Infant Behavior and Development 80 (2025) 102106

Contents lists available at ScienceDirect

Infant Behavior and Development

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

Full length article

Neural correlates of false belief understanding in 33- to 36-month-old infants

Shuting Li [*], Jörg Meinhardt, Beate Sodian

Department of Psychology, Ludwig-Maximilians-University Munich, Munich 80802, Germany

A R T I C L E I N F O

Keywords:
False belief understanding (FBU)
Event-related potential (ERP)
Brain-behavior connections
Mentalizing
Infants

A B S T R A C T

Very little research has addressed the neural correlates of false belief understanding in young children. Following up on a previous event-related potential (ERP) study examining false belief understanding in 4- to 6-year-old children, the present study grouped infants ($N = 45$, 33–36 months old) into passers and failers according to their behavioral performance on a low-demands false belief task. Their ERP responses to false belief and true belief conditions were examined in a novel ERP paradigm. The study found that a late positive waveform over the occipital electrode sites distinguished between the false belief and true belief conditions only in infants who passed the low-demands behavioral false belief task. In contrast, a late negative waveform over the frontocentral electrode sites consistently distinguished between the false belief and true belief conditions regardless of low-demands behavioral false belief task performance. These findings raise the possibility that a sensitive neural system supporting false belief understanding may emerge early in development. Specifically, the late positive waveform observed over the occipital electrode sites appears to be a potential neural marker for false belief understanding in infants.

1. Introduction

Theory of Mind (ToM), which refers to the comprehension of mental states underlying behavior, plays a pivotal role in socio-cognitive development. A crucial aspect of ToM is false belief understanding (FBU), the ability to discern between reality and an agent's false mental representation of the world (Tomasello, 2018; Wimmer & Perner, 1983). It involves grasping the causal link between people's access to information and their mental representations, as well as the causal influence of beliefs on actions (Wellman et al., 2001). Typically developing children begin to succeed in attributing false belief (FB) to themselves and others between approximately 3.5 and 5 years of age (Perner, 1991; Wimmer & Perner, 1983). For example, children aged 4 years and older can correctly predict that a story character, Maxi, who did not witness a critical event—such as the location transfer of an object—will search for the object in its original location, where he last saw it. In contrast, 3-year-olds typically predict that Maxi will search for the object in its new location. This developmental trend was stable across hundreds of studies using different types of FB tasks under diverse task conditions (see Wellman et al., 2001, for a meta-analysis), supporting the view that there is conceptual change in children's developing understanding of the mind between the ages of 3 and 5 years. While 2- and 3-year-olds interpret human behavior in terms of intentions and desires, beliefs are only conceptualized as a cause of action around the age of 4 years (Wellman et al., 2001). Understanding a person's FB involves representing this person's misrepresentation of a state of affairs (e.g., the location of an object),

* Correspondence to: Department of Psychology, Ludwig-Maximilians-University Munich, Leopoldstraße 13, Munich 80802, Germany.
E-mail addresses: Shuting.Li@psy.lmu.de (S. Li), jmeinhardt@psy.lmu.de (J. Meinhardt), Sodian@psy.lmu.de (B. Sodian).

https://doi.org/10.1016/j.infbeh.2025.102106
Received 23 January 2025; Received in revised form 29 June 2025; Accepted 5 July 2025
Available online 12 July 2025

the origin of the misrepresentation (e.g., insufficient access to information), and the consequences for the person's action (FB leads to mistaken action). Thus, according to conceptual change theories, around the age of 4 years, children acquire a representational ToM (Perner, 1991), whereas younger children may understand that behavior is motivated by mental states such as desires and thoughts that merely link agents to actions and outcomes.

1.1. Early false belief understanding

The conceptual change view has been challenged by recent findings on FBU in infants and toddlers (see Baillargeon et al., 2010, 2016; Scott & Baillargeon, 2017). In over 30 studies utilizing spontaneous response tasks—including anticipatory looking (Clements & Perner, 1994; Kaltefleiter et al., 2022; Schneider et al., 2012; Schuwerk et al., 2018; Senju et al., 2011; Southgate et al., 2007; Surian & Geraci, 2012; Thoermer et al., 2012), violation-of-expectation (Kovács et al., 2010; Onishi & Baillargeon, 2005; Scott et al., 2012; Scott & Baillargeon, 2009; Surian et al., 2007; Yott & Poulin-Dubois, 2012), and prompted action paradigms (Buttelmann et al., 2009, 2014; Knudsen & Liszkowski, 2012; Southgate et al., 2010)—infants in their second year of life have demonstrated sensitivity to agents' FBs when forming expectations about actions.[1] One interpretation of these findings is that they indicate conceptual continuity in ToM development from infancy through preschool age and beyond (Baillargeon et al., 2010, 2016). According to conceptual continuity theory, infants' ability to demonstrate FBU in standard elicited response tasks was often masked by task-related processing demands, notably response generation and inhibitory control difficulties (Scott et al., 2022; Scott & Baillargeon, 2017). Response generation involves infants' interpreting, retaining, and responding to a standard test question that predicts the protagonist's behavior. Inhibitory control requires them to suppress their knowledge of reality to accurately reflect the protagonist's FB. If such conceptual continuity indeed exists, then competence in understanding false beliefs should also be observable in infants during their third year, who are capable of responding verbally in elicited response tasks with decreased processing demands.

In a pioneering study, Setoh et al. (2016) showed that children younger than 3 years can pass explicit verbal FB tasks with reduced processing demands. Participants were told a story about a protagonist, Emma, who found an apple in one of two containers, moved it to the other container, and went outside. In her absence, her brother found the apple and took it away. Emma then returned to look for her apple. In the test trial, infants were shown pictures of the two containers and were asked the test question, "Where will Emma look for her apple?" The test object was removed from the scene to reduce demands for inhibitory control, thus obviating the requirement for infants to overcome the reality bias (Robinson & Mitchell, 1995). Importantly, infants were also given two practice trials to reduce demands on response generation. In one practice trial, infants saw an apple and a banana and were asked, "Where is Emma's apple?" in the other practice trial, they saw a ball and a frisbee and were asked, "Where is Emma's ball?". Under these conditions, 30- to 33-month-old infants performed above chance in the test trial; 25 of 32 (78 %) infants pointed to the container that Emma mistook to hold her apple (Setoh et al., 2016, Exp. 1). Grosso et al. (2019) replicated this finding in 33-month-old infants (74 % correct). Importantly, Scott et al. (2020) found FB competence below the age of 36 months also in a false belief about identity task with low demands. Furthermore, a recent longitudinal study found a predictive correlation between FBU assessed with the low-demands location FB task adapted from Setoh et al. (2016) at 33 months and FBU in a standard content FB task at 52 months, independent of language and executive function (Sodian et al., 2024). These findings support the view that the development of explicit FBU is characterized by conceptual continuity from infancy to childhood rather than fundamental conceptual change (Scott & Baillargeon, 2017).

To date, theoretical discussions of early FB competence have predominantly focused on behavioral evidence. Here, we investigate the neural correlates of FBU in infants under 36 months. Building on Liu et al. (2009b), who studied 4- to 6-year-olds, we classify infants as passers or failers based on the low-demands FB task by Setoh et al. (2016). Concurrently, we examined their neural response in FB and true belief (TB) conditions using a novel event-related potential (ERP) paradigm. By comparing the neural responses of passers and failers, we aim to determine whether a neural system supporting FBU emerges early in development.

1.2. The neural correlates of false belief reasoning in children and adults

Over the past two decades, significant progress has been made in identifying the neural correlates of FBU. Functional magnetic resonance imaging (fMRI) studies have consistently demonstrated the involvement of two primary brain regions during FB tasks in adults: the medial prefrontal cortex (MPFC) and the temporoparietal junction (TPJ) (Döhnel et al., 2012; Le Petit et al., 2022; Li et al., 2023; Saxe, 2009; Saxe et al., 2004a; Schuwerk et al., 2021; Sommer et al., 2007). These regions are similarly recruited when reasoning about mental states in children aged 6–12 years (Kobayashi et al., 2007; Richardson et al., 2018; Saxe et al., 2009; Sommer et al., 2010) and in early childhood (Grosse Wiesmann et al., 2020, 2017b; Li et al., 2023, 2025; Richardson & Saxe, 2020). Neuroimaging (e.g., MRI, EEG) studies indicated functional specialization for FB processing in both adults and children. For instance, a longitudinal study by Li et al. (2025) showed that early resting-state EEG alpha asymmetry may serve as an early neural marker of later explicit FBU.

The ERP technique's high temporal resolution has enabled the examination of the time course of neural responses (Sabbagh, 2013). Late waveforms, which can be negative or positive, emerge around 600 ms post-stimulus and continue to the end of one second of the recording epoch (Sabbagh, 2013). Previous ERP studies of mentalizing found a late waveform effect associated with FB processing (e.g., Liu et al., 2004; Sabbagh & Taylor, 2000). This effect has been replicated with many different kinds of stimuli (e.g., Geangu et al.,

[1] See Barone et al. (2019) for a meta-analysis of 56 FB conditions of spontaneous response tasks, and the ManyBabies2 consortium (e.g., Schuwerk et al., 2024) for an ongoing effort to test for the replicability and reliability of findings from spontaneous ToM tasks.

