the present design, a post hoc power analysis was conducted in G*Power for the within-between interaction of a repeated-measures ANOVA ($N = 32$, $\alpha = .05$). The analysis showed that the current sample size provided .78 power to detect a medium effect ($f = .50$) and .99 power to detect a large effect ($f = .80$).

Ethical approval. Written informed consent was obtained from the parents or legal guardians of all children. As most of the children were not yet able to read or write, verbal assent was obtained from them. All children received a small gift (toy) and a participation certificate as compensation for participation. The study was approved by the Ethics Committee of Istanbul Medipol University on 15.08.2018 (No. E.34153).

2.2. *Intelligence test*

Turkish version of the Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV) was applied to the children [24,25]. WISC-IV, which is thought to measure 6 to 16 aged-years-old children's intellectual abilities, typically evaluates children in 4 different areas (Verbal Comprehension [VC], Perceptual Reasoning [PR], Working Memory [WM], and Processing Speed [PS]) along with a general cognitive evaluation [26]. Due to the long experimental session required for EEG recordings, only two subscales of the WISC-IV, WM and PS, were administered in order to minimize fatigue and maintain motivation. These subscales were selected because they assess cognitive functions directly relevant to the memory encoding processes and closely aligns with the study's aims and assumptions regarding potential differences in memory-related cognitive processing. The assessment was conducted individually by a trained developmental psychologist who was blind to participants' group membership in a quiet, controlled, and child-friendly environment. The administration followed the standardized procedures outlined in the test manual. The subtests of the WM and PS were administered in their original order: Digit Span (WM), Coding (PS), Letter–Number Sequencing (WM), and Symbol Search (PS). The administration of these four subtests took approximately 15 min on average. The scores for these subscales among the groups are presented in Table 2.

2.3. *Task procedure*

The visual memory task was designed and presented using E-Prime software [27] (Psychology Software Tools Inc., Pittsburgh, PA).

Table 1
Demographics of the groups.

	NBW (N = 17) *M* ± *SD*	LBW/preterm (N = 15) *M* ± *SD*	*p*
Age (months)	83.24 ± 7.57	85.47 ± 8.80	.483[a]
Gender (F/M)	10/7	5/10	.149[c]
Education (year)	1.59 ± .51	1.67 ± 1.05	.823[a]
Birth Weight (kg)	3.69 ± .57	2.02 ± 0.65	.001[b]
Birth Week	39.25 ± 0.96	32.5 ± 3.25	.001[b]

M: Mean, SD: Standard Deviation, M: Male, F: Female, kg: Kilogram.
[a] Mann-Whitney U.
[b] *t*-test.
[c] Chi-square.

In this task, participants were presented with a series of object images during the encoding phase. This was followed by a retrieval phase, in which free recall was assessed. EEG was recorded only during the encoding phase (Fig. 2A).

Fifteen black and white pictures that could be easily named by children in the studied age range were selected from the Benton Naming Test (BNT) [28] as the stimuli for the visual memory task. After completion of the experiment, the pictures were shown again, and the children were asked to name the 15 items presented during the task. This procedure was used to confirm that the children were familiar with the item names.

The 15 selected items were presented with five repetitions, resulting in a total of 75 stimulus presentations in the visual memory task (Fig. 2B). At the beginning of the task, the full set of 15 items was presented, and in each subsequent repetition, the order of the items was rearranged. However, this sequence was kept identical across participants (i.e., pseudo-randomized). Children were instructed to try to memorize the items presented on the screen for later recall. Following the encoding phase, children were asked to recall the items they remembered, and visual memory free-recall scores were calculated as the number of correctly recalled items out of 15.

Before the actual task, a brief practice session was conducted to familiarize the children with the procedure and to confirm that they understood the instructions. The practice session consisted of three unique stimuli, different from those used in the main task, presented in pseudorandom order with two repetitions.

Stimulus presentation duration was fixed at 1 s, and inter-stimulus intervals varied randomly between 3 and 5 s (Fig. 2B). Visual stimuli were presented in full-screen mode on a 21-inch monitor (47.5 × 26.8 cm) with a refresh rate of 60 Hz. The monitor was positioned at a viewing distance of 70 cm, resulting in a visual angle of approximately 15° horizontally and 12.5° vertically for the stimuli.

2.4. EEG recording

EEG was recorded using a BrainAmp MR plus (Brain Product GmbH, Germany) system with a recording bandwidth of 0.01-250 Hz and at a 500 Hz sampling rate. The Brain Vision Recording software (Brain Product GmbH, Germany) was used to record the EEG. The gold (Au) cup electrodes, which were placed according to the international 10-20 system, were used for the EEG recording; and accordingly, EEG was recorded from 18 channels (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, P7, P8, T7, T8, TP7, TP8, O1, Oz, O2). Two connected electrodes (A1+A2) were positioned on the left and right earlobes as reference electrodes. The ground electrode was placed behind the right earlobe. Additionally, electrooculogram (EOG) was recorded using two electrodes placed on the medial upper and lateral orbital areas of the right eye. Electrode impedances were kept below approximately 10 kOhm. The children were seated in a soundproof and dimly illuminated Faraday cage throughout the EEG recording session. One of their parents was also seated behind the children, remaining silent and out of the children's line of sight.

2.5. EEG analysis

2.5.1. EEG data preprocessing

Before event-related time-frequency analyses, EEG data were preprocessed with Brain Vision Analyzer (Brain Product GmbH, Germany) software. As an initial step, the data were filtered between 0.01 and 60 Hz using Infinite Impulse Response (IIR) filters with a zero-phase shift Butterworth filter, and a 50 Hz notch filter was applied. Next, independent component analysis (ICA) was performed on the continuous data to eliminate components associated with eye movement artifacts. The restricted infomax algorithm was employed for the computation of ICA. All recorded EEG and two EOG channels were selected for the ICA decomposition. The number of ICA components calculated was the same as the number of selected channels. The ICA procedure was conducted semi-automatically. Each component underwent a thorough assessment, considering factors such as their topographical distribution, voltage ranges, and the enhancement of data quality achieved through their extraction. Components associated with eye movements were subsequently eliminated. Following the removal of these identified components (which were set to zero), the remaining components were recombined using inverse ICA. The maximum number of components removed for a given subject did not exceed two. Following ICA, data was divided into 2-s length segments considering stimulation onset (1 s before and 1 s after the stimulation). Because some items were later remembered whereas others were forgotten, EEG segments were created separately for remembered and forgotten items to compare these conditions and examine the subsequent memory effect. Remembered items were considered to reflect successful

Table 2
The scores of two subscales of the WISC-IV and the scores of the visual memory across the groups.

	NBW *M* ± *SD*	LBW/preterm *M* ± *SD*	*p*
VM	8.18 ± 2.16	7.73 ± 1.16	.729[a]
WISC-IV WM	100.88 ± 8.07	92.36 ± 9.91	**.015**[b]
WISC-IV PS	115.56 ± 11.55	106.53 ± 10.25	**.029**[b]

M: Mean, SD: Standard Deviation, M: Male, F: Female, VM: Visual Memory Scores, WISC-IV PS: The Wechsler Intelligence Scale for Children-IV Processing Speed Scores, WISC-IV WM: The Wechsler Intelligence Scale for Children-IV Working Memory Scores.

[a] Mann-Whitney U.

[b] *t*-test.

