Brain Research 1853 (2025) 149523

Contents lists available at ScienceDirect

Brain Research

journal homepage: www.elsevier.com/locate/brainres

Research paper

Resting-state EEG alpha asymmetry predicts false belief understanding during early childhood: An exploratory longitudinal study☆

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ARTICLE INFO

Keywords:
False belief understanding (FBU)
Theory of Mind (ToM)
Resting-state EEG alpha asymmetry
Longitudinal study
Toddlers

ABSTRACT

Theory of mind (ToM), the ability to attribute mental states to others, is fundamental to human socio-cognition. In child development, a full or explicit understanding of false beliefs (FB) and their impact on action emerges around the age of 4 years. There is evidence of functional specialization of right hemispheric activity related to FB processing in adults and children. However, it remains unclear whether this specialization is the cause or the consequence of ToM development. The present exploratory study investigates the longitudinal relationship of resting-state electroencephalogram (rsEEG) alpha asymmetry measured in infancy/toddlerhood and behavioral false belief understanding (FBU) at the age of 4 years. Employing a longitudinal design, Study 1 assessed rsEEG alpha asymmetry across frontal and parietal electrode sites ($N = 43$), implicit FBU at 34 months ($N = 38$), and explicit FBU at age 4 ($N = 22$). Study 2 is another independent longitudinal dataset that included rsEEG alpha asymmetry at 14 months ($N = 37$) and explicit FBU at age 4 ($N = 32$). We found that superior explicit FBU at age 4 was associated with greater right frontal activity at an earlier age, and better implicit FBU was cross-sectionally related to greater right parietal activity. Given the limited sample size, these results should be viewed as preliminary and warrant replication in future studies. Interpreted cautiously, these findings may suggest that rsEEG alpha asymmetry in frontal regions may serve as an early-appearing neural marker of children's later explicit FBU.

1. Introduction

Theory of Mind (ToM) is conceptualized as the ability to infer and understand the mental states of others, such as beliefs, desires, and intentions (Perner, 1991). A key entailment of a fully developed ToM is an understanding of the representational relationship between mind and world, for instance understanding that another person holds a false representation of a state of the world. Research indicates that a representational theory of mind, characterized by a full or explicit false belief understanding (FBU) and related concepts, emerges in child development between the ages of 3 and 5 years (see Wellman et al., 2001, for a review). Recent evidence indicates an explicit FBU in tasks with reduced processing demands in toddlerhood and an implicit FBU in infancy (see Scott et al., 2022, for a review).

Existing studies on the neural correlates of FBU in children have predominantly focused on children aged 6 to 12 years with well-developed FBU (e.g., Bowman et al., 2019; Gweon et al., 2012; Saxe et al., 2009). For example, a longitudinal study examined whether source-localized resting-state electroencephalogram (rsEEG) activity in the dorsal medial prefrontal cortex (MPFC) or the right temporoparietal junction (TPJ) at age 4 could predict ToM-specific functional magnetic resonance imaging (fMRI) responses 3.5 years later. The findings revealed that preschoolers' rsEEG activity in the dorsal MPFC predicted subsequent ToM-specific fMRI responses in the same region (Bowman et al., 2019). Further fMRI studies with school-aged children (ages 5 to 11) suggest that the right TPJ increasingly distinguishes mental states from physical facts as they age (Gweon et al., 2012; Saxe et al., 2009). In contrast, there is a lack of research on the neural correlates of FBU during the sensitive developmental period of 3 to 5 years. Grosse Wiesmann et al. (2017b) utilized structural MRI to show that FB

Abbreviations: ToM, theory of mind; FBU, false belief understanding; FB, false belief; EF, executive function; rsEEG, resting-state electroencephalogram; ERP, event-related potentials; MPFC, medial prefrontal cortex; TPJ, temporoparietal junction.

☆ This article is part of a special issue entitled: 'Brain asymmetry' published in Brain Research.

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https://doi.org/10.1016/j.brainres.2025.149523
Received 28 May 2024; Received in revised form 21 January 2025; Accepted 18 February 2025
Available online 20 February 2025

competence in 3- and 4-year-olds correlates with age-related increases in local white matter structure in regions such as the right ventral MPFC, right TPJ, and right posterior cingulate cortex (PC). Additional evidence supporting the right hemispheric lateralization of brain activity associated with FBU comes from a rsEEG source-localized analysis by Sabbagh et al. (2009). They identified individual differences in alpha oscillations linked to ToM performance in 4-year-old children. Specifically, regions in the dorsal MPFC and several right hemisphere areas—including the TPJ, precentral gyrus, cuneus, and inferior temporal cortex—were associated with representational ToM, suggesting that the maturation of these regions may underpin the development of FBU and related ToM abilities. Consistent findings have been observed in adult populations. Sabbagh and Flynn (2006) found that greater activation (reflected by reduced alpha power) in the right mid-frontal region predicted better mental-state decoding performance, a component of ToM. This finding suggests a potential trait-like aspect of rsEEG alpha asymmetry in ToM abilities. Overall, these studies indicate that the development of FBU may correlate with right asymmetric activity, including task-independent rsEEG asymmetry and task-dependent functional asymmetry.

It is important to acknowledge that findings from task-independent rsEEG asymmetry and task-dependent functional asymmetry should not be equated within the methodologies employed across various studies. The presence of functional activation does not necessarily imply its manifestation in resting state asymmetry patterns. Indeed, previous research has indicated that both forms of brain asymmetry typically exhibit a general pattern of right-lateralized activity associated with the development of ToM. Notably, some studies, such as Bowman et al. (2019), provided preliminary evidence supporting a potential association between rsEEG asymmetry and functional activation asymmetry. However, while Bowman et al. (2019) found preschoolers' rsEEG frontal activity at age 4 predicted later ToM-specific fMRI responses in the same brain regions at age 7.5, the applicability of this pattern to children younger than 4 years, and its involvement with right-lateralized asymmetry, remains uncertain.

Previous neural research on ToM in typically developing individuals has provided evidence linking right hemisphere activity, as measured by rsEEG, to the development of ToM (Sabbagh et al., 2009; Sabbagh & Flynn, 2006). Evidence for the relevance of task-independent asymmetric brain activity to ToM has also been found in studies involving individuals with autistic spectrum disorder, who show behavioral deficits in ToM abilities (e.g., Baron-Cohen, 2001). Stroganova et al. (2007) noted atypical broadband rsEEG asymmetry in autistic children aged 3 to 8, suggesting a reduced capability of the right temporal cortex for EEG rhythm generation. Brain lesion studies also revealed that damage to the right hemisphere, as opposed to the left, significantly impairs the ability to complete ToM tasks (Balaban et al., 2016; Griffin et al., 2006; Siegal et al., 1996; Weed et al., 2010; Winner et al., 1998).

Concluding from existing neurocognitive research in adults and fewer studies in children, there is indirect evidence for a functional specialization of the right hemispheric brain activity in ToM reasoning. It is unclear, however, whether this functional specialization is a cause or a consequence of representational ToM development (Sabbagh et al., 2009). To address this issue, gathering data on ToM-related brain activation in even younger children, such as infants and toddlers, is necessary. One way of doing so is to use longitudinal designs, where task-independent brain activity is measured in infants or toddlers. Then, children's individual differences in early brain activity can be longitudinally explored for predictive relations with representational ToM competence when they are around 4 years old. The present exploratory study focuses on one dimension of ToM-related brain activity: right lateralized asymmetry. Our exploratory research questions are whether the task-independent hemispheric asymmetry is associated with ToM processing during early childhood, whether this asymmetry precedes the development of representational ToM, and if it can predict later behavioral ToM performance.