2013; Kühn-Popp et al., 2013; Liu et al., 2009b, 2009a; Meinhardt et al., 2011, 2012). In ToM tasks, the late waveforms typically manifested extensively across the frontal and parietal electrode sites, a pattern frequently observed when participants engage with complex stimuli that required attributing mental states to others.

The late waveforms involved in FBU have been characterized as "late slow waveforms" (e.g., Bowman et al., 2012; Geangu et al., 2013; Guan et al., 2020; Meinhardt et al., 2012). Slow waveforms are tonic with less distinct peaks, persisting from several hundred milliseconds to several seconds (Rösler et al., 1997). In ERP studies on the neural correlates of FBU with adults and children, late slow waveforms showed differences in amplitude between mental state attribution processes and non-mental state attribution processes (e.g., Bowman et al., 2012; Guan et al., 2020; Liu et al., 2009a; Sabbagh & Taylor, 2000). For example, compared to false photo reasoning, FB reasoning exhibited a more positive late slow waveform over left-frontal regions (Sabbagh & Taylor, 2000). Belief reasoning versus reality understanding elicited a more negative late slow waveform over left-frontal sites in adults and children (Liu et al., 2004, 2009b). The late slow waveforms for FB reasoning differed from those observed in TB reasoning (e.g., Chen et al., 2012; Geangu et al., 2013; Meinhardt et al., 2011; Zhang et al., 2013), desire reasoning (Bowman et al., 2012; Liu et al., 2009a), and pretense (Kühn-Popp et al., 2013; Meinhardt et al., 2012). Previous studies proposed late slow waveforms to reflect processes associated with decoupling mental states from reality and meta-representation (e.g., Liu et al., 2004; Kühn-Popp et al., 2013; Meinhardt et al., 2012). Additionally, they were linked to working memory processes (Bailey et al., 2016; Barriga-Paulino et al., 2014), suggesting they may reflect extended working memory processing and allocation of attention resources during belief reasoning.

Developmental investigations comparing neural activation between 6- to 12-year-old children and adults consistently showed that children demonstrate a more diffuse distribution of late slow waveforms compared to adults (e.g., Guan et al., 2020; Kühn-Popp et al., 2013; Liu et al., 2009b; Meinhardt et al., 2011). Seven ERP studies (Bowman et al., 2012; Kühn-Popp et al., 2013; Liu et al., 2004, 2009b, 2009a; Meinhardt et al., 2011, 2012) facilitated direct comparisons of neural responses associated with FBU across adults and children by using ERP paradigms shared between studies. These studies compared neural responses to false and true belief (Meinhardt et al., 2011), belief versus reality (Liu et al., 2004, 2009b), FB, reality, and pretense (Kühn-Popp et al., 2013; Meinhardt et al., 2012), and belief, desire, and physical control conditions (Bowman et al., 2012; Liu et al., 2009a). Findings revealed that children and adults exhibit late slow waveforms to belief stimuli yet differ in scalp distribution and temporal characteristics. In adults, late slow waveforms related to belief processing typically manifested over frontal sites (Liu et al., 2004, 2009a; Meinhardt et al., 2011, 2012) or right posterior sites (Liu et al., 2009a) during the 600–900 ms interval. Importantly, school-age children also consistently differentiated FB from control conditions (Bowman et al., 2012; Kühn-Popp et al., 2013; Liu et al., 2009b; Meinhardt et al., 2011), predominantly exhibiting either a more diffused frontal scalp distribution or neural responses over parieto-occipital sites, which often emerged later than in adults. These findings enhance our understanding of the developmental patterns in brain activity related to belief reasoning between children and adults. They consistently demonstrated the presence of frontal late slow waveforms in reasoning about FBs. Additionally, there were developmental changes in the contribution of the parieto-occipital regions. The present study, which assessed the neural responses to FB, hypothesizes that in infants, these responses manifest as more diffused and less localized late waveforms, potentially encompassing broader frontal and parieto-occipital areas and occurring later than in older children and adults.

Investigating the neural correlates of FBU from infancy to preschool age is essential for understanding the neural processes that support FBU. However, at this age, limited attention spans, increased motor activity, and growing autonomy lead to difficulties maintaining engagement and adherence to ERP experiment protocols. To date, only two event-related electroencephalogram (EEG) studies (Bowman & Brandone, 2024; Liu et al., 2009b) and one study using functional near-infrared spectroscopy (fNIRS; Hyde et al., 2018) examined the neural correlates of belief reasoning within this sensitive age range. Hyde et al. (2015, 2018) found greater TPJ activity for false belief than true belief conditions in both adults and 7-month-olds during passive viewing of belief-related events. Bowman and Brandone (2024) used EEG spectral power to examine links between 3- and 5-year-old preschoolers' neural responses during passive FB viewing and their explicit ToM performance. Greater FBU was associated with increased right TPJ alpha suppression during a location-change event (when the protagonist's belief became false) and reduced suppression during the belief-based search. Liu et al. (2009b) provided further evidence for brain–behavior relations in FB reasoning by comparing ERP responses of 4- to 6-year--olds and adults during belief attribution versus reality judgments. Children were classified as passers or failers based on independent behavioral assessments. Passers showed a frontal late slow waveform in the FB condition, resembling the adult pattern but with a more diffuse distribution, while failers showed no neural differentiation between conditions.

These findings provided preliminary evidence of brain-behavior connections in FBU during early childhood, as well as ongoing developmental consolidation even after children reliably pass standard FB tasks. Nonetheless, it remains uncertain whether the ToM network undergoes a major change before age 3. To shed light on this issue, we need to investigate the neural correlates of behavioral FBU in younger children, specifically using the low-demands FB task developed by Setoh et al. (2016), which is mastered before the third birthday. A brain-behavior correlation in FB reasoning at this early age would support the view that a neural ToM network underlying conceptual understanding of belief may emerge early in development and remain continuous over the lifespan. Specifically, infants who passed the behavioral FB task before the age of 36 months should show a distinction between the FB and TB conditions on the neural level, similar to the distinction between passers and failers in 4- to 6-year olds in Liu et al.'s (2009b) study. The evidence for the early emergence of a neural ToM network associated with behavioral FB competence in infants would lend support to conceptual continuity accounts of ToM.

1.3. *The present study*

The present study was designed to systematically investigate the neural correlates of FB versus TB processing in infants under 36 months. This study extended the findings of Liu et al. (2009b) to infants, providing new insights into the developmental origins of FBU from a neural perspective. To address methodological challenges in this age group, we employed the low-demands behavioral FB task adapted from Setoh et al. (2016). An ERP paradigm named "Leo's belief task" was developed to assess infants' brain responses as they process information about a protagonist's (i.e., Leo's) true or false beliefs. This ERP paradigm (Fig. 1) was akin to the behavioral "explicit FB task" (Wellman & Bartsch, 1988; Wellman & Liu, 2004), which is part of the ToM scale. In Leo's belief task, infants were explicitly informed about reality (e.g., infants saw the ball in the box while the bucket was empty). Subsequently, infants were informed by verbal communication about Leo's true or false beliefs (e.g., "Leo thinks that the ball is in the box / bucket"). This information was followed by a behavioral test question: "Where will Leo look for (the target object)?". The explicit FB task has been shown to be equally challenging as other standard FB tasks that require children to infer the protagonist's FB from their access to information (Wellman & Bartsch, 1988). In the present ERP paradigm, however, we did not assess the neural response to behavior prediction; we chose the final spoken word in the sentence expressing Leo's belief as an ERP-eliciting event. This spontaneous response assessment enables a direct comparison of neural responses to information conveying Leo's false and true beliefs. We articulated Leo's beliefs through a single scenario where the positions of the two containers — namely, the box and the bucket — remained constant, and the protagonist consistently remained present without any instances of absence or return. Consequently, we propose that Leo's belief task is conducive to identifying the neural correlates of FB processing in infants.

In summary, the present study has two goals. The first goal is to explore late waveforms distinguishing FB and TB processing in 33–36-month-olds. Based on previous ERP studies on FBU, we hypothesize that late waveforms over anterior or posterior electrode sites will differentiate between the FB and TB conditions.[2] The second goal is to determine if behavioral FB competence is associated with a neural-level distinction. We measured behavioral FB competence with the low-demands FB task adapted from Setoh et al. (2016). If such competence aligns with a distinction on the neural level, we anticipate late waveforms to manifest exclusively in behavioral FB passers, as demonstrated by Liu et al. (2009b).