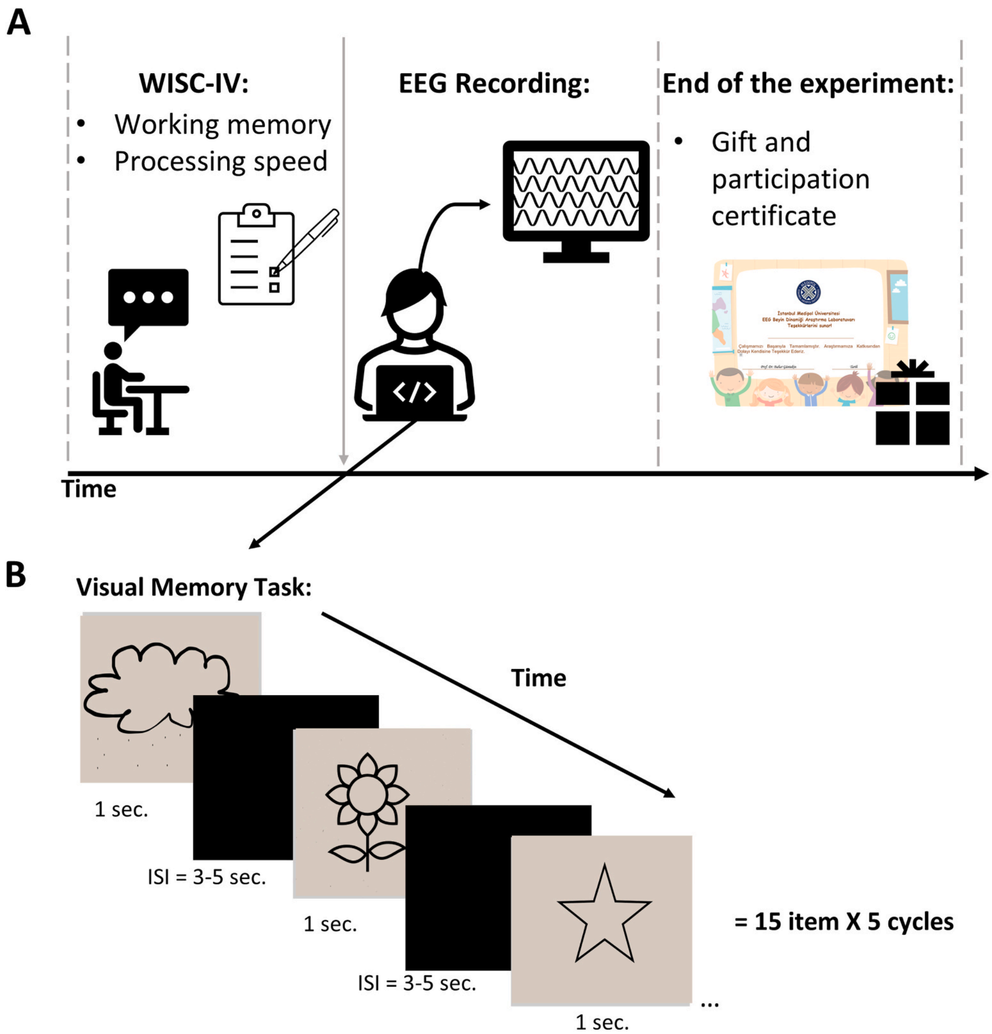

Fig. 2. Design of the study and task. A) The representation of the experimental design and B) the task design of the visual memory task applied during the EEG recording. * The given schematic images in Fig. 2B are not actual exemplars from the Boston naming test set; instead drawn by TA as an example. WISC-IV: Wechsler Intelligence Scale for Children-Fourth Edition, ISI: Inter-stimulus interval, Sec.: Second.

encoding, whereas forgotten items were considered to reflect encoding failure. After that, manual artifact rejection was applied to the segmented data to remove remaining artifacts, such as movement and muscle artifacts. The number of retained segments was balanced as much as possible across the groups (LBW/preterm and NBW) and conditions (Remembered and Forgotten) by randomly eliminating the segments. The average number of retained epochs per condition was as follows: in the LBW/preterm group, 15.5 (±4.8) remembered and 15.1 (±6.6) forgotten trials; and in the NBW group, 14.3 (±5.3) remembered and 15.1 (±6.3) forgotten trials were retained.

Although previous research has emphasized the role of fronto-central regions in memory processes [e.g., 29,30], posterior regions, including temporal, parietal, and occipital areas, are also relevant for visual perception and attention [31,32]. Therefore, twelve electrodes were selected to represent anterior and posterior regions, and EEG analyses were conducted across three regional groupings in both hemispheres: fronto-central (F3, F4, C3, C4), temporo-parietal (T7, T8, TP7, TP8), and parieto-occipital (P3, P4, O1, O2).

2.5.2. The event-related power analysis

Event-related power analysis quantifies changes in power over time within a selected frequency range and expresses these changes in decibels (dB). To calculate event-related power, a continuous wavelet transform (WT) was applied to the preprocessed data using a Gabor-normalized complex Morlet wavelet with a width of 4 cycles over the 4-24 Hz frequency range. For decibel normalization, baseline correction was performed using the pre-stimulus interval from −500 to −300 ms in order to reduce non-task-related activity. The frequency range of 4-24 Hz was divided into 60 bins by setting the frequency steps parameter to 60 and applying a logarithmic scale. WT was then computed for each frequency bin. The transform was applied to preprocessed single trials and subsequently averaged to obtain total power (evoked + induced power), reflecting both phase-locked and non-phase-locked responses [33,34].

For statistical analyses, point-mean normalized power values were extracted from predefined time-frequency windows. Specifically, values within the selected windows (theta: 0-300 ms, 4-7 Hz; alpha: 0-200 ms, 8-13 Hz; beta: 0-150 ms, 15-24 Hz) were summed and divided by the total number of data points within each window. These normalized values were then used in the statistical analyses for each participant.

2.5.3. The event-related phase-locking analysis

Phase-locking analysis, also referred to as inter-trial coherence, measures the consistency of phase angles across trials in event-related recordings. Unlike power analysis, phase-locking analysis does not directly assess signal magnitude [34–37]. Phase-locking values range from 0 to 1, with values closer to 1 indicating greater phase consistency across trials and values closer to 0 indicating lower phase consistency.

For the phase-locking analysis, the same wavelet method, parameters, and procedures described for the event-related power analysis were applied (see Section 2.5.2), except that phase values rather than power values were extracted.

2.5.4. The event-related connectivity analysis

The event-related connectivity analyses were not conducted to test one of the a priori hypotheses of the study. Rather, these analyses were performed as exploratory follow-up analyses in response to the findings obtained from the event-related power and phase analyses, which were used to test the study's main hypotheses. As reported in the Results section, the LBW/preterm group showed increased posterior alpha-beta EEG responses. To further examine this finding, we investigated whether the increased posterior EEG activity in the LBW/preterm group might be associated with altered anterior-posterior connectivity.

For the event-related connectivity analyses, Current Source Density (CSD) transformation was applied to the preprocessed data prior to WT in order to reduce reference-related effects and minimize volume conduction influences [38]. The following CSD parameters were used: Spline order: 4, Maximum degree of Legendre polynomials: 10, and the default lambda value of 1E-05. After the CSD transformation, WT was applied for both power-based and phase-based event-related connectivity analyses, as detailed below.

In the present study, time-frequency domain analyses were used to investigate event-related connectivity based on both power and phase. The same wavelet kernels used in the event-related power and phase analyses were also used for the connectivity analyses.