RsEEG provides a reliable measure of task-independent brain activity. Of particular interest has been developmental changes in the "alpha band" (6–9 Hz) of children's rsEEG. Alpha waves are thought to relate inversely to brain activity (Gevins, 1998; Klimesch, 1999), implying that higher alpha power in one hemisphere suggests increased activity in the opposite hemisphere (Allen et al., 2004; Reznik & Allen, 2018). RsEEG alpha asymmetry is usually measured by subtracting left from right alpha power, with negative values indicating dominant right hemisphere activity and positive values indicating dominance in the left hemisphere (Allen et al., 2004; Müller et al., 2015, 2018; Sabbagh & Flynn, 2006). Findings on cognitive task showed that rsEEG alpha asymmetry can predict task performance in a manner consistent with lesion and neuroimaging studies (Hoptman & Davidson, 1998). Roughly 60 % of the variance in alpha asymmetry indices is believed to reflect a stable trait-like neural characteristic associated with various psychological constructs (Fox et al., 1995; Hagemann et al., 2002; Stewart et al., 2011). Research indicates that rsEEG frontal alpha asymmetry is a stable characteristic over time across various age groups in children (Fox et al., 1992; Jones et al., 1997; Müller et al., 2015). For instance, studies have reported its stability over a 6–36-month span in children aged 3–6 (Jones et al., 1997; Vuga et al., 2008) and over a 4-year-span in ages 4–8 (Kim & Bell, 2006). Furthermore, similar findings have been observed over extended periods of up to 69 months across infants and preschoolers. For example, Müller et al. (2015) demonstrated high individual stability of frontal alpha asymmetry from 14 to 83 months of age. Collectively, these findings suggest a consistent pattern of stability in frontal alpha asymmetry across early child development.

FBU is considered the 'litmus test' for evaluating children's ToM abilities (e.g., Wellman & Woolley, 1990), with significant improvements in explicit FB tasks observed between ages 3 and 4 (Wellman et al., 2001). The present study investigates the relationship between task-independent asymmetric brain activity before the age of 3 years and behavioral FBU at the age of 4 years. The findings may offer new insights into the neural mechanisms underlying the emergence of ToM. To our knowledge, research has yet to explore this aspect. The present paper utilizes longitudinal datasets to examine the relationship between asymmetric brain activity and FBU across the developmental trajectory from infancy to 4 years of age. By examining rsEEG alpha asymmetry in children at 14 months and 34 months, we aim to determine whether individual differences in relevant asymmetric brain activity, such as those in the frontal and parietal regions, are evident before the emergence of FBU or whether they develop alongside FBU as neural correlates. In exploring the potential relationship between rsEEG alpha asymmetry and behavioral FBU, we differentiated the behavioral FB tasks into explicit and implicit FB tasks.[1]

The present research used two independent longitudinal datasets, each containing EEG and behavioral assessments of FBU. Study 1 conducted EEG assessments at 34 months and behavioral assessments at 34 and 52 months. It included an anticipatory-looking task to measure implicit FBU at 34 months, and explicit FBU was assessed at 52 months using the location and content FB tasks. Study 1 explores the correlation between rsEEG alpha asymmetry and both implicit and explicit FBU.

[1] In the current study, explicit FB tasks are defined as those that require participants to provide elicited responses to direct questions regarding an agent's false belief (Baron-Cohen et al., 1985; Wellman et al., 2001; Wimmer & Perner, 1983). In contrast, implicit FB tasks involve inferring children's understanding of an agent's false belief based on their spontaneous behaviors, such as looking behaviors while observing an unfolding scene (Clements & Perner, 1994; Kaltefleiter et al., 2022; Southgate et al., 2007).

While not initially conceived as a follow-up, Study 2[2] leverages an existing longitudinal dataset to complement these explorations. It focuses on earlier rsEEG measures at 14 months and their predictive power for later explicit FBU at 51 months. See Fig. 1 for a timeline and sample size of each study. To mitigate concerns about the small sample sizes in each individual study, we also combined the data from both studies to form a larger sample, thereby increasing power and assessing the generalizability of the potential relationship between rsEEG alpha asymmetry and explicit FBU. This combined sample represents the largest dataset reported in this research area to date. We acknowledge that the combined sample may introduce concerns such as data independence. Nonetheless, the decision to merge the samples was made to provide a comprehensive analysis given the available data. Moreover, given that children's performance in FB tasks correlates with their developing language skills (de Villiers & de Villiers, 2014; Milligan et al., 2007) and executive function (Devine & Hughes, 2014), we additionally included standard language skills and executive function assessments.

In summary, our study aims to explore the correlation between rsEEG alpha asymmetry and FBU during early childhood. Building on previous studies on the neural correlates of ToM in young children (e.g., Bowman et al., 2012; Sabbagh et al., 2009), rsEEG brain asymmetry study of ToM in adults (Sabbagh & Flynn, 2006), and studies involving individuals with autistic spectrum disorder (Stroganova et al., 2007), we pose two exploratory research questions:

Q1: Is there a correlation between rsEEG asymmetry and FBU in children?

Q2: Does the rsEEG asymmetry precede the development of representational ToM, and, if so, can it predict later behavioral FB performance?

2. Study 1 methods

2.1. Participants

This study was part of a larger longitudinal study[3] for which children were recruited from an urban area in Germany. The final sample included in our research consisted of 43 children (24 girls, $M_{age} = 33.79$ months, $SD = 1.25$ months, age range = 32.50 – 37.03 months) at Time 1 and 27 children (18 girls, $M_{age} = 52.27$ months, $SD = 0.48$ months, age range = 51.70–53.83 months) at Time 2. Seven data points from children were missing because children refused to participate in parts of the included tasks (i.e., Implicit FB task at T1 = 5; Content FB task at T2 = 1; Location FB task at T2 = 1); Three data points from children were missing because of experimenter mistakes (i.e., Location FB task at T2 = 3). Additionally, 16 children withdrew from T2 data collection. All parents gave written consent after being informed about the experiment procedure. Each child received a personal gift for their participation at each measurement point, and parents were compensated for their travel expenses. The local ethics committee approved the study based on the ethical principles of the European Federation of Psychologists' Associations.

2.2. Electrophysiological assessment at T1

2.2.1. EEG recording

During brain electrical activity (EEG) recording, children sat quietly on their mother's lap and were presented with brightly colored bubbles on a computer screen (Fig. 2). This kind of stimuli resembles others used in rsEEG research (Kühn-Popp et al., 2016; Licata et al., 2015; Müller et al., 2015; Mundy et al., 2000; Paulus, Kühn-Popp, et al., 2013) and was used to keep the children's visual attention with reduced movement during the recording time. The recording lasted for at least 3 min until the child lost interest in the stimulus, as evidenced by yawning, crying, or strong motor activity.

Recordings were made from 33 electrode sites using an infant-size cap with Ag/AgCl active electrodes (ActiCap, Brain Products, Gilching, Germany) with a layout following the extended international 10–20 system (see Fig. 3 for an overview). The electrical activity from each lead was amplified using BrainAmp amplifier (Brain Products, Gilching, Germany), sampled at 500 Hz and referenced to the vertex (Cz), band passed from 0.016 to 100 Hz, impedances were kept below 10 kΩ. Fp1 and Fp2 were inserted to detect blinks and vertical eye movements; F9 and F10 were included to detect horizontal eye-movements.