2. Methods

2.1. Participants

A total of 128 infants participated in ERP belief task (55 boys, $M_{age} = 34.82$ months, $SD = 1.71$ months, age range: 32.50–37.37 months). Data obtained from 70 infants (30 boys, $M_{age} = 34.84$ months, $SD = 1.71$ months, age range: 32.50–37.23 months) fulfilled the artifact criterion, which will be explained in the subsequent section. These data constituted the final ERP dataset. Fifty-eight infants were tested but not included in the final sample because of the following reasons: 1) they did not meet the established minimum of five usable trials—an accepted threshold for reliable infant ERP data (Elsner et al., 2013; Stets et al., 2012; Stets & Reid, 2011)—because of inattention, excessive body movements, or fatigue ($n = 49$), 2) technical problems (e.g., no record stimuli markers in these infants) during the data recording ($n = 6$), or 3) the data recording process was not completed ($n = 3$). The exclusion rate was 41.18 %, similar to other EEG studies with young children (Hoehl & Wahl, 2012; Stets et al., 2012).

Forty-five (18 boys, $M_{age} = 34.51$ months, $SD = 1.62$ months, age range: 32.93–37.23 months) of the 70 infants who met the ERP artifact criteria and completed the low-demands behavioral FB task concurrently were included into the final sample for data analysis. The final sample size ($N = 45$) exceeded that of comparable studies investigating the neural correlates of children's ToM (e.g., Kühn-Popp et al., 2013; Liu et al., 2009b; Meinhardt et al., 2011). Furthermore, a power analysis conducted using G*Power 3.1.9.4 (Faul et al., 2009) indicated that a sample size of 45 participants is sufficient to detect an effect size of 0.40 with a power of 0.85 and an alpha level (α) of 0.05.

According to parent reports, all infants had normal or corrected-to- normal visual acuity, normal hearing, no neurological disorders, or regular medication. German was the mother tongue or the primary language of all participants. Prior to the commencement of data collection, written informed consent was obtained from a parent or legal guardian for each participating child. The local ethics committee approved the study based on the ethical principles of the European Federation of Psychologists' Associations.

2.2. ERP paradigm and procedure

2.2.1. ERP belief task (Leo's belief task)

Leo's belief task is an ERP paradigm designed to assess FBU in infants. Thirty-two test trials (16 FB and TB condition trials, respectively) and eight control conditions were presented to participants in a pseudo-randomized order. All auditory commentaries were recorded in high quality in WAV format (44.1KHz / 16 bit sampling) by a trained speaker and played back at a volume of approximately 65 dB/A via JBL Control One monitor loudspeakers.

Five static scenes were presented in each trial as a film sequence with verbal commentary (Fig. 1). The first scene depicted two containers, a box (German: Koffer) and a bucket (German: Eimer), which remained in the same positions throughout the trial. In the second scene, one of four possible objects (a ball, a fish, a cup, or a car) was shown in one container, and the following verbal comment was made: "Look! This is Leo's ball. The ball is in the box." (German: "Schau! Das ist Leo's Ball. Der Ball ist im Koffer."). Object positions were counterbalanced across all trials. The third scene showed the containers closing, accompanied by a corresponding sound. In the fourth scene, the protagonist, Leo, appeared on the screen and expressed his belief about the object's location ("Leo thinks

[2] Since it is unclear whether the term "slow waveform" can be applied to characterize late waveforms emerging as neural correlates of mentalizing in infants, we opt to speak more generally of a "late waveform" in the present ERP study of FB reasoning in infants.

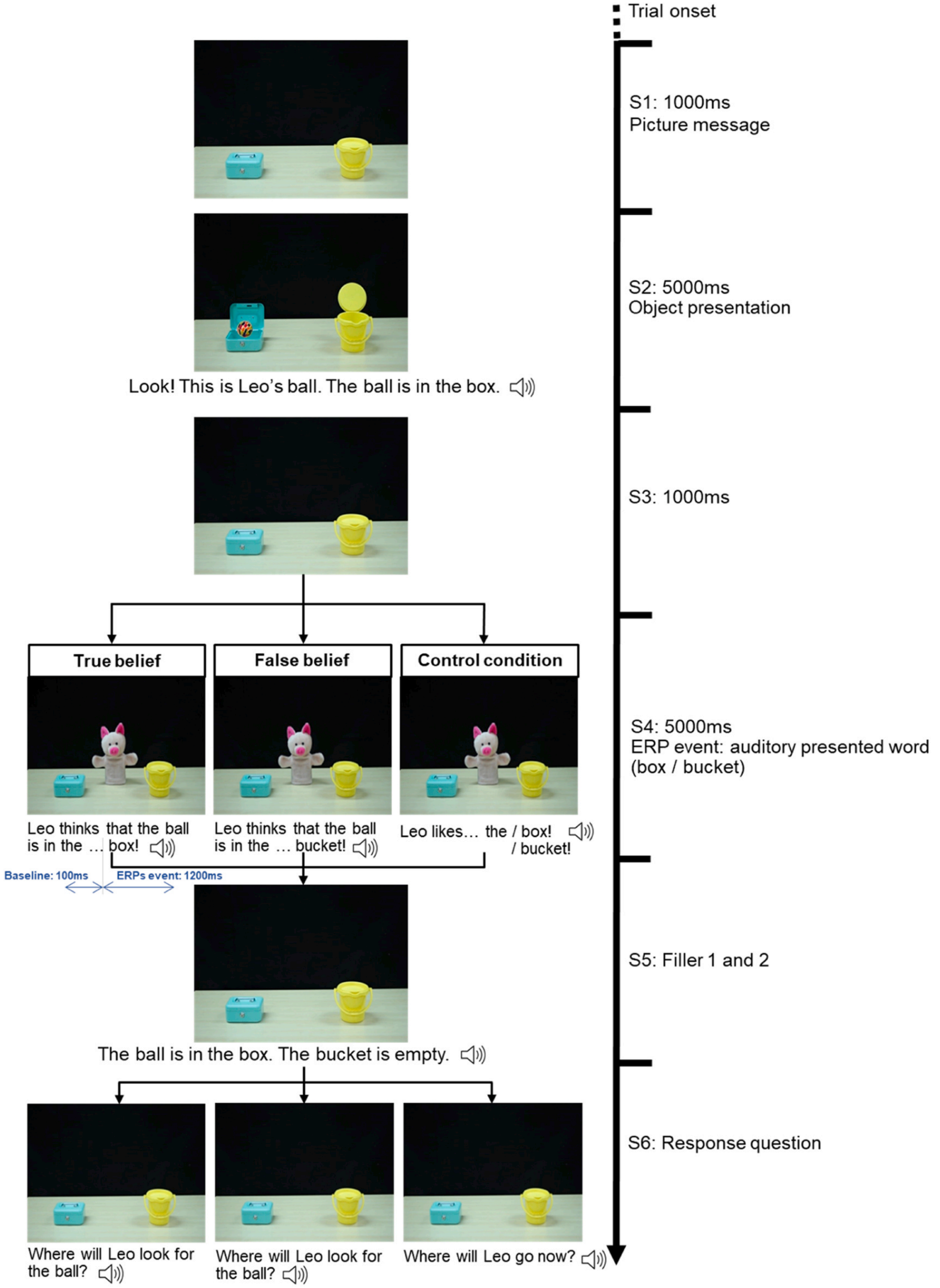

Fig. 1. Illustration of ERP belief task. ERP events were elicited from the auditory presented word box / bucket in all experimental conditions. The loudspeaker symbol indicates the auditory presented information.

the ball is in the box/bucket", German: "Leo denkt, der Ball ist im Koffer / Eimer."). In the TB conditions, Leo's belief corresponded to the object's true location. In the FB conditions, Leo's belief contradicted the real location of the object. In control conditions, Leo's belief was replaced by a location preference statement (e.g., "Leo likes the box / bucket"). Leo's preferences were counterbalanced across control conditions. The final container word (i.e., box or bucket), signifying Leo's presumed location for the object, was used to segment ERP events. The two containers (i.e., box and bucket) were shown again in the fifth scene. Two filler sentences were used to prevent the behavioral response from being influenced by the aforementioned location. The empty container was indicated (i.e., "The box / bucket is empty." German: "Der Koffer / Eimer ist leer."), and the object's true location was repeated (e.g., "The ball is in the box.", German: "Der Ball ist im Koffer."). The order of these two filler sentences was counterbalanced across trials. Each trial ended with a test question (Belief conditions: "Where will Leo look for the ball?"; Control conditions: "Where will Leo go now?"). The final scene remained on the screen until the child responded orally.

2.2.2. Procedure

ERP belief task was conducted in a dimly lit, soundproof, and electromagnetically shielded room by IAC (Industrial Acoustics Company). Infants sat on a highchair in front of the experimenter or on their parent's lap if preferred. Stimuli were displayed on a 19-inch screen (Dell Inc.) with a resolution of 1280 × 1024. The image on screen measured 25.5 cm in height and 38 cm in width, with the protagonist occupying roughly two-thirds of the image on a dark grey frame background [RGB (96, 96, 96)], which was completely visible during inter-trial breaks.