Power-based event-related connectivity analysis was used to assess the degree of similarity between electrode pairs across trials. In this approach, stronger similarity between two channels is reflected by values approaching 1, whereas weaker similarity is reflected by values approaching 0. For power-based connectivity analysis, the WT output was set to “Wavelet Coefficients - Complex Values [μV],” and magnitude-squared coherence [39] was calculated between the selected electrode pairs (F3-P3, F3-O1, F4-P4, F4-O2, C3-P3, C3-O1, C4-P4, C4-O2).

Phase-based event-related connectivity was quantified using the Phase Locking Value (PLV), as introduced by Lachaux et al. (1999). PLV is a time-frequency domain measure of connectivity that reflects the stability of phase differences between two channels across trials [40]. A consistent phase difference over time, indicating stronger synchronization, results in a PLV value approaching 1, whereas an inconsistent phase difference indicates weaker synchronization, with PLV values approaching 0. For PLV analysis, the WT output was set to the complex values of wavelet phase, after which normalized correlation measures were applied and the results were rectified. As in the power-based connectivity analysis, connectivity was calculated for the same eight anterior-posterior electrode pairs.

To obtain connectivity values, the same procedure was applied here as in the event-related analyses; namely, point-mean normalized values within the specified time-frequency windows were used in the statistical analyses.

2.6. Statistical analysis

Statistical analyses were performed with Jamovi software (The jamovi project, 2024) [41].

For behavioral and demographic data, group comparisons were conducted using either independent-samples t-tests or Mann-Whitney U tests, depending on whether the assumptions for parametric testing were met. Independent-samples t-tests were used for WISC-IV Processing Speed scores, visual memory scores, birth weight, and week, whereas Mann-Whitney U tests were used for age, education, and WISC-IV Working Memory scores. Group differences in sex distribution were assessed using the chi-square test.

In the statistical analysis of the event-related EEG data, in order to see the topographic distribution (location and hemisphere) among groups (LBW/preterm and NBW) for memory conditions (remembered and forgotten), these were included in the analysis design as factors.

For both the event-related power and phase analyses, separate mixed-design repeated-measures ANOVAs were performed for each frequency band (theta, alpha, and beta) using the same model. A $2 \times 2 \times 3 \times 2$ mixed-design ANOVA was conducted, with group (LBW/preterm, NBW) as the between-subjects factor and memory condition (remembered, forgotten), location (fronto-central: F3, F4, C3, C4; temporo-parietal: T7, T8, TP7, TP8; parieto-occipital: P3, P4, O1, O2), and hemisphere (left, right) as within-subject factors.

For the connectivity analyses, which were conducted as exploratory follow-up analyses to the event-related EEG findings, separate mixed-design repeated-measures ANOVAs were performed for the alpha and beta frequency bands. In this case, a $2 \times 2 \times 4 \times 2$ mixed-design ANOVA was used, with group (LBW/preterm, NBW) as the between-subjects factor and memory condition (remembered, forgotten), electrode pair (frontal-parietal, frontal-occipital, central-parietal, central-occipital), and hemisphere (left, right) as within-subject factors.

To examine associations between EEG measures and behavioral performance, two-tailed Pearson correlation analyses were conducted separately within each group. For these analyses, EEG measures showing significant group differences in the ANOVA results were selected. Specifically, event-related power and phase values from the relevant regional clusters (fronto-central, temporo-parietal, and parieto-occipital) in the alpha and beta bands were used. WISC-IV Processing Speed and Working Memory scores were included as behavioral variables, as these measures differed significantly between groups.

The significance level was set at $p < .05$ for all statistical analyses. For the ANOVAs, Greenhouse-Geisser-corrected p-values were reported where appropriate. Uncorrected p-values were reported for post hoc comparisons.

Outliers in the behavioral data were identified using the interquartile range (IQR) method. Extreme outliers, defined as values below Q1 - 3 × IQR or above Q3 + 3 × IQR, were excluded. Outliers were assessed separately for each behavioral measure, and any excluded values were removed only from the corresponding analysis. The number of excluded outliers, when applicable, was reported in the Results section.

3. Results

3.1. Behavioral results

Scores of LBW/preterm and NBW groups were compared using either a *t*-test or Mann-Whitney *U* test after checking the test assumptions to assess potential differences across the groups in terms of their performance on applied tests, including the WISC-IV Working Memory (WM), WISC-IV Processing Speed (PS), and visual memory (VM) assessments. Here, three outlier subjects were removed from the dataset (for WISC-IV WM: 2 subjects, 1 from each group; for WISC-IV PS: 1 subject from NBW group). The scores of two subscales of the WISC-IV (WM and PS) and the scores of the visual memory (remembered items during the visual memory task) for each group were presented in Table 2.

The mean scores of VM were 8.19 ($SD = 2.23$) and 7.73 ($SD = 1.16$) for NBW and LBW/preterm groups, respectively. While there was no significant difference between groups for the score of the VM, $U = 118$, $p = .729$, there are significant differences for the WISC-IV PS, $t(29) = 2.30$, $p = .029$, and WISC-IV WM, $t(28) = 2.60$, $p = .015$, test scores. Accordingly, NBW group exhibited higher WISC-IV WM scores ($M = 100.88$, $SD = 8.07$) compared to LBW/preterm ($M = 92.36$, $SD = 9.91$) (Table 2). Similarly, the mean score for WISC-IV PS was higher among NBW group ($M = 115.56$, $SD = 11.55$) than LBW/preterm group ($M = 106.53$, $SD = 10.25$) (Table 2).

3.2. Results of the event-related power analysis

3 (Location: Fronto-Central, Temporo-Parietal, and Parieto-Occipital) X 2 (Hemisphere: Right, Left) X 2 (Memory condition: Remembered, Forgotten) X 2 (group: LBW/preterm, NBW) mixed design repeated measures ANOVA results were reported in the following sub-sections for the event-related theta, alpha, and beta power analysis, respectively.

3.2.1. Theta power

There were no significant main effects of any factor (For the location, $F(1.92, 57.59) = 2.029$, $MSe = 3.221$, $p = .142$, $\eta p2 = .063$, for the hemisphere, $F(1.00, 30.00) = 1.649$, $MSe = 0.842$, $p = .209$, $\eta p2 = .052$, for the memory condition, $F(1.00, 30.00) = 0.177$, $MSe = 4.103$, $p = .677$, $\eta p2 = .006$, and for the group, $F(1.00, 30.00) = 1.02$, $MSe = 5.21$, $p = .321$, $\eta p2 = .033$) on event-related theta power.

There were significant Condition*Hemisphere*Group interactions, $F(1.00, 30.00) = 10.317$, $MSe = 0.665$, $p = .003$, $\eta p2 = .256$. We followed up this 3-way interaction by performing separate two-way repeated measure ANOVAs for the two groups (LBW/preterm & NBW) to see whether the condition*hemisphere effect is group specific. Results showed that the condition*hemisphere interaction was significant for only NBW group (for NBW: $F(1.00, 16.00) = 10.0$, $MSe = 0.62$, $p = .006$, $\eta p2 = .38$; for LBW/preterm: $F(1.00, 14.00) = 2.19$, $MSe = 0.72$, $p = .16$, $\eta p2 = .13$). Accordingly, in NBW, pairwise comparisons showed that children born with NBW had higher theta power in the right hemisphere than in the left hemisphere, $t(16) = 2.97$, $p = .009$, for the forgotten memory condition while there was no such a hemispheric difference for the remembered condition, $t(16) = -1.27$, $p = .22$, in the theta power.