2.2.2. EEG analysis

EEG data were analyzed using BrainVision Analyzer Software (Brain Products, Gilching, Germany). Offline, all electrodes were re-referenced to common average reference, and a digital bandpass filter of 1 to 20 Hz (4th order) was applied. The EEG data were segmented into equal sized epochs of 1024 ms (512 time points). To ensure that EEG was only analyzed from epochs in which the children were attending to the bubble stimulus, epochs with artifacts were detected through visual inspection and a semiautomatic artifact rejection function (Minimal-maximal difference ± 300 μV, amplitude exceeding ± 100 μV), and were eliminated from further analyses if they contained eye movements, blinks, or motor artifacts. Data rejection was done blind to conditions by the experimenter. An average of 77.67 % of all epochs were included from subsequent analyses, providing on average 133.60 ($SD = 28.45$, range: 61 – 172) epochs per child.

Spectral power, expressed as mean square microvolts (μV^2), was calculated via Fast Fourier Transform (FFT, Hanning window: 10 %, frequency resolution: 0.977 Hz). To analyze alpha asymmetry in activation, spectral power (μV^2) was computed for the 6- to 9-Hz (Alpha) frequency band, which corresponds to the frequency band for infants (Kühn-Popp et al., 2016; Licata et al., 2015; Marshall et al., 2002; Müller et al., 2015; Paulus, Hunnius, et al., 2013; Saby & Marshall, 2012). Following previous research investigating EEG alpha asymmetry, EEG power was normalized using natural logarithm transformation (Gasser et al., 1982). RsEEG asymmetry indices were computed by subtracting the ln-transformed EEG power at a given left hemisphere site from the ln-transformed EEG power at its homologous right hemisphere site (Müller et al., 2015, 2018; Sabbagh & Flynn, 2006). That is, the rsEEG alpha asymmetry score for the frontal sites (AsymF) was computed by subtracting the average natural logarithm (ln) left power (F3, F7, FC1, FC5) from the average ln right power (F4, F8, FC2, FC6). Similarly, rsEEG alpha asymmetry scores for parietal sites (AsymP) was calculated by subtracting left power (P3, P7, CP1, CP5) from right power (P4, P8, CP2, CP6). Electrode sites were chosen based on earlier research investigating children's resting state asymmetry (Fox et al., 1995; Müller et al., 2015; Paulus, Kühn-Popp, et al., 2013).

2.3. Behavioral assessment

From the broader array of tasks integrated into the longitudinal study, only those pertinent to the research aim of the current study was chosen for analysis.

2.3.1. Behavioral assessments at time 1

Implicit false belief task (Anticipatory-looking false belief task)

The implicit FB task (Grosse Wiesmann et al., 2017a; Kaltefleiter et al., 2022) was used to assess children's implicit FBU by measuring anticipatory-looking behavior. In the task, children's gaze direction was

[2] Study 2 analyzed an independent existing dataset to explore the generalizability of findings between rsEEG alpha asymmetry and explicit FBU in Study 1; however, as it was not preregistered, future research should aim to address this limitation. Even so, in the current study, we tried to be as transparent as possible with the procedure for the results of Study 1 and Study 2.

[3] "The role of language in early Theory of Mind development", Crossing the Borders, https://crossing-project.de/, see Kaltefleiter et al., 2021, 2022).

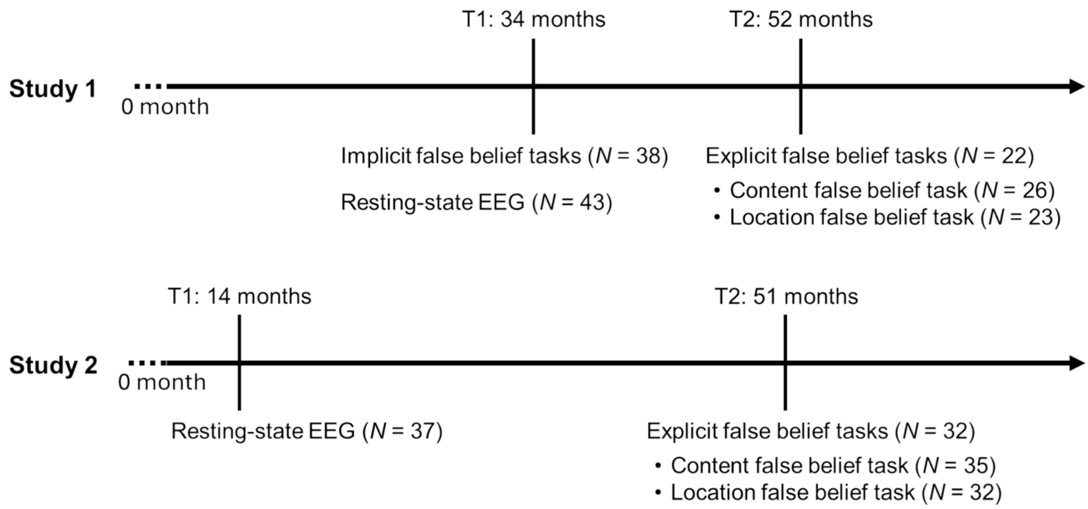

Fig. 1. Timeline of the longitudinal study in Study 1 and Study 2. The directional arrow indicates the progression of time from left to right.

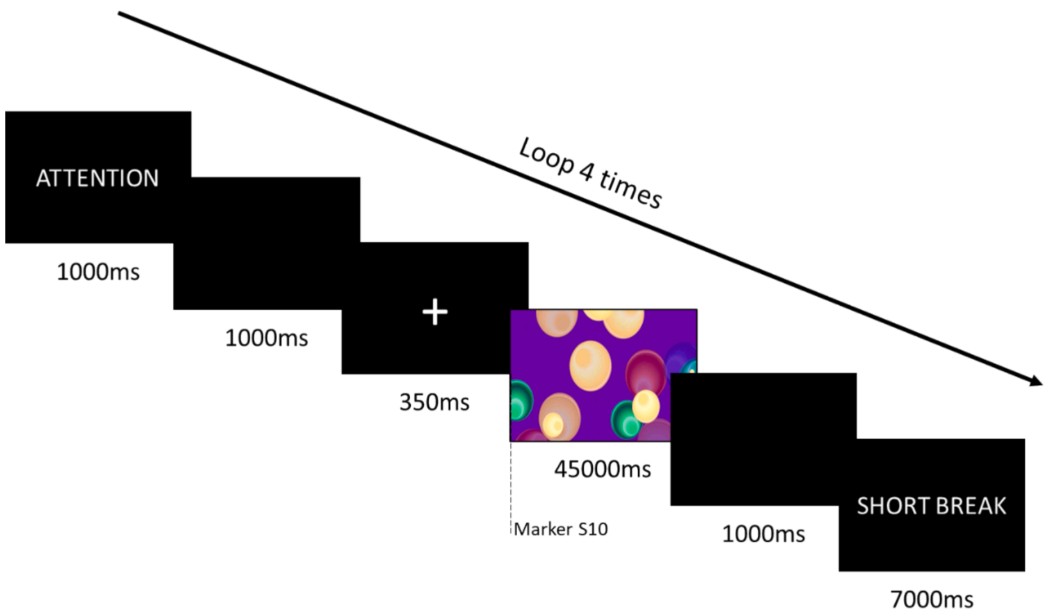

Fig. 2. Schematic diagram of resting-state EEG recording.

recorded while watching an agent search for a mouse to assess their implicit tracking of others' beliefs. The task included 10 familiarization trials where the agent consistently found the mouse, and 12 FB trials divided into two different conditions of six trials each. During FB trials, the mouse switched between boxes unknown to the agent, who held a false belief about its location. We concentrated on false belief 1 (FB1) trials in our study.[4] In FB1 trials, the agent observed the mouse's transfer but was unaware of its subsequent departure, continuing to falsely believe the mouse was in its final hiding place despite its actual absence.