At the start of the experiment, infants were asked to watch the following videos carefully and to answer the question at the end of each trial. Prior to the start of the trial, short "eye-catching" videos were interspersed to draw the infants' attention to the monitor and counteract disinterest. The entire task took about 15–20 min (including short breaks), plus another 25–30 min for preparation (application of the cap, further technical preparations, and instruction). Presentation software was used to deliver the stimulus (Neurobehavioral Systems).

2.2.3. Electrophysiological recordings and pre-processing

The electroencephalogram (EEG) was recorded with Cz reference from 33 active electrodes (ActiCap System, Brain Products, Gilching, Germany) placed on standard positions of the extended international 10–20 System. The bandpass of the recording system (BrainAmp DC amplifiers, Brain Products, Gilching, Germany) was set to 0.016–100 Hz, and data were sampled at 500 Hz. All impedances were kept below 10 kΩ. Fp2 was used to monitor vertical eye movements and blinks. Horizontal eye movements were monitored via positions F9 and F10. Channel AFz served as grounding.

The EEG data were analyzed offline using Brain Vision Analyzer software (Version 2.2.2, Brain Products GmbH, Gilching, Germany). Channels (i.e., F7, F8, T7, T8, P7, P8, TP9, TP10) near the EEG cap's edge (e.g., neck, cheeks, and forehead) were omitted since they tended to produce most of the movement-related noise. Data from EEG channels over the scalp surface (F3, F4, Fz, Fpz, FC1, FC2, FC5, FC6, C3, C4, Cz, CP1, CP2, CP5, CP6, P3, P4, Pz, O1, O2, Oz, $n = 21$) and EOG related electrodes (F9, F10, Fp1, Fp2) were retained for further analysis (See Fig. 2). Offline data were re-referenced to common average reference[3] and were digitally bandpass filtered from 0.30 Hz (-24 dB) to 30 Hz (-12 dB). An automatic inspection procedure was applied to discard data containing excessive eye movement or muscular artifacts before the ocular correction (Gratton et al., 1983). In this procedure, sections were automatically marked as artifacts and excluded if the amplitude of the EOG channel exceeded ± 125 μV and the EEG channel exceeded ± 100 μV. ERP segments time-locked to the ERP trigger (the onset of the auditory presented word, i.e., box, bucket) were extracted from −100 ms (pre-stimulus baseline) to 1200 ms after stimulus onset. Following the automatic artifact reduction process, a meticulous visual inspection was conducted. Video sequences (Analyzer Video Plug-In, Brain Products) recorded simultaneously with EEG data were used to identify visible inattentiveness (such as infants looking away from the monitor) and inappropriate activities, further mitigating the potential contamination from eye movements and other artifacts. Segment rejection was done blind to conditions by the experimenter. Detailed coding scheme for segment exclusion was listed in the supplemental materials (S1). Subsequently, data were baseline corrected (−100 to 0 ms), and artifact-free segments were averaged separately for the FB ($M = 7.11$, $SD = 2.01$, value range: 5 – 12) and TB ($M = 7.61$, $SD = 2.83$, value range: 5 – 15) conditions. The number of usable trials did not differ significantly between groups ($F(1, 43) = 0.552$, $p = .461$), did not differ significantly between belief conditions ($F(1, 43) = 2.668$, $p = .110$), and did not interact between belief and group ($F(1, 43) = 0.830$, $p = .367$).

2.3. Behavioral tasks and procedure

2.3.1. Low-demands behavioral false belief task (Lily's belief task)

Lily's belief task, which closely followed the procedure by Setoh et al. (2016), is a change-of-location FB task with reduced processing demands. We created a picture book with nine pages to present the task, composed of clear plastic sheet protectors (32 cm × 56 cm) holding white paper backgrounds to which 11 pictures were attached (20 cm × 25 cm). A solid black paperboard (50 cm tall ×

[3] Common average reference has been critiqued for possibly inducing 'mirror potentials,' where specific ERP waveforms might appear as their inverse at different scalp locations (Dien, 1998; Picton et al., 2000). To assess such possible bias, we reprocessed our data using the linked-mastoid re-reference, a technique less prone to mirror potentials (see supplementary materials S5). The late waveform patterns and their topographical characteristics were consistent irrespective of the re-referencing strategy, thereby ensuring the robustness of the observed polarity reversal in ERP patterns.

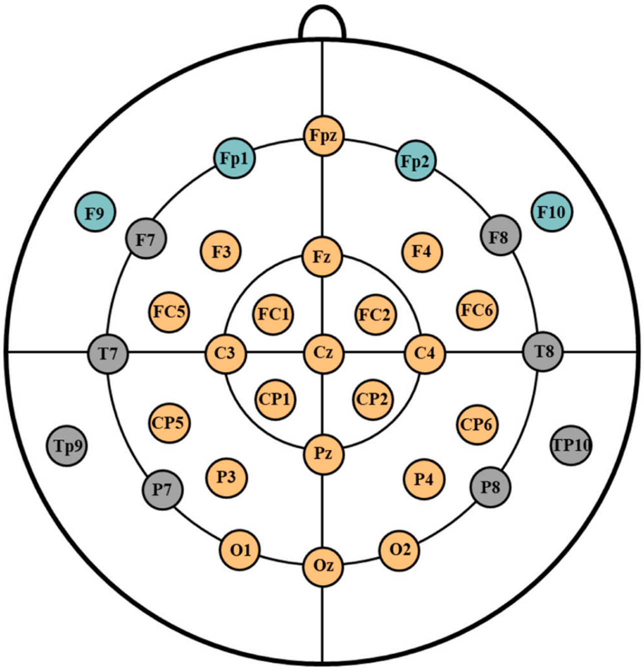

Fig. 2. Electrode layout of the ERP measurement. All channels were included in the ERP measurement. Channels marked in teal and orange show the electrodes included in the ERP preprocessing.

56 cm wide × 20 cm deep) kept the pages in place via four binder rings mounted on the upper edge. The stand allowed the screen to be positioned at a 70-degree angle via a black ribbon connecting the frontal and back frames. All photos were centered at the bottom of the page, with double photos placed 4.5 cm apart one from the other.

During the low-demands behavioral FB task (Fig. 3), the child and one experimenter sat beside each other with the easel in the middle of the table. The event was recorded with a hand-held camera focused on the book and the child, capturing the child's pointing movements. Another experimenter documented the child's behavior during the experiment. A verbal answer by the child and ambiguous response behavior (e.g., the pointing gesture and the verbal answer did not match) were recorded for all exercises and test runs. Six story events, two practice trials, and one test trial were presented to the child in total. After flipping each page to reveal the respective picture, the experimenter repeated the accompanying line of that event verbatim. In the first two pictures, the protagonist, Lily, found an apple in a bucket covered with a towel. In the first practice trial, a picture of the apple and a picture of a banana was shown, and the child was asked, "Where is Lily's apple?". Then, in the third and fourth pictures, Lily moved the apple into the basket covered with a plate and went outside to play with a ball. In the second practice trial, the experimenter presented a picture of a rattle and a picture of the ball and asked, "Where is Lily's ball?". The story continued with the arrival of Lily's brother Peter, who took away the apple from the scene. In the last picture, Lily came back and looked for her apple. In the test trial, the experimenter revealed a picture of the basket and a picture of the bucket and asked, "Where will Lily look for her apple?". A pointing gesture or verbal referral to the container where Lily falsely believed the apple was located was coded as a correct response. Cases in which the child needed prompts (e.g., "Can you show me where Lily's apple is?" or "Show me where the apple Is!") were documented, as in the original study design.

All responses from the child were independently coded from video recordings by two raters, who reached very high inter-rater reliability for all questions (Cohen's kappa = 1). For each practice and test trial, we coded the pointing and vocal reply of the child and eventual response behavior (e.g., inconsistent verbal or pointing responses, such as pointing at one location but mentioning the other). Out of the 70 infants who met the ERP artifact criteria as mentioned earlier, 25 were excluded from the analysis of behavioral FB task for the following reasons: 1) Ambiguous or absent responses ($n = 4$); 2) Lack of engagement with the task ($n = 15$); 3) Errors in task instructions by experimenters ($n = 6$). Detailed coding scheme and reasons for exclusion were listed in the supplemental materials (S2). The infants who completed the behavioral FB task were categorized into two groups: those who passed were coded as 1 (passers), while the others were coded as 0 (failers).

2.3.2. Control measures

To control for the effects of general cognitive abilities and language skills, we conducted the Kaufman Assessment Battery for Children-Second Edition (KABC-II) (Melchers & Melchers, 2015) and the Language development test for three- to five-year-old children (SETK3) (Grimm et al., 2015).