In addition, to provide more direct group comparisons of the same 3-way interaction, we conducted further 2 (Group: LBW/preterm vs. NBW) X 2 (Condition: Remembered vs. Forgotten) ANOVAs separately for each hemisphere. These additional follow-up analyses did not reveal significant main or interaction effects for group and condition, neither in the right (Group: $F(1,30) = 0.52$, $p = .476$, $\eta p^2 = .017$; condition*group: $F(1,30) = 1.40$, $p = .246$, $\eta p^2 = .045$) nor in the left hemisphere (Group: $F(1,30) = 1.55$, $p = .222$, $\eta p^2 = .049$; condition*group: $F(1,30) = 1.50$, $p = .231$, $\eta p^2 = .048$).

3.2.2. Alpha power

There were no significant main effects of location, $F(1.72, 51.65) = 0.253$, $MSe = 3.824$, $p = .74$, $\eta p2 = .008$, memory condition, $F(1.00, 30.00) = 0.358$, $MSe = 2.080$, $p = .55$, $\eta p2 = .012$, and group, $F(1.00, 30.00) = 0.398$, $MSe = 6.11$, $p = .53$, $\eta p2 < .013$, on event-related alpha power. The hemisphere main effect was significant for alpha power, $F(1.00, 30.00) = 7.918$, $MSe = 1.626$, $p = .009$, $\eta p2 = .209$. Pairwise comparisons showed that the right hemisphere alpha power was higher than the left hemisphere, $t(30) = 2.81$, $p = .009$.

The condition*location interaction was significant, $F(1.74, 52.11) = 5.324$, $MSe = 1.224$, $p = .011$, $\eta p2 = .151$. We followed up this 2-way interaction by performing separate ANOVAs for the three locations (Fronto-Central, Temporo-Parietal, and Parieto-Occipital) to see whether the memory conditions effect is location specific. Results showed that memory conditions main effect is significant only for the PO location, $F(1.00, 31.00) = 6.83$, $MSe = 0.626$, $p = .014$, $\eta p2 = .181$. Accordingly, PO alpha power in response to remembered items was lower compared to forgotten items, $t(31) = -2.61$, $p = .014$, while there was no such memory condition differentiation in other locations (in FC, $t(31) = -0.022$, $p = .982$; in TP, $t(31) = 1.57$, $p = .128$) (Fig. 3B).

Although group*location interaction was not statistically significant, $F(1.72, 51.65) = 2.850$, $MSe = 3.824$, $p = .074$, $\eta p2 = .087$, there was a trend that indicates the NBW group had higher alpha power in more anterior locations (FC and TP) whereas LBW/preterm group had higher alpha power in posterior locations (PO) (Fig. 3A).

3.2.3. Beta power

There were no significant main effects of group, $F(1.00, 30.00) = 1.31$, $MSe = 5.19$, $p = .262$, $\eta p2 = .042$, memory condition, $F(1.00, 30.00) = 0.384$, $MSe = 1.537$, $p = .540$, $\eta p2 = .013$, and hemisphere, $F(1.00, 30.00) = 4.094$, $MSe = 1.064$, $p = .052$, $\eta p2 = .120$,

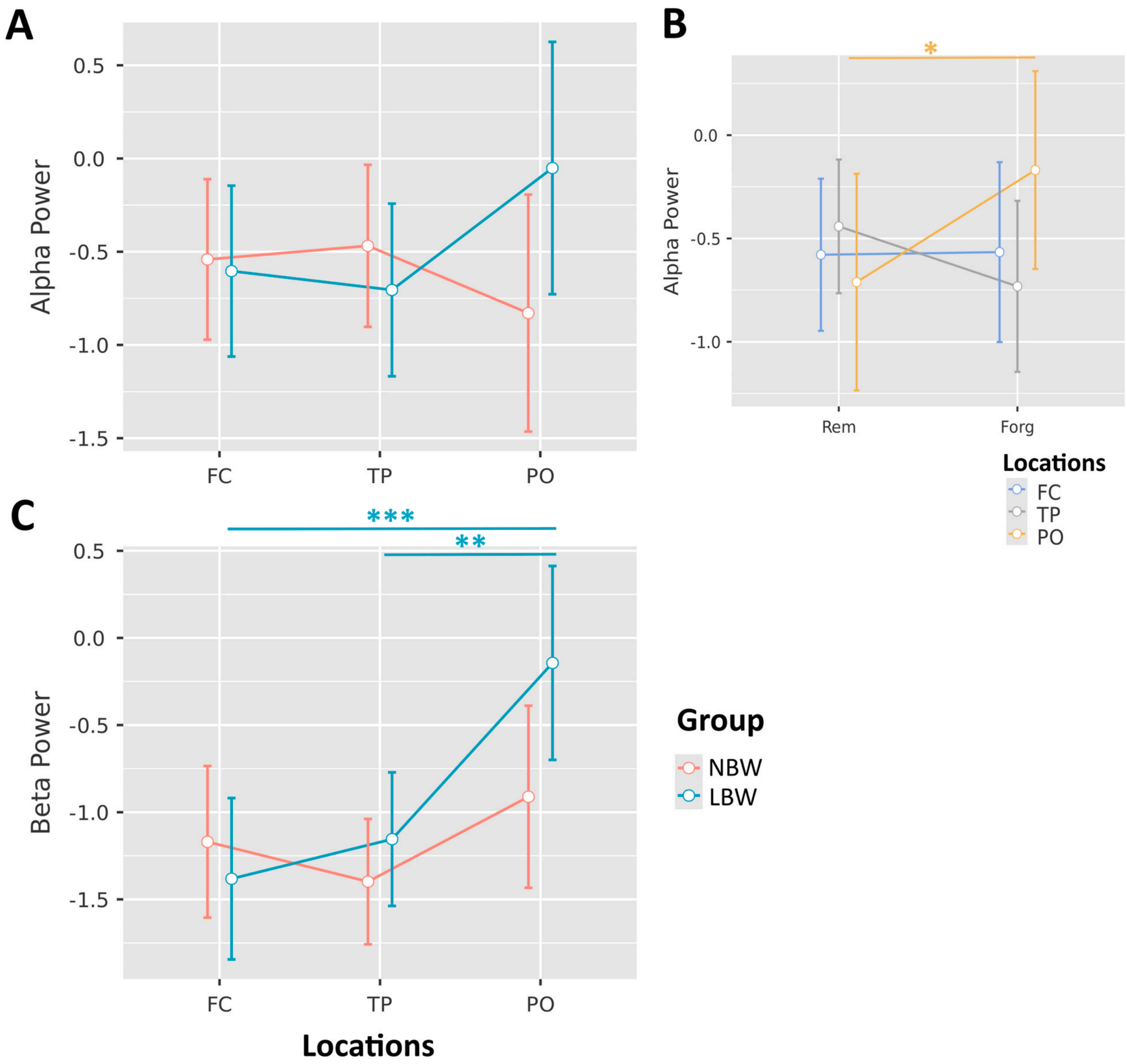

Fig. 3. Event-related alpha and beta power across the groups. A) The plots of the Location * Group interaction for event-related alpha power. Although group*location interaction was not statistically significant ($p = .074$) there was a trend that indicates NBW group had higher alpha power in more anterior locations (FC and TP) whereas LBW/preterm group had higher alpha power in posterior locations (PO). **B)** The plots of the Location * Condition interaction for event-related alpha power. The condition*location interaction was significant ($p = .011$). PO alpha power in response to remembered items was lower compared to forgotten items ($p = 0.014$), while there was no such memory condition differentiation in other locations (in FC, $p = 0.982$; in TP, $p = 0.128$). **C)** The plots of the Location * Group interaction for event-related beta power. The location main effect is significant only for the LBW/preterm group ($p < .001$). The LBW/preterm group had higher beta power values in PO than in FC and TP locations (FC vs PO, $p = .001$; TP vs PO, $p = .003$) while in NBW, there was not any significant topological differentiation (For the location, $p = .251$). NBW: normal birth weight, LBW: low birth weight, FC: Fronto-central, TP: Temporo-parietal, PO: Parieto-Occipital. Asterisks indicate statistical significance (*: $p \leq .05$, **: $p \leq .01$, ***: $p \leq .001$).

for event-related beta power.