Two identical areas of interest (AOIs) were defined for all trials. An overview of the task stimuli and two AOIs can be found in the supplementary materials S1. The "Implicit FB DLS score" is a differential looking score (DLS) calculated per trial by subtracting incorrect AOI looking duration from the correct AOI looking duration, divided by the total looking duration at both AOIs (Kaltefleiter et al., 2022). The implicit FB score is the average of these DLS values across all trials, where a chance performance is 0.

2.3.2. *Behavioral assessments at time 2*

At T2, two explicit FB tasks (Wellman & Liu, 2004) were conducted to assess explicit FBU. These tasks were particularly suited for 4-year-olds, aligning with the age when explicit FB reasoning typically emerges. The explicit FB sum score at T2 was computed as the sum of the content FB task score and location FB task score. The explicit FB sum score was chosen because the aggregate measures can offer a more reliable and stable assessment of explicit FBU (Grosse Wiesmann et al., 2017a; Kaltefleiter et al., 2022).

Content false belief task

In the content FB task, children were presented with a Smarties box

[4] Additionally, our task included another trial type (FB2), wherein the agent did not witness the mouse's transfer and mistakenly believed it remained in the initial location. Our data analysis excluded FB2 trials due to the children's performance in the FB2 trials was significantly below chance. In the FB2 trials, children might not have taken into consideration that the agent did not watch the target's transfer. Rather, they mostly looked at the last place where they themselves observed the mouse going, neglecting that the agent did not have this information. The detailed methodological reasons can be found in Kaltefleiter et al. (2022).

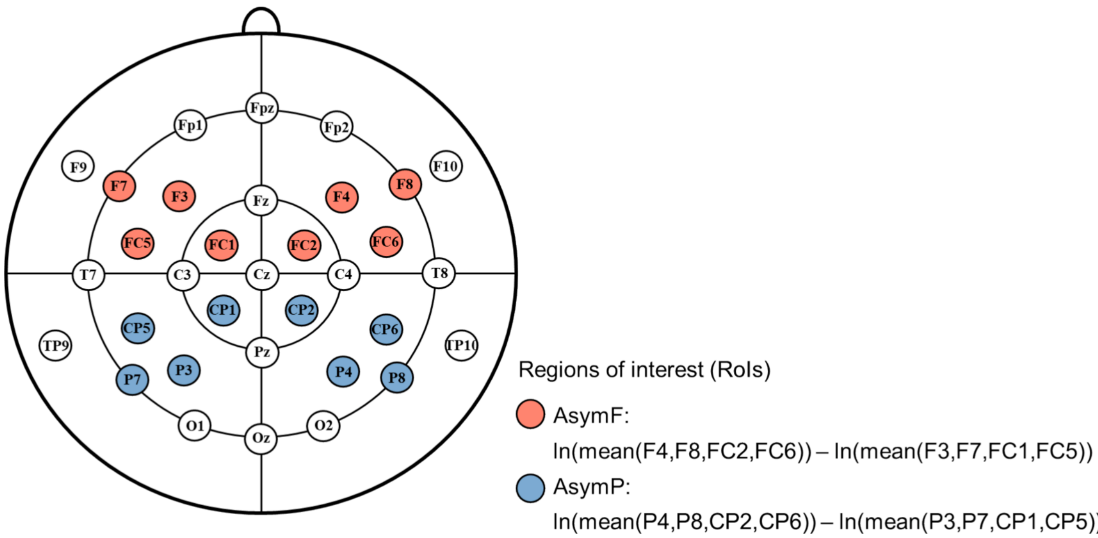

Fig. 3. Electrode layout of the rsEEG measurement. All channels were included in the EEG measurement. Colored channels show the electrodes included in the data analysis for the rsEEG alpha asymmetry scores.

and asked to speculate about its content. After the children named Smarties as the content, the true content (i.e., a piglet figurine) was revealed. Subsequently, the piglet figurine was returned to the box, and children were asked to identify the content as a memory control. Following this, the figurine Lucas, who had not seen the box's content, was introduced. Children were then posed with a test question (i.e., "What does Lucas think inside the box? Smarties or a piglet?") and a control question (i.e., "Has Lucas looked inside the box before?"). A correct response to both questions earned children one point, resulting in a score range of 0 to 1. The chance level was 25 %, as correct responses were required for both the corresponding test and control questions.

Location false belief task

In the location FB task, children were presented with pictures of a backpack and a closet. They were informed that the figurine Paul was searching for his gloves, which could be in the backpack or the closet. Subsequently, children were informed that Paul's gloves were actually in his backpack, but he falsely believed they were in his closet. The test question asked where Paul would search for his gloves, and the control question inquired about the actual location of Paul's gloves. Children were awarded one point for correctly answering both questions, yielding a score range of 0 to 1. The chance level was 25 %, as correct responses were required for both the corresponding test and control questions.

2.3.3. Language skills assessment

At T1 and T2, the four age-appropriate subtests of the standardized German language development test for three- to five-year-old children [Sprachentwicklungstest für drei- bis fünfjährige Kinder] (SETK 3–5, Grimm et al., 2015) were administered according to manual instructions. At T1, these subtests encompassed sentence comprehension, encoding semantic relations, phonological working memory, and morphological rule formation. At T2, the subtests included sentence comprehension, sentence memory, phonological working memory, and morphological rule formation. Raw scores obtained in each subtest were converted into standardized T-values using age-specific norm tables. The mean of the T-scores across corresponding subtests (SETK mean score), served as an indicator of children's general language skills.

2.3.4. Executive function

To assess children's inhibition skills as their executive function, a day-night Stroop task (Gerstadt et al., 1994) was conducted at T2. Initially, children were required to tell the experimenter when (at night or during day) the sun/moon and stars are typically in the sky. Subsequently, they were instructed to respond 'night' when shown a sun card and 'day' for a moon or star card, following a brief practice with two cards. The training phase, involving up to 12 cards, required children to answer correctly on 4 consecutive cards to until all cards were presented. Corrective feedback was provided during this phase. In the test phase, no feedback was given, and children's responses to 16 cards were scored based on their correct responses. Incorrect responses, including self-correction and uncertain responses were noted. The total number of correct responses ranged from 0 to 16.

2.4. Statistical analysis

Data preparations and all remaining analyses were conducted in IBM SPSS Statistics 29. In light of our exploratory question regarding whether FBU are associated with rsEEG alpha asymmetry, two-tailed testing and a significance level of 0.05 was used for all analyses. Multiple comparisons between rsEEG alpha asymmetry and FBU were corrected using the Bonferroni corrections (Dunn, 1961). For the Bonferroni correction, the significance level ($\alpha = 0.05$) is divided by the number of tests (i.e., 2), resulting in a corrected α value of 0.025. The number of tests depends on the 2 scalp sites' asymmetries (i.e., AsymF and AsymP) $\times$ 1 behavioral FB task (i.e., explicit or implicit FB task). Given that explicit and implicit FB tasks are considered independent tasks, with ongoing debate regarding their potential intercorrelations (e.g., Poulin-Dubois et al., 2023; Sodian et al., 2020), it is appropriate to treat them as independent when applying the Bonferroni correction.