In the KABC-II task, the infants underwent the five age-appropriate tasks, which collectively measure three-year-olds' intellectual processing index. These tasks assessed infants' memory, attention, and concentration, as well as their simultaneous and sequential

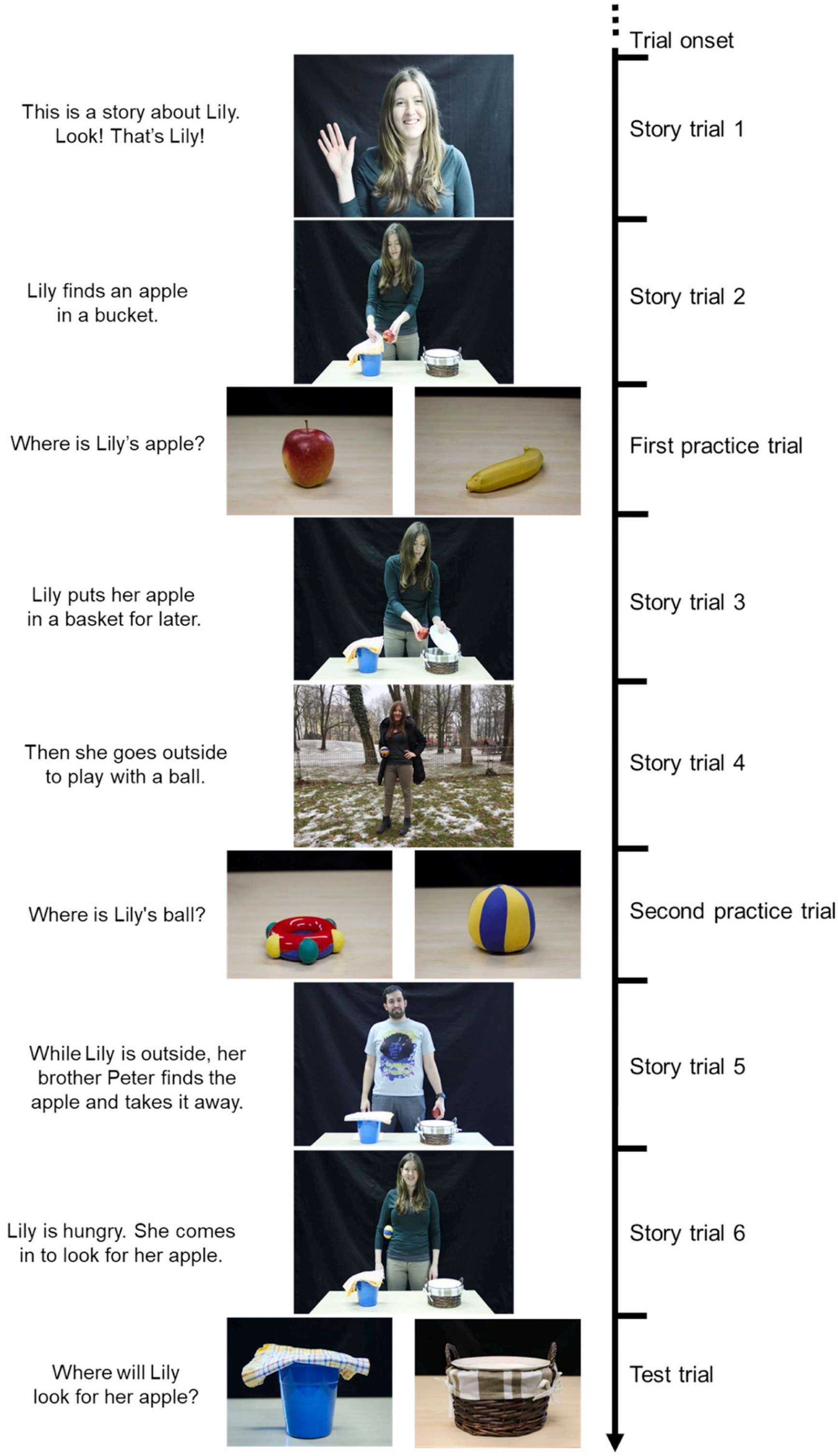

Fig. 3. Illustration of the low-demands behavioral FB task. The participant saw a six-part story with two practice questions and a test question. After each page turn, the experimenter read out the text belonging to this page. A pointing gesture or verbal response to the container (basket) in which Lily left the apple counted as a correct answer.

information processing and coding.

We conducted four subtasks from the SETK3 test battery: comprehension of sentences, encoding of semantic relations, phonological working memory, and morphological rule formation. All tasks were conducted and scored as described in the manual, and the raw values were transformed into standardized T-values according to the age-specific norm table.

2.4. Statistical analysis

2.4.1. Analysis of ERP data grouped by performance in the low-demands false belief task

We used nonparametric cluster-based permutation analysis to determine the electrode clusters and time windows of interest for late waveforms. Specifically, we submitted EEG data in the time window from 600 to 1200 ms after the auditory presented word (i.e., box or bucket) and over all electrodes to a dependent-sample permutation t test to examine the main effect of belief condition. The main effect of belief condition has been extensively demonstrated in both adult and child studies (e.g, Geangu et al., 2013; Meinhardt et al., 2011). This specific time window was selected based on prior studies in children, which consistently observed the emergence of late waveforms associated with belief reasoning approximately 600 ms after stimulus onset (e.g., Bowman et al., 2012; Geangu et al., 2013; Meinhardt et al., 2011, 2012). Then, the mean amplitude of the late waveforms per belief condition was calculated over the electrode clusters that revealed a significant difference between the FB and TB conditions. To confirm the significant effect of belief condition and to explore the potential interaction between group, belief condition and electrode cluster, we performed 3-way mixed-measures ANOVA on these data. In cases where a significant 3-way interaction was observed, we conducted 2 kinds of post-hoc analyses: (i) To further explore the effects of belief condition and electrode cluster on late waveforms' amplitude, we conducted post-hoc 2-way ANOVAs separately for the passers and failers, and post hoc pairwise comparisons were conducted when a significant 2-way interaction was observed. (ii) To further explore performance differences between the 2 groups in each sub-condition, we broke down the 3-way interaction by focusing on the effect of group for each level of the other 2 factors (i.e. belief condition and electrode cluster). However, late waveforms' amplitude between the 2 groups were not further explored when neither the 3-way or 2-way interaction between group and other factors nor the main effect of group was significant.

2.4.2. Analysis of ERP data grouped by accuracy on the behavioral questions in the ERP belief task

Due to generally low accuracy in the ERP belief task, classifying children into passers and failers directly based on performance in the behavioral test questions was not feasible. Instead, we used an independent low-demands behavioral task where children performed above chance levels, allowing for classification into FB passers and failers. This design might raise concerns about whether the ERP task and the behavioral task reflect the same belief understanding process. To address this concern, we conducted an additional analysis focusing solely on the ERP task (Refer to Section 3.2.2 for detailed results).

We used nonparametric cluster-based permutation analysis in all infants who fulfilled the ERP artifact criterion ($N = 70$) to determine the electrode clusters and time windows of interest for late waveforms. Specifically, we submitted EEG data in the time window from 600 to 1200 ms after the auditory-presented word (i.e., box or bucket) and over all electrode clusters to a dependent-sample permutation t test. Then, the mean late waveform amplitude per belief condition and electrode clusters were calculated over the cluster that revealed a significant difference between the FB and TB conditions. We then categorized children based on their performance in the ERP task into two groups: the top 25 % for FB accuracy (40–63.64 %) and the bottom 25 % for FB accuracy (0–12.5 %). This approach aimed to amplify differences despite overall low accuracy. To confirm the significant effect of belief condition and to explore the potential interaction between group, belief condition and electrode cluster, we performed a 3-way mixed-measures ANOVA on these data and conducted planned pairwise comparisons between FB and TB in infants with top 25 % FB accuracy, as well as between FB and TB in infants with bottom 25 % FB accuracy.

All statistical analyses except permutation analyses were performed using the SPSS software (version 29; IBM Corp, 2023) and Rstudio (Version: 2024.09.0 +375; RStudio Team, 2024). Cohen's d was calculated as the effect size for t-tests. The Greenhouse-Geisser correction was applied in case of violations of the sphericity assumption. For the sake of brevity, the uncorrected degrees of freedom were reported.

Permutation analyses were performed using the FieldTrip toolbox (Oostenveld et al., 2011). This type of analysis allows for statistical tests over entire data points while still controlling for multiple comparisons (Maris & Oostenveld, 2007). More specifically, for each permutation test used in the present study, adjacent spatiotemporal points for which t-values exceed a threshold were clustered (dependent *t*-test; two-tailed; cluster-defining threshold $p = .05$; iterations = 5000). The absolute sum of the *t*-values within each cluster was defined as the cluster's weight. This weight served as the sole criterion for determining the cluster's significance. Cluster-based permutation estimates the likelihood of each cluster's weight in the actual data compared to random permutations of the dataset. The *p*-value for each cluster is defined as the proportion of random iterations that resulted in a higher cluster weight. Clusters with $p < .05$ were considered significant. For each significant cluster, we report the cluster weight, *p*-value, and the corresponding electrode clusters and/or time window.