The location main effect was statistically significant, $F(1.77, 52.98) = 10.698$, $MSe = 2.524$, $p < .001$, ηp2 = .264. However, this significant location effect was dependent on the other factors, since the condition*location*hemisphere*group interaction was significant, $F(1.85, 55.39) = 3.971$, $MSe = 0.495$, $p = .027$, ηp2 = .117. Firstly, we followed up this 4-way interaction by performing separate 3-way ANOVAs for each memory condition (Remembered and Forgotten). The results of the 3-way ANOVAs showed that the location*hemisphere*group interaction was significant only for the remembered memory condition, $F(1.68, 50.35) = 4.102$, $MSe =$

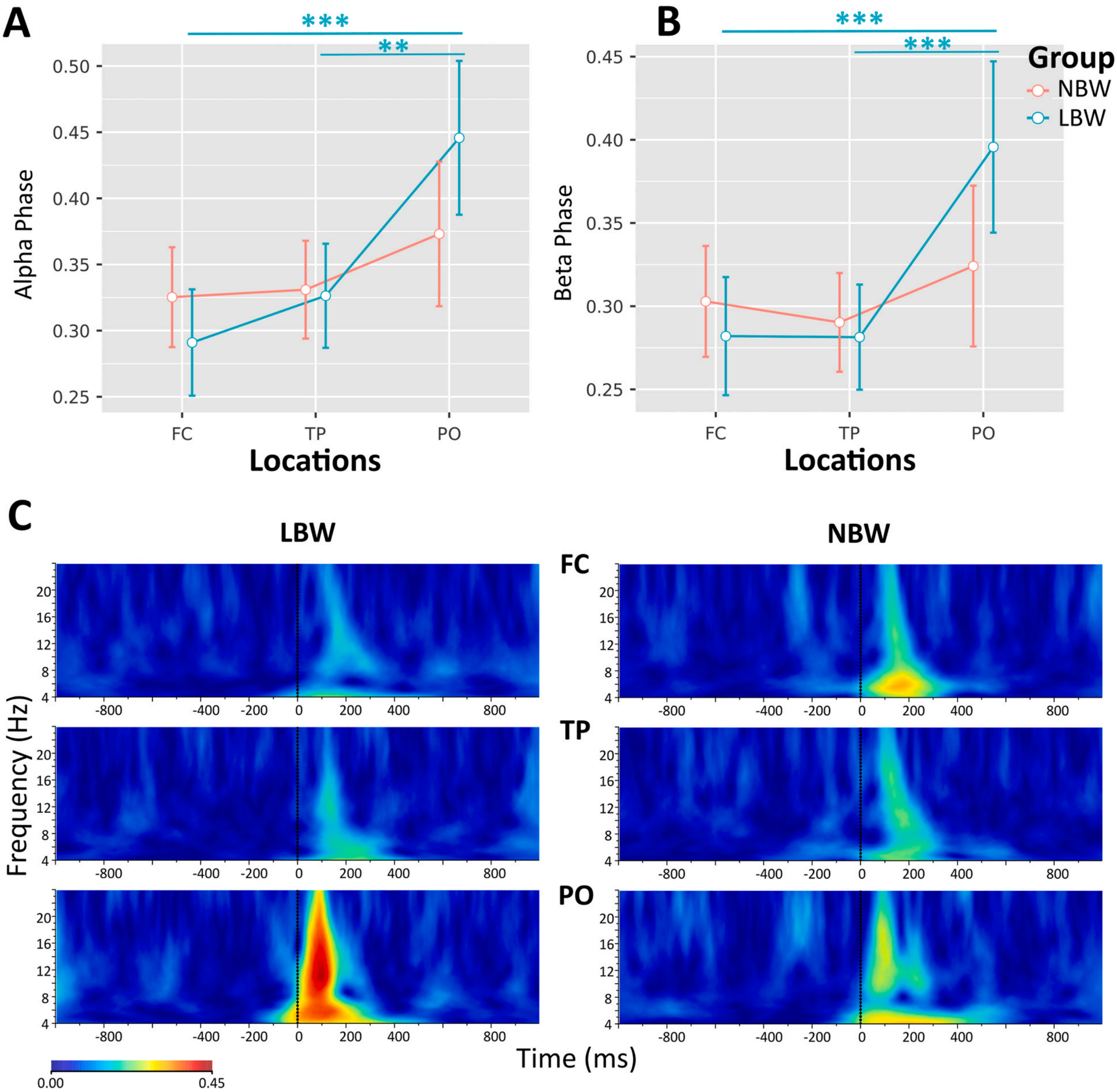

Fig. 4. Event-related alpha and beta responses across the groups. A) The plots of the Location * Group interaction for event-related alpha phase. The location*group interaction was significant ($p = .017$) for event-related alpha phase. The LBW/preterm group had higher alpha phase values in PO than in FC and TP locations (FC vs PO, $p = .001$; TP vs PO, $p = .009$) while there was no such location main effect in NBW ($p = .055$) **B)** The plots of the Location * Group interaction for event-related beta phase. The location*group interaction was significant ($p = .006$) for event-related beta phase. The LBW/preterm group had higher beta phase values in PO than in FC and TP locations (FC vs PO, $p < .001$; TP vs PO, $p < .001$) while there was no such location main effect in NBW ($p = .208$). **C)** The grand average figures of event-related phase analysis (4-24 Hz) in the time-frequency domain during the encoding phase of visual memory task. The fronto-central area (upper), temporo-parietal (middle), and parieto-occipital (bottom) areas were presented for both groups in the figures. The X-axis represents time, and the Y-axis represents frequency; the point at which the stimulus arrives is marked as a zero point on the X-axis. NBW: normal birth weight, LBW: low birth weight, FC: Fronto-central, TP: Temporo-parietal, PO: Parieto-Occipital. Asterisks indicate statistical significance (*: $p \leq .05$, **: $p \leq .01$, ***: $p \leq .001$).

0.528, $p = .028$, ηp2 = .120. Here, no other significant interaction or main effect included the group factor. Therefore, we followed up this 3-way interaction found in remembered memory condition by performing separate ANOVAs for the two groups (LBW/preterm and NBW) to see whether the topological differentiation (location and hemisphere effects) is group specific. The results showed that the location main effect is significant only for the LBW/preterm group, $F(1.88, 26.34) = 11.456$, $MSe = 1.209$, $p < .001$, ηp2 = .450. Accordingly, LBW/preterm group had higher beta power values in PO than in FC and TP locations (FC vs PO, $t(14) = -4.08$, $p = .001$; TP vs PO, $t(14) = -3.65$, $p = .003$) while in NBW, there was not any significant topological differentiation (For the location, $F(1.65, 24.73) = 1.45$, $MSe = 1.400$, $p = .251$, ηp2 = .088, for the hemisphere, $F(1.00, 15.00) = 3.81$, $MSe = 0.439$, $p = .070$, ηp2 = .202) (Fig. 3C).