3. Study 1 results

3.1. Descriptive statistics

Descriptive and inferential statistics are presented in Table 1. Independent sample t-tests were conducted to examine potential gender effects on performance in all FB task scores. No significant gender effects were observed (all p's > 0.05; see supplementary materials S2 for detailed results).

3.2. Correlation results

To answer the question of whether there are correlations between rsEEG alpha asymmetry scores and behavioral FB task scores, we first examined Pearson correlations between rsEEG alpha asymmetry scores at T1 and behavioral FB task scores at both time points. To further

Table 1
Descriptive statistics of the tasks and binomial tests respectively one-sample t-tests again chance performance in Study 1.

	N	*M*	*SD*	Value Range	Test Statistic	*p*
Implicit FB DLS score at T1	38	0.11	0.32	−1 to 1	$t(37) = 2.11$	$p = 0.042$ [a]
Content FB task score at T2	26	0.73	0.45	0 to 1		$p < 0.001$[b]
Location FB task score at T2	23	0.65	0.49	0 to 1		$p < 0.001$[b]
Explicit FB sum score at T2	22	1.36	0.73	0 to 2		
AsymF [c]	43	−0.02	0.09	−0.26 to 0.20		
AsymP [c]	43	0.00	0.11	−0.17 to 0.30		
Language at T1 (SETK3)	39	52.76	6.90	36.50 to 66.50		
Language at T2 (SETK4)	26	53.51	6.42	40 to 63.25		
EF at T2(day-night Stroop task score)	24	10.79	4.73	1 to 16		

Note. FB = false belief. [a] One-sample *t*-test against chance level (Shapiro-Wilk normality test, p's > 0.05). [b] Binomial test against chance performance. [c] Negative rsEEG alpha asymmetry scores indicate greater relative right than left cortical activity.

investigate the relationships between rsEEG alpha asymmetry scores and implicit as well as explicit FB task scores, we then calculated partial correlations between rsEEG alpha asymmetry scores and behavioral FB task scores, controlling for co-developing factors (e.g., age, language skills, executive function). Missing data were pairwise deleted.

Results showed a significant negative correlation between rsEEG alpha asymmetry scores of parietal sites and the implicit FB DLS scores (r = -0.382, $p = 0.018$, $N = 38$) at T1. The greater relative right than left parietal activity, the higher scores were in the implicit FB task at T1 (see Table 2). After controlling for age and language skills, the partial correlation between parietal rsEEG alpha asymmetry and implicit FB DLS score still significant ($r\text{-}partial = -0.374$, $p = 0.025$, $N = 38$).

For the correlation between rsEEG alpha asymmetry scores and the explicit FB sum score, results showed a significant negative correlation between rsEEG alpha asymmetry scores of frontal sites at T1 and the explicit FB sum score at T2 ($r = -0.444$, $p = 0.039$, $N = 22$). The greater relative right than left frontal activity, the higher explicit FB sum score (see Table 3). After controlling for age, language skills and executive function, the partial correlation between frontal rsEEG alpha asymmetry and explicit FB sum score still significant ($r\text{-}partial = -0.528$, $p = 0.036$, $N = 19$).

Table 2
Bivariate correlations among study variables regarding implicit FBU in Study 1.

		1	2	3	4	5
1. Implicit FB DLS score	*r*	–	0.159	**−0.382***	0.171	0.025
	p		0.340	**0.018**	0.305	0.880
	N		38	**38**	38	38
2. AsymF	*r*		–	0.132	−0.043	0.123
	p			0.400	0.783	0.455
	N			43	43	39
3. AsymP	*r*			–	−0.045	0.174
	p				0.777	0.290
	N				43	39
4. Age	*r*				–	−0.004
	p					0.978
	N					39
5. Language	*r*					–
	p					
	N					

Note: † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (two-tailed). FB = false belief. In bold font: $p = 0.036$ Bonferroni corrected.

Table 3
Bivariate correlations among study variables regarding explicit FBU in Study 1.

		1	2	3	4	5	6
1. Explicit FB sum score	*r*	–	**−0.444***	0.016	0.407†	−0.164	0.324
	p		**0.039**	0.944	0.060	0.477	0.163
	N		**22**	22	22	21	20
2. AsymF	*r*		–	0.132	0.113	0.116	−0.297
	p			0.400	0.574	0.572	0.159
	N			43	27	26	24
3. AsymP	*r*			–	0.047	0.227	−0.314
	p				0.814	0.265	0.135
	N				27	26	24
4. Age	*r*				–	−0.230	0.371†
	p					0.258	0.074
	N					26	24
5. Language	*r*					–	−0.446*
	p						0.033
	N						23
6. EF	*r*						–
	p						
	N						

Note: † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (two-tailed). FB = false belief. EF = executive function. In bold font: $p = 0.078$ Bonferroni corrected.

4. Study 1 discussion

In Study 1, we conducted correlation analyses between rsEEG alpha asymmetry and the development of ToM capabilities, specifically implicit and explicit FBU. To trace the predictive value of early neural activity patterns for later FBU performance, our study employed a longitudinal assessment of rsEEG alpha asymmetry at 34 months (T1) and its relationship to performance on explicit FB tasks at 52 months of age (T2). Results indicate that rsEEG alpha asymmetry correlated both with implicit and explicit FBU: Firstly, greater relative right than left frontal activity was significantly correlated with enhanced performance in explicit FB tasks at T2. Secondly, greater relative right than left parietal activity was associated with better performance in an implicit FB task at T1. Importantly, these correlations (i.e., the correlation between implicit and explicit FBU and rsEEG alpha asymmetry) were noted independently of age and other cognitive abilities commonly associated with FBU, including language skills and executive function.

These results showed correlations between FBU and rsEEG alpha asymmetry, indicating that there may be hemispheric asymmetry in FBU processing. Furthermore, such asymmetry may manifest early in development, even before the emergence of FBU. The distinctions we observed between the neurodevelopmental trajectories of implicit and explicit FBU delineate a nuanced relationship between rsEEG alpha asymmetry and FBU during early childhood. Nevertheless, given the relatively small sample size in Study 1, these findings should be regarded as preliminary evidence pointing potentially to early-appearing neural precursor underlying FBU between ages 3 and 4. Further research with an independent dataset will be necessary to substantiate and extend initial findings.

5. Study 2 and combined samples

To further support the preliminary evidence from Study 1 concerning explicit FBU in a limited cohort, another independent longitudinal dataset[5] was included. We then analyzed the Study 2 and the combined samples from Study 1 and Study 2 to replicate and strengthen the initial findings on the relationship between rsEEG alpha asymmetry and explicit FBU.

[5] Longitudinal Study on Theory of Mind in Infancy and Early Childhood, see Sodian et al. (2020).

6. Study 2 Methods

In Study 2, rsEEG data collection took place with 14-month-old infants. Furthermore, the age at which the explicit FB tasks (i.e., a content FB task and a location FB task) were administered aligned with that in Study 1, that is, around the age of 51 months. No implicit FBU was assessed in this study. In both Study 1 and Study 2, language skills and executive function measures were employed.