3. Results

3.1. Behavioral results

Based on the low-demands behavioral FB task performance, 27 infants were assigned to the passers group, while 18 infants were in the failers group. There was no significant difference between passers and failers in gender, age, general cognitive abilities, and

Table 1
The participants' demographic information.

	All participants	Passers	Failers	χ^2 | t	p
N	45	27	18		
Gender (m:f)	18:27	9:18	9:9	1.25	.264
Age (months)	34.51 (1.62)	34.49 (1.63)	34.54 (1.64)	0.087	.931
Age-range (months)	32.93–37.23	32.93–37.23	33.00–37.03	-	-
KABC-II (N = 36)	98.67 (8.41)	98.57 (8.91)	98.80 (7.95)	0.079	.937
SETK3 (N = 35)	53.52 (6.24)	53.68 (5.66)	53.31 (7.13)	−0.171	.865

Note. Standard deviations are presented in parentheses. IQ is measured with KABC-II task. Language skills are measured with SETK3 task.

language skills (see Table 1).

In the ERP belief task, mean response accuracy in the FB conditions (behavioral test question) for the passers and failers was 31.37 % ($SD = 18.30$) and 28.61 % ($SD = 21.57$), respectively. There was no significant difference in FB accuracy between the two groups ($t(43) = 1.169$, $p = .249$). Mean response accuracy in the TB conditions for the passers and failers was 43.24 % ($SD = 23.27$) and 51.50 % ($SD = 23.08$), respectively, and there was no significant difference in TB accuracy between the two groups ($t(43) = -0.460$, $p = .648$). In both groups, the mean response accuracy in the FB conditions was below 50 % (passers: $t(26) = -5.291$, $p < .001$; failers: $t(17) = -4.207$, $p = .001$) and was close to 50 % (passers: $t(26) = -1.508$, $p = .144$; failers: $t(17) = 0.275$, $p = .786$) in the TB conditions.

3.2. ERP results

3.2.1. ERP responses grouped by performance in the low-demands false belief task

Among 45 participants who met the ERP artifact criteria and completed the low-demands behavioral FB task concurrently, we used nonparametric cluster-based permutation tests to identify electrode clusters and time windows showing potential differences in late waveforms' amplitude across the two belief conditions (FB and TB). The permutation analysis revealed significant clusters for the effect of belief condition on late waveforms' amplitude (Negative cluster: electrodes: FC2, FC6, C3, C4; time window: ~691–910 ms and ~936–1004 ms after the auditory presented word; $t_{weight} = -1048.17$ and -286.40; $p = .002$ and.023. Positive cluster: electrodes: O1, Oz, O2; time window: ~721–914 ms and ~924–1064 ms after the auditory presented word; $t_{weight} = 932.76$ and 633.84; $p = .003$ and.007). See Fig. 4 and the supplementary materials (S3) for the distribution of these significant clusters.

Based on the amplitude of the late waveforms averaged separately over the negative and positive electrode clusters, the 3-way mixed-measures ANOVA revealed a significant interaction between group, belief condition, and electrode cluster ($F_{1,43} = 4.21$, $p = .046$, $\eta_p^2 = .09$) (see Table 2). To further explore the 3-way interaction effect, we conducted post-hoc pairwise comparisons between belief condition and electrode cluster on participants' performance on the low-demands FB task; we conducted post hoc 2-way ANOVAs separately for the passers and failers. These analyses revealed significant interactions between belief condition and electrode cluster only in passers (passers: $F_{1,26} = 28.62$, $p < .001$, $\eta_p^2 = .52$; failers: $F_{1,17} = 2.86$, $p = .109$, $\eta_p^2 = .14$). Post-hoc pairwise comparisons (see Fig. 5A) showed that, among the passers, the FB condition triggered a significantly more negative amplitude than the TB condition over the frontocentral electrode sites ($t_{43} = 3.45$, $p = .001$, Cohen's $d = 0.38$). The FB condition triggered a significantly more positive amplitude than the TB condition over the occipital electrode sites ($t_{43} = -5.33$, $p < .001$, Cohen's $d = -1.05$). Among the failers, the FB condition triggered a more negative amplitude than the TB condition over the frontocentral electrode sites ($t_{43} = 3.45$, $p = .001$, Cohen's $d = 0.38$), while no significant amplitude difference between the FB and TB conditions was observed ($t_{43} = -1.76$, $p = .467$, Cohen's $d = -0.18$) over the occipital electrode sites. The waveforms and topographical maps elicited under different belief conditions and groups are shown in Fig. 6.

Additionally, to explore amplitude differences between the 2 groups in each sub-condition, we also broke down the 3-way interaction by focusing on the effect of group for each level of the other 2 factors (i.e., belief condition and electrode cluster). The results showed that amplitude was significantly more positive in passers than failers in the FB condition over occipital electrode sites ($t_{43} = -2.11$, $p = .041$, Cohen's $d = -0.61$). However, there were no significant differences in amplitude between groups in the other 3 conditions (all p's > 0.05; see Fig. 5B). That is, within the context of participants who passed the low-demands FB task compared to those who failed, the FB condition elicited a higher amplitude over occipital electrode sites.

Furthermore, paired-sample t tests compared the FB and control conditions over the occipital electrode sites (i.e., O1, Oz, O2) in separate groups to ensure that the late waveforms observed in the FB condition in passers reflected FBU rather than detecting a match or mismatch between Leo's beliefs and reality (see Fig. 7). Among the passers, the FB condition triggered a significantly more positive amplitude than the control condition ($t_{23} = 3.09$, $p = .005$, Cohen's $d = 0.63$) over the occipital electrode sites, while no significant difference between conditions was found among the failers ($t_{14} = 0.86$, $p = .405$, Cohen's $d = 0.22$). Additional paired-samples t tests were also conducted to compare the TB and control conditions over the occipital electrode sites in separate groups. No significant differences were observed between the conditions in either group (Passers: $t_{23} = -1.43$, $p = .167$, Cohen's $d = 0.29$; Failers: $t_{14} = 0.51$, $p = .616$, Cohen's $d = 0.13$).

3.2.2. ERP responses grouped by accuracy on the behavioral questions in the ERP belief task

Among 70 participants, the permutation analysis revealed significant clusters for the effect of condition on late waveforms

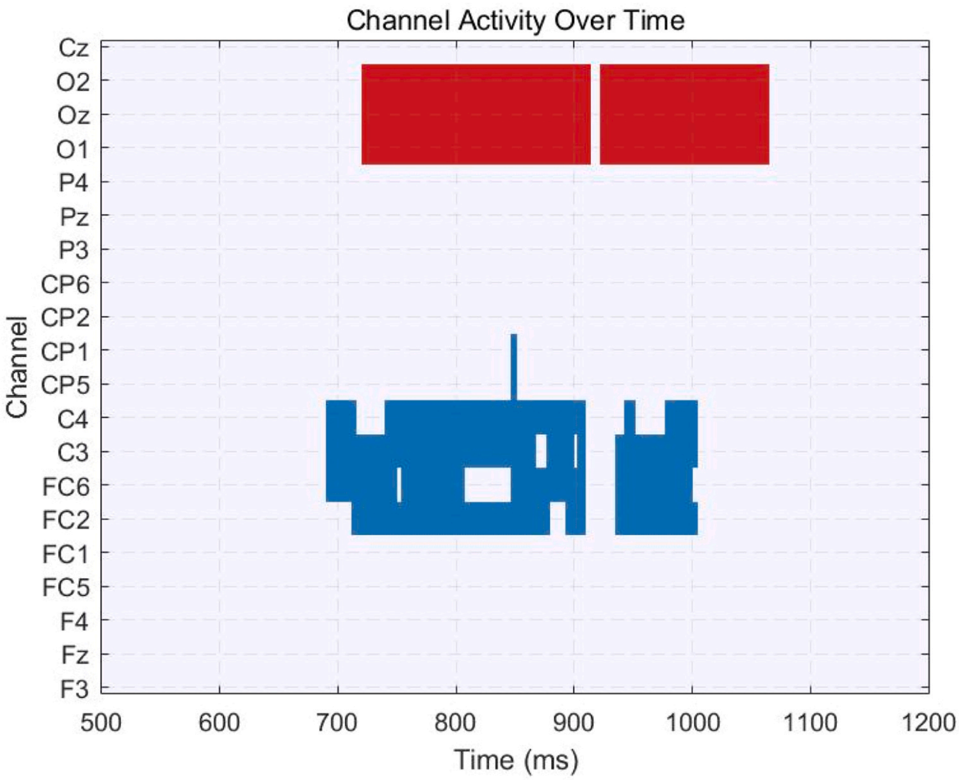

Fig. 4. Raster diagrams depicting significant differences in amplitude between the FB and TB conditions from the ERP belief task (i.e., Leo's belief task), as determined by a cluster-based permutation test (Sample size $N = 45$). Red and blue areas represent electrodes/time points where late waveforms' amplitude in the FB condition are more positive or more negative relative to the TB condition, respectively. Black areas indicate electrodes/time points where no significant differences were observed. In the first cluster (red area), significant effects are localized to electrodes O1, Oz, and O2. In the second cluster (blue area), significant effects are primarily localized to electrodes FC2, FC6, C3, and C4.