In addition, to provide more direct group comparisons of the same 3-way interaction, in the remembered condition, we conducted further 2 (Group: LBW/preterm vs. NBW) X 3 (Location: FC, TP, PO) ANOVAs separately for each hemisphere. These additional analyses revealed that the group*location interaction was significant only in the right hemisphere, $F(1.90, 56.96) = 3.94$, $p = .027$, $\eta p^2 = .116$, while no such interaction emerged in the left hemisphere, $F(1.99, 59.72) = 2.11$, $p = .131$, $\eta p^2 = .066$. Pairwise comparisons in the right hemisphere further confirmed that children in the LBW/preterm group exhibited significantly higher beta power in PO compared to FC location (FC vs PO, $t(14) = -2.65$, $p = .013$). No significant topographical differences were observed within the NBW group. Importantly, direct pairwise comparisons between-group comparisons at each location (FC: $t(30) = 1.35$, $p = .186$; TP: $t(30) = 1.80$, $p = .082$; PO: $t(30) = 1.10$, $p = .278$) did not reveal significant differences, suggesting that the observed effects stem from distinct within-group topographical patterns, particularly the higher posterior beta in the LBW/preterm group.

3.3. Results of the event-related phase-locking analysis

3 (Location: Fronto-Central, Temporo-Parietal, and Parieto-Occipital) X 2 (Hemisphere: Right, Left) X 2 (Memory condition: Remembered, Forgotten) X 2 (group: LBW/preterm, NBW) mixed design repeated measures ANOVA results were reported in the following sub-sections for the event-related theta, alpha and beta phase-locking analysis, respectively.

3.3.1. Theta phase

The main effect of the group, $F(1.00, 30.00) = 0.01$, $MSe = 0.05$, $p = .92$, ηp2 < .001, and memory condition, $F(1.00, 30.00) = 0.006$, $MSe = 0.001$, $p = .42$, ηp2 = .02, were not statistically significant for theta phase-locking. On the other hand, there were statistically significant main effects of location, $F(1.82, 54.75) = 15.31$, $MSe = 0.023$, $p < .001$, ηp2 = .34, and hemisphere, $F(1.00, 30.00) = 16.24$, $MSe = 0.008$, $p < .001$, ηp2 = .35. These significant main effects were dependent on each other, since the location*hemisphere interaction was significant, $F(1.77, 53.19) = 4.27$, $MSe = 0.004$, $p = .023$, ηp2 = .12. As there were no indications of any birth weight or memory condition effects interaction with the location and hemisphere, and our primary focus was on differences between the LBW/preterm and NBW groups, we did not explore these interaction results further.

3.3.2. Alpha phase

The main effect of the group, $F(1.00, 30.00) = 0.224$, $MSe = 0.054$, $p = .640$, ηp2 = .007, and memory condition, $F(1.00, 30.00) = 1.984$, $MSe = 0.012$, $p = .169$, ηp2 = .062, were not statistically significant for alpha phase-locking. On the other hand, the hemisphere main effect was statistically significant, $F(1.00, 30.00) = 7.762$, $MSe = 0.018$, $p = .009$, ηp2 = .206. Accordingly, the right hemisphere alpha phase was higher than the left hemisphere, $t(30) = 2.79$, $p = .009$.

The location main effect was also statistically significant, $F(1.60, 48.09) = 18.297$, $MSe = 0.025$, $p < .001$, ηp2 = .379. However, this significant location effect was dependent on the group factor, since the location*group interaction was significant, $F(1.60, 48.09) = 4.868$, $MSe = 0.025$, $p = .017$, ηp2 = .140. We followed up this 2-way interaction by performing separate ANOVAs for the two groups (LBW/preterm and NBW) to see whether the location effect is group specific. Results showed that the location main effect is significant only for the LBW/preterm group, $F(1.55, 21.71) = 14.4$, $MSe = 0.009$, $p < .001$, ηp2 = .507. Accordingly, LBW/preterm group had higher alpha phase values in PO than in FC and TP locations (FC vs PO, $t(14) = -4.57$, $p = .001$; TP vs PO, $t(14) = -3.49$, $p = .009$) while there was no such location main effect in NBW, $F(1.66, 26.63) = 3.44$, $MSe = 0.004$, $p = .055$, ηp2 = .177 (Fig. 4A and . C).

In addition, to provide more direct group comparisons regarding the observed location*group interaction, we examined between-group differences at each location. These follow-up pairwise comparisons did not reveal any statistically significant group differences at individual locations (FC: $t(30) = 1.27$, $p = .214$; TP: $t(30) = -0.03$, $p = .969$; PO: $t(30) = -1.86$, $p = .073$), although there was a trend toward higher alpha phase values in the LBW/preterm group at the PO location. These findings suggest that the observed topographical differences in alpha phase were primarily driven by within-group variation rather than direct group effects at specific electrode location.

3.3.3. Beta phase

The main effect of the group, $F(1.00, 30.00) = 0.403$, $MSe = 0.046$, $p = .530$, ηp2 = .013, and memory condition, $F(1.00, 30.00) = 0.099$, $MSe = 0.012$, $p = .756$, ηp2 = .003, were not statistically significant for beta phase-locking. On the other hand, the hemisphere main effect was statistically significant, $F(1.00, 30.00) = 9.426$, $MSe = 0.006$, $p = .005$, ηp2 = .239. Accordingly, the right hemisphere beta phase was higher than the left hemisphere, $t(30) = 3.07$, $p = .005$.

The location main effect was also statistically significant, $F(1.49, 44.74) = 17.483$, $MSe = 0.016$, $p < .001$, ηp2 = .368. However, this significant location effect was dependent on the group factor, since the location*group interaction was significant, $F(1.49, 44.74) = 6.571$, $MSe = 0.016$, $p = .006$, ηp2 = .180. We followed up this 2-way interaction by performing separate ANOVAs for the two groups (LBW/preterm and NBW) to see whether the location effect is group specific. Results showed that the location main effect is significant only for the LBW/preterm group, $F(1.34, 18.76) = 20.3$, $MSe = 0.005$, $p < .001$, ηp2 = .592. Accordingly, LBW/preterm group had higher beta phase values in PO than in FC and TP locations (FC vs PO, $t(14) = -4.53$, $p < .001$; TP vs PO, $t(14) = -5.05$, $p < .001$) while there was no such location main effect in NBW, $F(1.56, 25.03) = 1.69$, $MSe = 0.004$, $p = .208$, ηp2 = .095 (Fig. 4B and . C).

In addition, to provide more direct group comparisons regarding the observed location*group interaction, we examined between-group differences at each location. Similarly, these follow-up pairwise comparisons revealed a significant group difference in the PO location, with the LBW/preterm group showing significantly higher beta phase values compared to the NBW group, $t(30) = -2.07$, $p = .047$. No significant group differences were observed in the FC ($t(30) = 0.88$, $p = .388$) or TP ($t(30) = 1.03$, $p = .312$) locations.

3.4. Results of the event-related connectivity analysis

As evident in the event-related power and phase analysis results, the LBW/preterm group shows a greater alpha-beta EEG response in the posterior region. To more effectively discuss this finding, we aimed to investigate if this greater posterior EEG response in the LBW/preterm group stems from a disturbance in anterior-posterior connectivity, using event-related power-based and phase-based connectivity analyses.

4 (Electrode pair: frontal-parietal, frontal-occipital, central-parietal, central-occipital) X 2 (Hemisphere: Right, Left) X 2 (Memory condition: Remembered, Forgotten) X 2 (group: LBW/preterm, NBW) mixed design repeated measures ANOVA results were reported in the following paragraphs for the event-related power-based alpha and beta connectivity and event-related phase-based alpha and beta connectivity, respectively.