6.1. Participants

The final sample for Study 2 comprised 37 children (18 girls, M_{age} = 13.99 months, $SD = 0.22$ months, age range = 13.60 – 14.43 months) at Time 1 and 35 children (17 girls, M_{age} = 50.72 months, SD = 0.99 months, age range = 49.70 – 54.57 months) at Time 2. An additional three children participated in the rsEEG recording but were excluded from the final sample due to fussiness. These children were drawn from a larger cohort in a longitudinal study, Theory of Mind in Infancy and Early Childhood (TOMII/TOMEC) study, which assessed ToM across multiple time points (see Kloo et al., 2022; Kloo & Sodian, 2017; Osterhaus et al., 2022, for a further description of the sample). Parental written consent was obtained before participation. The local ethics committee approved the study based on the ethical principles of the European Federation of Psychologists' Associations.

6.2. Electrophysiological assessment at T1

6.2.1. EEG recording

The EEG recording setup for the resting state in Study 2 paralleled that of Study 1, adjusted for a younger cohort with an EEG cap sized for 14-month-old infants. Data were collected from 17 electrode sites (Fp1, Fp2, F3, F4, F7, F8, F9, F10, C3, Cz, C4, T7, T8, P3, P4, O1, O2) using an infant-specific cap with Ag/AgCl active electrodes (ActiCap, Brain Products, Gilching, Germany), following the 10/20 system guidelines.

6.2.2. EEG analysis

EEG data were examined and analyzed using BrainVision Analyzer Software (Brain Products, Gilching, Germany). Offline, all electrodes were re-referenced to common average reference, and a digital bandpass filter of 1 to 20 Hz (4th order) Hz was applied. The EEG data were segmented into equal sized epochs of 1024 ms (512 time points). To ensure that EEG was only analyzed from epochs in which the children were attending to the bubble stimulus, epochs with artifacts were detected through visual inspection and a semiautomatic artifact rejection function (Minimal-maximal difference ± 300 μV, amplitude exceeding ± 120 μV), and were eliminated from further analyses if they contained eye movements, blinks, or motor artifacts. Data rejection was done blind to conditions by the experimenter. On average 56.39 % of all epochs were included from subsequent analyses, providing on average 149.51 (SD = 48.07, value range = 68——249) epochs per infant.

Artifact-free epochs were extracted through a Hanning window and power spectra were calculated via Fast Fourier Transform. To analyze asymmetry in activation, power (μV^2) was computed for the 6 – 9 Hz (alpha) frequency band. A grand average of the FFTs was calculated for every participant. Subsequently, an asymmetry score for frontal sites (AsymF) was calculated by subtracting the average natural logarithm (ln) left power (F3, F7) from the average ln right power (F4, F8). Similarly, asymmetry scores for parietal sites (AsymP) were calculated by subtracting left power (P3) from right power (P4).

6.3. Behavioral assessment

The assessed explicit FB tasks (i.e., a content FB task and a location FB task) and the language skills assessment (i.e., SETK4) were the same as in Study 1. The explicit FB sum score at T2 was calculated by summing the scores of the content and location FB tasks, as in Study 1.

We used the 'Simon Says' task to measure executive function (Strommen, 1973). Children were engaged in a game with clear instructions: "Now, we are playing a game. I'll do all the exercises. Sometimes you are to do them with me and sometimes you are not. Only if I say 'Simon says' you do them. If I don't, you don't do them." Children initially practiced through one Simon and one non-Simon trial with corrective feedback to ensure understanding. This was followed by 20 test trials, evenly split between Simon and non-Simon types, without feedback. The experimenter executed all actions (e.g., 'touch your nose', 'stamp your feet') in a predetermined yet randomized order, with a rule's reminder after the first 10 trials. Performance was rated on a 0–2 scale per trial: a '2' for correctly following or ignoring commands based on trial type, a '1' for partial or incorrect responses, and a '0' for failing to adhere to instructions. Scores were summed for each trial type, allowing a maximum of 20 points per type. Only non-Simon trial scores were evaluated for analysis.

7. Results in Study 2 and combined samples

7.1. Descriptive statistics in Study 2

Descriptive performance on all tasks is presented in Table 4. Independent sample t-tests were conducted to examine potential gender effects on performance in all FB task scores. No significant gender effect was observed ($p > 0.05$; see the supplementary materials S2 for detailed results).

7.2. Correlations between rsEEG alpha asymmetry scores and explicit FB sum scores in Study 2

For the correlation between rsEEG alpha asymmetry scores and the explicit FB sum score (see Table 5), results showed a significant negative correlation between rsEEG alpha asymmetry scores of frontal sites at T1 and the explicit FB sum score at T2 ($r = -0.450$, $p = 0.010$, $N = 32$). The greater relative right than left frontal activity, the higher the explicit FB sum score. The partial correlation analyses, controlling for age, co-developing language skills, and executive function simultaneously, yielded a non-significant result ($r\text{-}partial = -0.344$, $p = 0.092$, $N = 28$).

7.3. Results on explicit FBU from combined data of Study 1 and Study 2

Study 2 is an independent longitudinal dataset assessing the explicit FBU and rsEEG alpha asymmetry. To consolidate these findings in Study 1 regarding the explicit FBU, we further combined the samples from Study 1 and Study 2, resulting in a total of N = 80 children (42 girls, M_{age} = 24.63 months, SD = 9.97 months, age range = 13.60–37.03 months) who completed the rsEEG recording, and 54 children (29 girls, M_{age} = 51.34 months, SD = 1.14 months, age range = 49.70–54.57 months) who completed the explicit FB tasks. Analysis of this combined

Table 4
Descriptive statistics of rsEEG alpha asymmetry and behavioral tasks performance in Study 2.

	N	*M*	*SD*	Value Range	*p*
Content FB task at T2	35	0.31	0.47	0 to 1	$p = 0.242$ [a]
Location FB task at T2	32	0.41	0.50	0 to 1	$p = 0.038$ [a]
Explicit FB sum score at T2	32	0.72	0.73	0 to 2	
AsymF	37	−0.07	0.24	−0.78 to 0.40	
AsymP	37	−0.02	0.47	−1.97 to 0.88	
Language (SETK4)	34	55.88	10.55	32 to 74	
EF (Simon Says task score)	31	6.16	6.25	0 to 18	

Note: FB = false belief. EF = executive function. [a] Binomial test against chance performance.

Table 5
Bivariate correlations among study variables regarding explicit FB performance in Study 2.

		1	2	3	4	5	6
1. Explicit FB sum score	*r*	–	**−0.450****	−0.190	−0.237	0.443*	−0.043
	p		**0.010**	0.298	0.192	0.011	0.828
	N		**32**	32	32	32	28
2. AsymF	*r*		–	0.241	0.276	−0.350*	−0.114
	p			0.151	0.109	0.042	0.541
	N			37	35	34	31
3. AsymP	*r*			–	0.031	−0.005	−0.042
	p				0.858	0.977	0.824
	N				35	34	31
4. Age	*r*				–	−0.088	−0.009
	p					0.619	0.962
	N					34	31
5. Language	*r*					–	0.183
	p						0.332
	N						30
6. EF	*r*						–
	p						
	N						

Note: † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (two-tailed). FB = false belief. EF = executive function. In bold font: $p = 0.020$ Bonferroni corrected.

sample revealed a significant negative correlation between rsEEG alpha asymmetry scores of frontal sites and the explicit FB sum score, indicating that greater relative right than left frontal activity correlates with a higher explicit FB sum score (see Table 6. $r = -0.282$, $p = 0.039$, $N = 54$). After controlling for age, language skills and executive function, the partial correlation between frontal rsEEG alpha asymmetry and explicit FB sum score still persisted (*r-partial* $= -0.327$, $p = 0.031$, $N = 47$).