Table 2
ANOVA results on late waveforms amplitude, FB competence grouped by FB competence in the low-demands behavioral task.

Factor	$F_{(df=1,43)}$	p	η_p^2
Group	2.24	.142	.05
Belief Condition	2.93	.094	.06
Electrode Cluster**	12.24	.001	.22
Group × Belief Condition**	10.27	.003	.19
Group × Electrode Cluster	0.03	.861	.00
Condition × Electrode Cluster***	21.98	< .001	.34
Group × Belief Condition × Electrode Cluster*	4.21	.046	.09

Note: * $p < .05$; ** $p < .01$; *** $p < .001$.

amplitude (Negative cluster: electrodes: FC2, FC6, C3, C4; time window: ~625–807 ms and ~813–916 ms after the auditory presented word; $t_{weight} = -884.37$ and -477.75; $p = .003$ and.009. Positive cluster: electrodes: O1, Oz, O2; time window: ~607–1038 ms after the auditory presented word; $t_{weight} = 1937.29$; $p < .001$). See Fig. 8 and the supplementary materials (S4) for the distribution of these significant clusters.

Behavioral competence within the ERP belief paradigm, on average, was observed to be below chance levels, as anticipated. Consequently, to further investigate the brain-behavior connection, comparisons were made between extreme groups, specifically the top 25 % ($N = 18$) and bottom 25 % ($N = 18$) of performers based on FB accuracy of behavioral test questions in the ERP belief paradigm. Among 36 participants, the permutation analysis revealed significant clusters for the effect of condition on the late waveform's amplitude (Negative cluster: electrodes: FC6, C3, C4; time window: ~653–747 ms and ~761–803 ms after the auditory presented word; $t_{weight} = -458.74$ and -204.24; $p = .009$ and.045. Positive cluster: electrodes: O1, Oz, O2; time window: 717–867 ms after the auditory presented word; $t_{weight} = 572.81$; $p = .007$).

Based on the amplitude of the late waveforms averaged separately over the negative and positive clusters, the 3-way mixed-measures ANOVA revealed a marginally significant interaction between group, condition, and electrode ($F_{1,43} = 3.19$, $p = .083$, η_p^2

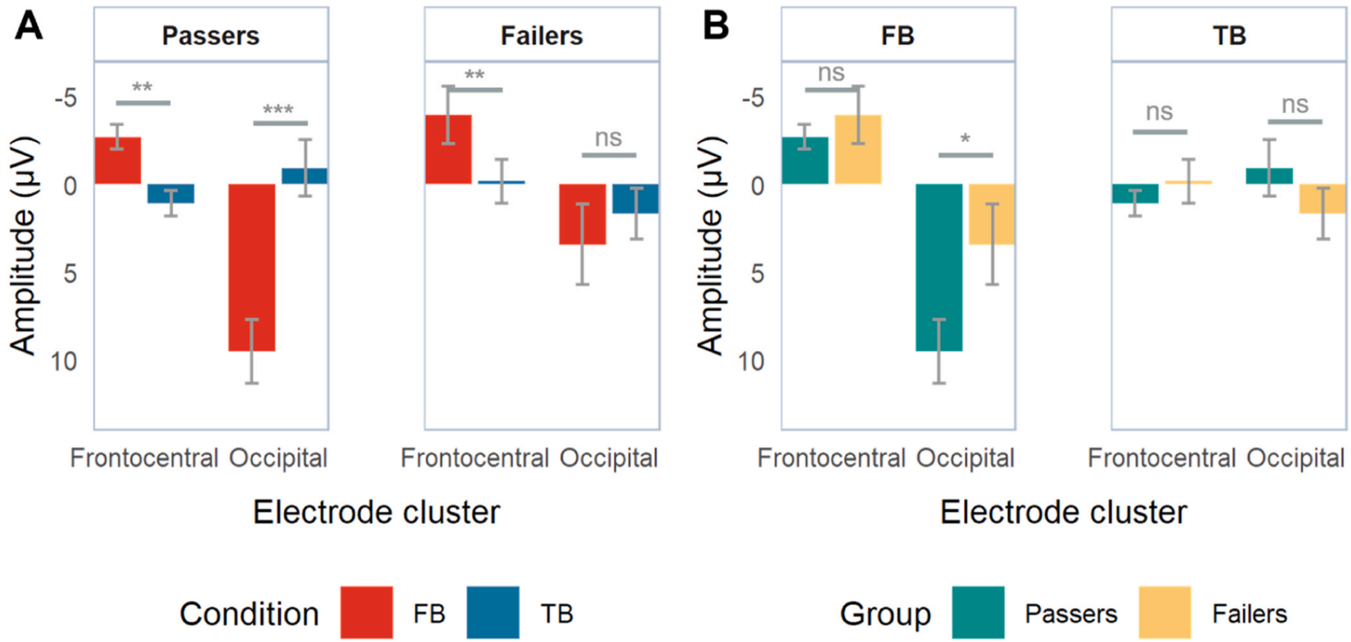

Fig. 5. (A) A late positive waveform over the occipital electrode sites distinguished between the FB and TB conditions only in passers, while a late negative waveform over the frontocentral electrode sites consistently distinguished between the FB and TB conditions regardless of the low-demands behavioral FB task performance. (B) Compared with failers, passers responded with a higher amplitude late waveform in the FB condition over occipital electrode sites. Data are expressed as mean ± SE. Note that, in (A), the SE refers to the standard error of the pairwise difference between the 2 compared sub-conditions; in (B), the SE refers to the standard error of the difference between the 2 independent means. ns: not significant; * $p < .05$; ** $p < .01$; *** $p < .001$.

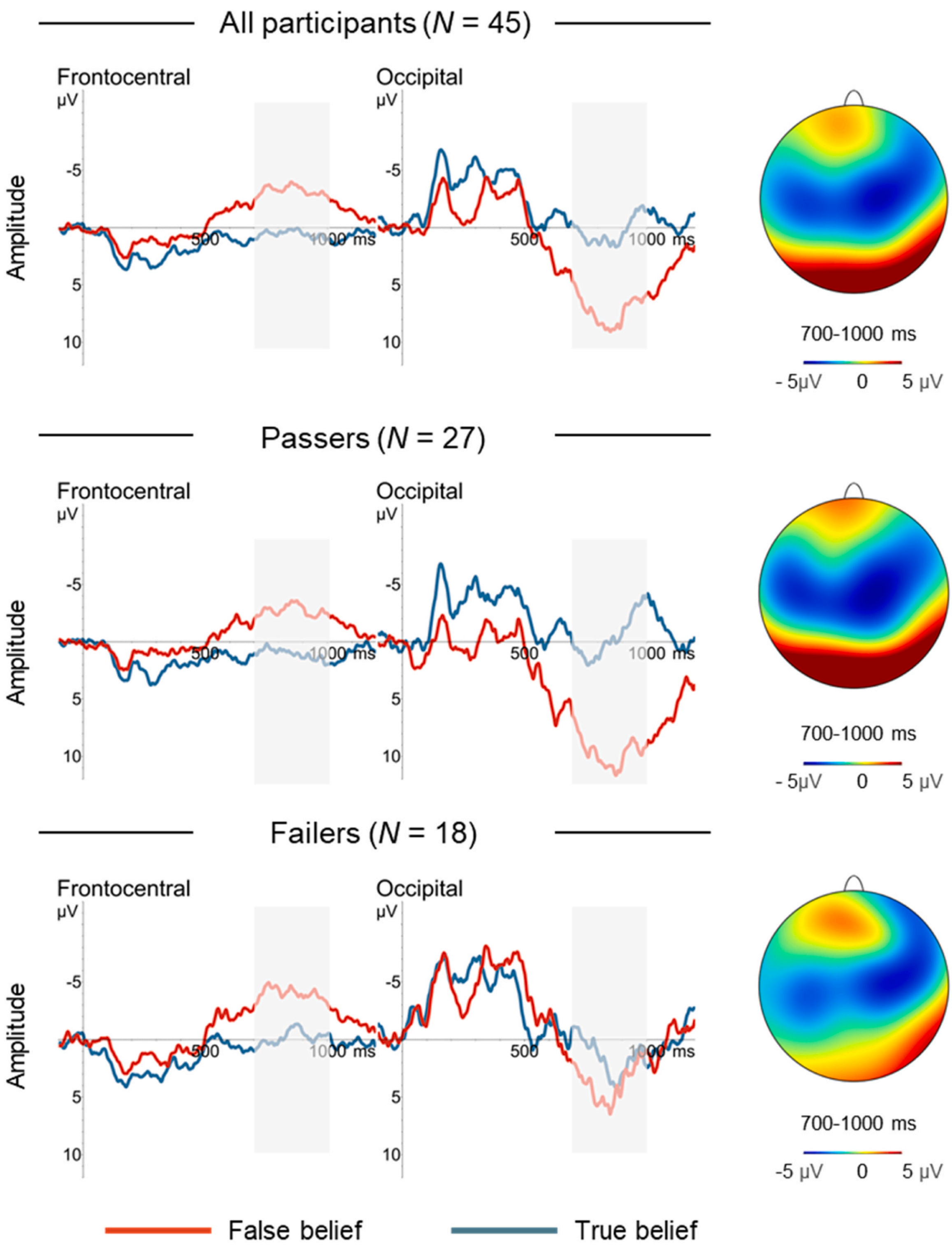

Fig. 6. Late waveforms separated for "condition" (FB, TB) and "group" (passers, failers) plotted over the averaged frontocentral (across FC2, FC6, C3, C4) and occipital (across O1, Oz, O2) electrode clusters. Red line: late waveforms in the FB condition; blue line: late waveforms in the TB condition. Topographic maps showed mean amplitude difference between late waveforms of the TB condition subtracted from the FB condition.