For the event-related power-based alpha connectivity, the electrode pairs main effect was statistically significant, $F(1.92, 57.63) = 39.670$, $MSe = 0.012$, $p < .001$, ηp2 = .569. However, this significant location effect was dependent on the other factors, since the condition*electrode pair*hemisphere*group interaction was significant, $F(2.45, 73.54) = 5.434$, $MSe = .003$, $p = .004$, ηp2 = .153. We followed up this 4-way interaction by performing separate 3-way ANOVAs for each memory condition (Remembered and Forgotten). The results of the 3-way ANOVAs showed that there was not any significant interaction or main effect that included the group factor for both remembered and forgotten conditions (all $ps > .05$).

For the event-related power-based beta connectivity and event-related phase-based alpha and beta connectivity, ANOVAs showed that there was not any significant interaction or main effect that included the group factor.

3.5. Results of the EEG-behavior interaction

In correlation analysis, locational event-related EEG power and phase values (FC, TP, PO) for alpha and beta, in which prominent differences were observed between groups in the ANOVA results, were used as EEG data. WISC-IV PS and WISC-IV WM test scores were used as behavioral data since these behavioral measures significantly differed across the groups. The correlations were calculated within each group separately. The same outliers were removed as in the behavioral data analyses above.

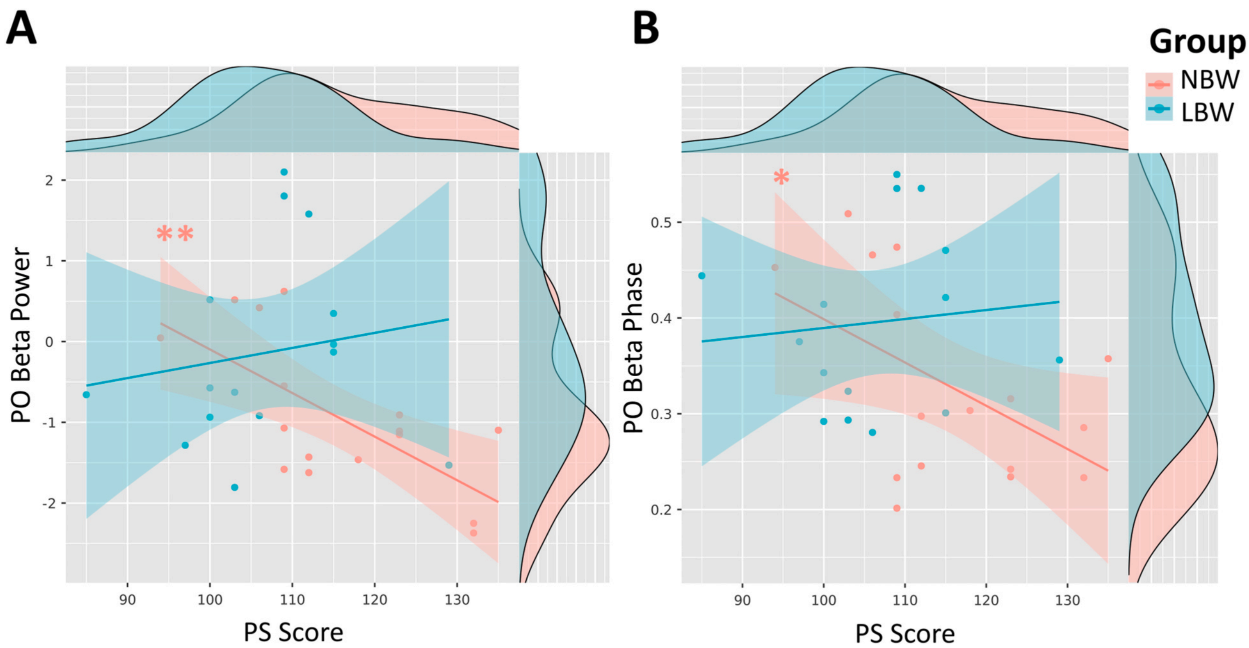

Fig. 5. Scatter plots of the correlations between WISC-IV PS score and event-related PO A) beta power and B) phase. The shaded area denotes the standard error. Density marginals for each group were presented outside the plot. Dots represent the observed scores. Asterisks indicate statistical significance (*: $p \leq .05$, **: $p \leq .01$, ***: $p \leq .001$).

No significant correlations were observed between any of the WISC-IV scores and event-related alpha power and phase values at any of the tested locations for any of the groups (all *ps* > .05). On the other hand, in the NBW group, WISC-IV PS (processing speed) score was negatively correlated with event-related beta power and phase values of the PO (parieto-occipital) (power: $r = -.675$, $p = .004$, phase: $r = -.513$, $p = .042$) (Fig. 5A and . B). However, other than these two significant correlations, no other correlations reached significance for beta values (all *ps* < .05).

4. Discussion

Children born with low birth weight are at increased risk for long-term cognitive difficulties, including in memory-related domains. These difficulties are often accompanied by alterations in resting-state electrophysiological activity. In the present study, we aimed to investigate how event-related brain oscillations (i.e., theta, alpha, and beta) reflect the effects of birth weight during a visual memory encoding in early school-aged children. To do so, we used event-related EEG methodology to understand the neural correlates of birth weight. Although the literature consistently indicates that children born with low birth weight exhibit weaker performance across various cognitive domains that often persist into young adulthood, their underlying neural dynamics remain less understood. To our knowledge, this is the first study to compare event-related brain oscillations between low and normal birth weight children during a visual memory encoding using event-related EEG methodology. As a reflection of the birth weight effect, which is measurable for several cognitive domains, we expected differentiated brain oscillations between children with low and normal birth weights during visual memory encoding. Our behavioral results showed that LBW/preterm group had lower working memory (WM) and processing speed (PS) scores than NBW peers, which is in line with the previous studies. For the brain oscillations, most profoundly, the results showed that LBW/preterm group exhibited increased event-related alpha-beta phase and power values in the posterior region compared to their NBW peers. No such topological differences were observed in theta oscillatory responses during the visual memory encoding process. This increased posterior alpha-beta activity in LBW/preterm group is interpreted within the framework of over-activation, as discussed in detail below. Furthermore, in NBW children, it is shown that the posterior beta responses were negatively correlated with PS scores.

Our behavioral assessments focused on three domains: WM and PS, as measured by the Wechsler Intelligence Scale for Children (WISC-IV), and visual memory task. The results indicated that NBW group had higher WM and PS scores compared to LBW/preterm group. Although not statistically significant, NBW group showed a slight advantage in visual memory tasks. These behavioral findings align with existing literature [6,8,9,11] and replicate the pattern where low birth weight children are observed to be behind their normal birth weight peers in various cognitive domains during early school years. It is important to note that the cognitive performance gap between children born with low birth weight and normal birth weight can be influenced by environmental factors and may be mitigated through targeted interventions [42–44]. This study included only children aged six to seven years, marking their primary education's start, and none received special interventions.