Table 6
Bivariate correlations among study variables regarding explicit FB performance in combined data of Study 1 and Study 2.

		1	2	3	4	5	6
1. Explicit FB sum score	*r*	–	**−0.282***	−0.109	0.402**	0.181	0.083
	p		**0.039**	0.434	0.003	0.193	0.577
	N		**54**	54	54	53	48
2. AsymF	*r*		–	0.230*	0.148	−0.294*	−0.151
	p			0.040	0.191	0.022	0.272
	N			80	80	60	55
3. AsymP	*r*			–	0.035	0.007	−0.090
	p				0.756	0.960	0.516
	N				80	60	55
4. Age	*r*				–	−0.133	0.011
	p					0.310	0.937
	N					60	55
5. Language	*r*					–	−0.009
	p						0.950
	N						53
6. EF	*r*						–
	p						
	N						

Note: † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (two-tailed). FB = false belief. EF = executive function. In bold font: $p = 0.078$ Bonferroni corrected. Given the differing assessments of EF in Study 1 and Study 2, we utilized the Z-score of EF for the further analyses.

To further explore the relationship between rsEEG alpha asymmetry and explicit FBU, hierarchical linear regression models[6] were conducted to examine whether AsymF explained additional variance in explicit FBU after accounting for age, language skills, and executive function (see Table 7). Model 1, which included age, language skills, and executive function, was significant, $F(3,43) = 5.959$, $p = 0.002$, and explained approximately 24.4 % of the variance in explicit FBU (*Adjusted* $R^2 = 0.244$). Model 2, which added AsymF to the predictors, was also significant, $F(4,42) = 6.139$, $p < 0.001$, and explained 30.9 % of the variance in explicit FBU (*Adjusted* $R^2 = 0.309$). The inclusion of AsymF in Model 2 significantly improved the explained variance in explicit FBU ($\Delta R^2 = 0.075$, $\Delta F(1, 42) = 5.012$, $p = 0.031$). This suggests that frontal asymmetry contributes unique variance to the prediction of explicit FBU beyond age, language skills, and executive function.

8. Discussion of results on explicit FBU from Study 2 and the combined samples.

Results of Study 2 and the combined data confirmed that superior explicit FB performance at age 4 years was associated with greater right than left frontal activity at younger age. However, the partial correlation in Study 2 decreased to non-significance when controlling for age, language skills, and executive function simultaneously. We attribute this reduction to the limited sample size, which may have affected statistical power. This interpretation was supported by the results from the combined sample, where right frontal activity remained significantly related to representational FB performance, when age, language skills, and executive function were controlled for simultaneously. Nevertheless, to support this assumption, a replication with a larger sample is required. These findings highlight the potential influence of individual differences in task-independent frontal activity on the development of explicit FBU; however, it is important to interpret these findings with caution due to the limited sample size. In the General Discussion, we will synthesize these results to discuss the relationship between rsEEG alpha asymmetry and FBU development more comprehensively.

9. General discussion

Around the age of 4 years, children begin to develop representational ToM, enabling them to understand others' false beliefs and the influence of these beliefs on actions. The present study explored the neural mechanisms underlying representational ToM during early childhood and offers preliminary evidence of longitudinal continuity in the brain systems that support ToM reasoning. Specifically, through two independent longitudinal studies, this study explored the relationship between rsEEG alpha asymmetry and behavioral FB competencies during early childhood. Results identified a pattern in which greater right parietal activity is correlated with superior implicit FBU at age 3, while greater right frontal activity at 14 and 34 months is longitudinally associated with better performance on explicit FB tasks at age 4. This longitudinal pattern tentatively suggests that brain lateralization in frontal rsEEG alpha power may emerge prior to the observable behavioral manifestations of ToM and could potentially serve as a neural marker for the later development of explicit FBU.

Important to highlight, the present findings are preliminary and exploratory due to limitations in statistical power because of the low

[6] A commonly cited rule of thumb for sample size in multiple regressions suggests a minimum of 10 observations per predictor variable (Howell, 2010). With 4 predictor variables, this would require a minimum sample size of 40. Therefore, the regression model, incorporating age, language skills, executive function, and rsEEG alpha asymmetry, was conducted using the combined samples ($N = 47$). Due to the limited sample sizes of Study 1 and Study 2 individually, separate regression analyses were not included in the current manuscript.

Table 7
Results of hierarchical linear regression predicting the explicit FB sum score at T2 from rsEEG alpha asymmetry score at T1 in combined samples.

Model	Variable	Estimate	*SE*	*Beta*	*t*	*p*	*Adjusted* R^2
Model1	(Intercept)	−1.007	0.708		−1.423	0.162	0.244**
	Age	0.045	0.011	0.524	4.047	< 0.001	
	Language	0.018	0.011	0.198	1.535	0.132	
	EF	0.098	0.104	0.121	0.940	0.353	
Model2	(Intercept)	−0.744	0.687		−1.083	0.285	0.309***
	Age	0.049	0.011	0.568	4.535	< 0.001	
	Language	0.010	0.011	0.116	0.901	0.373	
	EF	0.067	0.100	0.082	0.663	0.511	
	AsymF	−1.290	0.576	−0.294	−2.239	0.031	

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. EF = executive function.

sample size. Although we augmented our sample size by combining data from two studies, future research is necessary to include larger samples to replicate and confirm these findings. Nevertheless, given the limited focus of previous research on neural activity during the sensitive periods of FBU development in infancy/toddlerhood, we think our longitudinal study provides valuable insights into the potential relationship between rsEEG alpha asymmetry and FBU development. In the following sections, we will discuss and cautiously interpret the key findings of this research and offer suggestions for future research. All our interpretations should be read in light of the small sample size.

The finding that greater right than left frontal activity, observable in infancy and toddlerhood predicts explicit FBU competence by age 4 tentatively supports the view that the lateralization involved in the functional specialization of ToM reasoning in the brain is a neural marker that appears prior to the behavioral development of ToM. Our results suggesting longitudinal continuity and align with previous, albeit limited, cross-sectional studies which have identified the right MPFC as associated with representational ToM reasoning in children. Notably, Bowman et al. (2012) observed right mid-frontal activations linked to mental-state reasoning in 7- to 8-year-old children, suggesting a shared neural pattern across tasks involving reasoning about beliefs and desires. While the functional asymmetry of ToM activity may not directly correspond to its anatomical asymmetry, developmental neural research indicates that FB competence correlates with anatomical changes, including increased fractional anisotropy in the white matter of the right MPFC around ages 3 to 4 (Grosse Wiesmann et al., 2017b). Extending these prior findings, our data carefully suggest that task-independent right frontal brain activity in children younger than 3 years old is associated with better ToM behavioral responses at age 4.