Despite the known role of event-related theta oscillations in memory [e.g.,45], which is also sensitive to the development [13,16,46–48], our study did not observe any group differences between LBW/preterm and NBW groups in theta responses that would indicate an effect of birth weight. On the other hand, our results consistently revealed a significant interaction effect of the location*group on the alpha phase, beta phase, and beta power. Given the close parallelism between the alpha and beta results, and their presentation as a continuum in the time-frequency analysis visuals, this section of the discussion collectively addresses the findings related to both alpha and beta. Accordingly, higher posterior activation was observed in LBW/preterm group compared to NBW group. In the previous studies of our group, increased posterior alpha responses were found in children compared to young adults both during encoding phase of the same visual memory task [16] and the day-night Stroop tasks (assess inhibitory processes) [49], and these results were mostly associated with the immature processing dynamics in the children that goes with the perceptual dominancy in the cognitive processing contrary to young adults. Our study also noted increased posterior alpha and beta responses in LBW/preterm group compared to NBW group despite being of the same age. Accordingly, together with the results of the previous studies that compared the children and young-adults, current results direct our discussion points to the more dominant perceptual processing in LBW/preterm group during the item encoding, which is differentiated from their NBW group. This interpretation is also consistent with recent EEG findings in school-age preterm children, in whom enhanced neural responses during face processing were discussed as reflecting additional recruitment of perceptual or featural visual-processing strategies rather than more efficient higher-level processing [50].

As Ofen and Shing (2013) proposed, memory systems undergo gradual differentiation throughout development, marked by a dynamic shift from perceptual to semantic processes [51]. In line with this theory, Köster et al. (2017) demonstrated that younger children exhibit less pronounced posterior alpha suppression (increase in alpha activity) compared to the young adults as reflection of developmental shifts in semantic encoding processes [13]. This suggests that the increased alpha suppression during encoding in adults may signify more efficient processing of new information through more abstract representations. Therefore, we may speculate that the birth weight effect is mostly seen in the perceptual versus semantic processing differentiation during memory encoding. Our finding could indicate that children born with low birth weight, similar to younger children in Köster et al.'s study, rely more on developmental stages of mnemonic processing that precede the efficient, abstract semantic representation-based processing seen in older children and adults. Thus, these differentiated memory processes, accompanied by distinct oscillatory dynamics during memory encoding, might affect cognitive performance in children born with low birth weight.

Through the event-related connectivity analyses, we also attempted to test whether this increased posterior EEG response in the LBW/preterm group is due to a disruption in anterior-posterior connectivity. However, these analyses did not reveal any differentiated connectivity pattern between the anterior and posterior regions for alpha and beta responses among the LBW/preterm and NBW groups that would suggest an influence of birth weight. Hence, we did not find any indication that the increased posterior responses in the LBW/preterm group specifically originated from disrupted connectivity.

Although our study's primary hypothesis did not revolve around “successful memory encoding”, in our statistical analysis, we also included the memory condition to see whether EEG responses differentiated between successfully recalled items (remembered) and those not recalled (forgotten) across the LBW/preterm and NBW groups. Our findings revealed a significant interaction effect of the hemisphere*memory condition*group on theta power. Accordingly, during the encoding phase, NBW group had lower theta power in the left hemisphere than in the right hemisphere for the forgotten memory condition, but no such difference was observed in LBW/preterm group. This might suggest that the higher theta power in right hemisphere compared to the left hemisphere might be one of the components of unsuccessful encoding. Another notable finding involving the memory condition was observed in the alpha power in the interaction between memory condition and location. During the encoding of remembered items, parieto-occipital alpha power was lower compared to that of forgotten items, whereas this distinction between memory conditions was not observed in other brain regions. This observation could be speculated to stem from the disrupted attention processes; given the role of posterior alpha in attention [52,53], a disruption in the inhibition mechanism accompanied by the increased posterior alpha response during encoding might trigger a cascade leading to a failed encoding. Simultaneously considering these two findings, when children encode visual stimuli to recall later, higher theta power in the right hemisphere and increased alpha power in the posterior region might indicate difficulties in executing a successful encoding process, leading to challenges in efficient recall. Our data indicates that the inability to suppress right hemisphere theta and posterior alpha sufficiently seems to disrupt a healthy continuation of the encoding process, creating a sort of cascade effect hindering successful encoding.

Our correlation results suggest that in the NBW group, the posterior (but not anterior) beta power and phase values (but not alpha) are linked to processing speed performance. The negative correlation between PS scores and PO beta in the NBW group is a complementary observation to the increased posterior beta seen in the LBW/preterm group. This negative relationship between the PS score and posterior beta in the NBW group might indicate that increased posterior beta could be a sign of ineffective cognitive processing, which aligns with our observation of the overactive posterior beta in the LBW/preterm group compared to the NBW group. Given the closely parallel results of alpha and beta responses, the presence of correlation exclusively in beta and not in alpha was unforeseen. We speculate that one reason for this might be our approach to defining the frequency boundaries for alpha and beta within the conventional limits established in the literature, as opposed to employing a more data-driven approach. This consideration is particularly relevant in light of the continuum of activity from alpha to beta, which is evident in the time-frequency analysis visuals.

In addition to all above-mentioned findings, regardless of birth weight, our findings indicated an asymmetry favoring the right hemisphere during the encoding across almost all EEG measures that we analyzed (event related theta phase, alpha power, phase, beta power, and phase). This observation might be linked to our visual memory task, including the presentation of stimuli in the visual modality [54,55].

This study has certain limitations that must be acknowledged, including our EEG recordings being limited to the encoding phase of the memory task. Extending the recording duration to include other memory processes, such as recall phases, could have allowed for a more elaborate understanding of the oscillatory responses of children born with low and normal birth weight across all these memory processes. Therefore, in forthcoming research, it would be beneficial to assess these components of visual memory as well. Another limitation of the present study is the heterogeneity within the LBW/preterm group. While the majority of the sample consisted of children who were both low birth weight and preterm ($n = 12$), the group also included one child with low birth weight only and two children who were preterm only. Therefore, although low birth weight and prematurity may have distinct developmental effects, the observed differences between the LBW/preterm and NBW groups most likely reflect the combined influence of both factors, rather than the effect of either condition in isolation. Due to the limited sample size, separate analyses of the low birth weight-only and preterm-only subgroups were not statistically feasible. Additionally, future research could benefit from investigating the birth effect in latter ages as well to be able to see if there is an education effect over this EEG-brain oscillation differentiation between the LBW/preterm and BNW groups.

5. Conclusion

Our findings indicate that cognitive differences in those born with low birth weight might be associated with enhanced event-related alpha and beta responses in posterior brain regions in early school-age children. During the encoding phase of visual memory task, this overactivity in the posterior regions of LBW/preterm group, relative to NBW group, suggests a reliance on more perceptual processing during the encoding phase. Such overactivity could be indicative of distinct cognitive processing approaches between the two groups. In light of these observations, it may be beneficial to provide tailored educational strategies that acknowledge the unique neurodevelopmental profiles of children born with low birth weight. Monitoring the impact of birth weight on cognitive functions through posterior event-related alpha and beta oscillations might offer valuable insights for optimizing learning experiences and outcomes.

CRediT authorship contribution statement

Tuba Aktürk: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ömer Ceran:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Simay Alptekin:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Figen Eroğlu Ada:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Ebru Yıldırım:** Investigation, Formal analysis, Writing –

review & editing. **Hakan Uzunlar:** Investigation, Formal analysis, Writing – review & editing. **Pervin Çalışoğlu:** Investigation, Formal analysis, Writing – review & editing. **Enver Atay:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Bahar Güntekin:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Statement for consent declaration

Written informed consent was obtained from the parents or legal guardians of all children. As most of the children were not yet able to read or write, verbal assent was obtained from them. All children received a small gift (toy) and a participation certificate as compensation for participation.

Statement from ethics declaration

The study was approved by the Ethics Committee of Istanbul Medipol University on 15.08.2018 (No. E.34153).

Data availability statement

The data that support the findings of this study are available from the corresponding author, TA, upon request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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