Furthermore, our longitudinal data showed a stable correlation between early-appearing right frontal activity and later explicit FBU across early childhood. Previous research using rsEEG technique has demonstrated high individual stability of frontal alpha asymmetry from 14 to 83 months of age (Müller et al., 2015). Based on these findings, we propose that neural stability in frontal asymmetry is likely to persist from 14 to 34 months. Our results support this proposition, suggesting that explicit FBU at age 4 exhibits significant longitudinal correlations with frontal rsEEG alpha asymmetry, regardless of whether it is assessed at 14 months or 34 months. Intriguingly, the stability on the neural level occurs despite notable advancements in explicit FBU, as demonstrated by behavioral tests where 4-year-olds performed above chance, even though they had not developed explicit FBU 1 or 3 years earlier. The neural consistency observed in our data, amid changes in conceptual performance, suggests that the cognitive capacities supported by frontal regions are probably established earlier in development and remain stable into early childhood. Importantly, Bowman et al. (2019) found that frontal rsEEG brain activity by age 4 correlates with specialized neural responses in the same brain regions at 7.5 years. This finding provided preliminary evidence that the early developments in the region of dorsal MPFC that is important for ToM in 4-year-olds are also associated with the extent of functional specialization of that same region for ToM reasoning 3.5 years later, suggesting early stability in the neural system for ToM reasoning, and longitudinal continuity in this neural system despite behavioral-cognitive advancements (Bowman et al., 2019). Our study extends this implication for neural longitudinal continuity of explicit FBU prior to age 4, although these results remain tentative and call for further investigation to confirm these early findings.

One key aspect of our study design at both T1 and T2 is that the continuities in frontal rsEEG alpha asymmetry relate to ToM reasoning. We controlled for age, language skills, and executive function in our design, acknowledging that these factors are known to co-develop and can potentially influence children's performance on explicit FB tasks. Our results demonstrated that right frontal activity was significantly associated with representational FB performance, even when these co-developing factors were taken into account. This suggests that the observed longitudinal correlation between frontal rsEEG alpha asymmetry and ToM performance is unlikely to be merely a byproduct of these co-developing constructs. However, to further validate these results, we recommend that future studies incorporate larger sample sizes to ensure adequate statistical power and thereby strengthen the credibility of the evidence.

To briefly summarize, our findings regarding the potential relationship between frontal asymmetric activity and explicit FBU extend prior research on the role of the frontal cortex in explicit FBU. The observed longitudinal association between increased right frontal activity and enhanced explicit FBU provides preliminary insights into the developmental onset and progression of explicit FBU in young children. Nevertheless, considerable caution is warranted when interpreting these results due to the small sample size and the potential for spurious correlations. It is imperative to conduct further research with larger and more generalizable samples, as well as additional evaluation time points along the developmental trajectory, to confirm and expand upon these findings. Additionally, further investigation is required to elucidate the role of right frontal activity in the explicit FBU during early childhood. This inquiry could extend to examining the relationship between right frontal activity and a wider variety of early-emerging socio-cognitive skills, such as perspective-taking (Tullett et al., 2012), self-other distinctions (Schuwerk et al., 2014), and cognitive empathy (Rueckert & Naybar, 2008), which previous research has linked to ToM. It is pertinent to explore whether right frontal activity might underpin a broader spectrum of ToM-related functions from an early age (Krause et al., 2012; Schuwerk et al., 2014; Sebastian et al., 2012).

Additionally, our study investigated the relationship between task-independent brain activity and implicit FBU, assessed with an anticipatory looking task (see Grosse Wiesmann et al., 2017a; Kaltefleiter et al., 2022). We found a significant cross-sectional correlation between superior performance on the implicit FB task and greater right than left parietal-related activity at the age of 3 years. This finding aligns with earlier neuroimaging research showing sensitivity to others' beliefs in the right parietal regions in toddlers (Grosse Wiesmann et al., 2017b; Richardson & Saxe, 2020; Sabbagh et al., 2009) and even in 7-month-olds (Hyde et al., 2018). Previous research may emphasize the association of right parietal activity with both explicit FBU (e.g., Sabbagh et al., 2009; Saxe & Wexler, 2005) and implicit FBU (e.g., Boccadoro et al., 2019; Hyde et al., 2018). However, our findings are partially inconsistent with prior studies (e.g., Perner et al., 2006; Richardson & Saxe, 2020), as we found significant correlations between greater right parietal activity and better performance on implicit FB tasks, but not on explicit FB tasks. Caution is warranted in interpreting the nonsignificant correlations between parietal rsEEG alpha asymmetry scores and explicit FBU. It is important to note that a relatively small sample size may limit the statistical power to detect a significant effect if one exists. Therefore, it is impossible to draw a definitive conclusion about the existence of such a relationship based on nonsignificant results, and we suggest future research with a larger sample to further investigate this question. Additionally, the absence of significant longitudinal correlations between parietal asymmetry and explicit FBU at age 4 may also reflect the potential instability of parietal asymmetry (Bowman et al., 2019; Harmon-Jones et al., 2010; Li et al., 2014; Müller et al., 2015; Xiao et al., 2016). Future investigations should also clarify the stability and developmental influence of parietal asymmetry in both implicit and explicit FBU across a broader age range.

While our findings underscore the correlations between rsEEG alpha asymmetry and behavioral FB competencies, they also point to several unresolved questions. It remains unclear to what extent the distinct neural correlates are independent of variations in task formats, particularly between anticipatory looking in implicit FB tasks and verbally elicited responses in explicit FB tasks. Furthermore, the precise nature of the observed asymmetrical cortical activity—greater relative right than left activity in parietal regions for implicit FB tasks and that in frontal regions for explicit FB tasks—warrants further exploration. Future research should, therefore, directly contrast brain activation during the nuanced processes of the implicit and explicit FBU to determine how neural correlates vary independently of task formats in early childhood.

In summary, drawing on previous neural research, which highlighted asymmetry in functional activation patterns related to ToM reasoning, our study represents the first exploration into the potential connection between resting-state asymmetric brain activity and FBU during early childhood. Across two independent longitudinal studies and combined samples, we observed preliminary evidence that a greater relative right than left frontal activity at 34 months and even at 14 months was associated with better performance in explicit FB tasks at 4 years of age. Additionally, enhanced performance in implicit FB tasks at age 3 appeared to correlate with greater relative right versus left parietal activity. While these findings provide preliminary evidence of potential relationships between rsEEG alpha asymmetry in the frontal and parietal regions and FBU, limitations in power and sample size warrant that these results be interpreted as exploratory. We attempted to alleviate concerns related to limited sample size by combining samples; however, further research is needed to confirm and refine these findings. Nonetheless, given the rarity of rsEEG data collected from infants and toddlers, these results may serve as a valuable initial exploration for future research in this field.

Ethics statement

The local ethics committee approved the study based on the ethical principles of the European Federation of Psychologists' Associations.

Data and code availability statement

Data are available from the corresponding author upon reasonable request, given appropriate ethical, data protection, and data-sharing agreements.

CRediT authorship contribution statement

Shuting Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Barbara C.N. Müller:** Writing – review & editing, Supervision, Methodology, Data curation. **Jörg Meinhardt:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Beate Sodian:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Acknowledgements

This work was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) to Beate Sodian [grant numbers SO 213/33-1,2 and SO 213/27-1,2] and the China Scholarship Council (CSC) to Shuting Li [grant number CSC202006040034]. Shuting Li would also like to thank the Erasmus+ "Short-Term Doctoral Mobility" program for the travel bursary. Study 1 is part of the project "The role of language in early Theory of Mind development" in the "Crossing the Borders" research unit. Study 2 is part of the project "Theory of Mind in Infancy and Early Childhood (TOMII/TOMEC)". We thank the children, parents, and students who participated in these studies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brainres.2025.149523.

Data availability

Data will be made available on request.

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