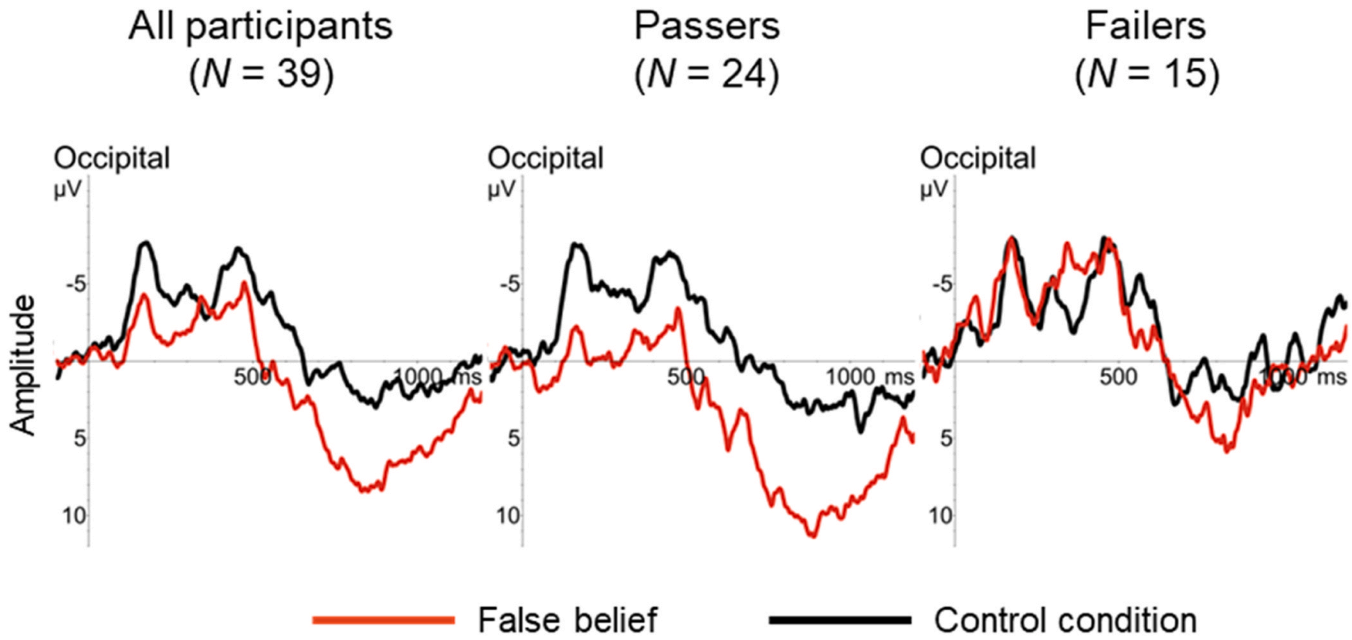

Fig. 7. Late waveforms separated for "condition" (FB, control condition) and "group" (all participants, passers, failers) plotted over the averaged occipital electrode sites (i.e., O1, Oz, O2). The additional analysis was narrowed down to 39 participants (Control condition: $M_{\text{-trials}} = 5.56$, $SD = 0.79$, range: 5–8), as six others had fewer than five control conditions recorded, which made their data incomplete.

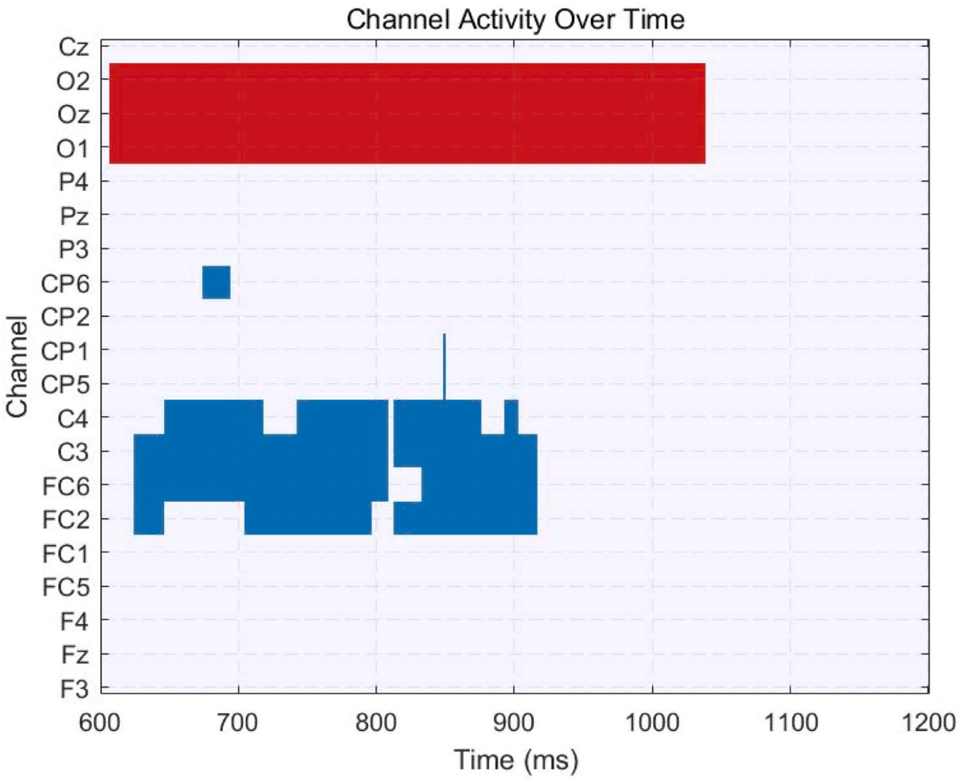

Fig. 8. Raster diagrams depicting significant differences in ERPs between the FB and TB conditions from Leo's belief task, as determined by a cluster-based permutation test (Sample size $N = 70$). Red and blue areas represent electrodes/time points where ERPs in the FB condition are more positive or more negative relative to the TB condition, respectively. Black areas indicate electrodes/time points where no significant differences were observed. In the first cluster (red area), significant effects are localized to electrodes O1, Oz, and O2. In the second cluster (blue area), significant effects are primarily localized to electrodes FC2, FC6, C3, and C4.

=.09) (see Table 3). To further explore the 3-way interaction effect, we conducted post-hoc pairwise comparisons between condition and electrode on participants' performance on the behavioral test questions in the ERP belief task; we conducted post-hoc 2-way ANOVAs separately for the top 25 % group and bottom 25 % group. These analyses revealed significant interactions between the belief condition and electrode only in the top 25 % group (top 25 % group: $F_{1,17} = 21.70$, $p < .001$, $\eta_p^2 = .56$; bottom 25 % group: $F_{1,17} = 3.62$, $p = .074$, $\eta_p^2 = .14$). Post hoc pairwise comparisons (see Fig. 9A) showed that, among the passers, the FB condition triggered a significantly more negative amplitude than the TB condition over the frontocentral electrode sites ($t_{34} = 4.56$, $p < .001$, Cohen's $d = 0.43$). The FB condition triggered a significantly more positive amplitude than the TB condition over the occipital electrode sites ($t_{43} = -3.56$, $p = .001$, Cohen's $d = -0.89$). Among the failers, the FB condition triggered a more negative amplitude than the TB condition over the frontocentral electrode sites ($t_{34} = 3.86$, $p < .001$, Cohen's $d = 0.37$), while no significant amplitude difference between the FB and the TB conditions was observed ($t_{34} = -0.85$, $p = .401$, Cohen's $d = -0.21$) over the occipital electrode sites. The waveforms and topographical maps elicited under different belief conditions and groups are shown in Fig. 10.

Additionally, to explore amplitude differences between the 2 groups in each of the sub-conditions, we also broke down the 3-way interaction by focusing on the effect of group for each level of the other 2 factors (i.e., belief condition and electrode). However, there were no significant differences in amplitude between groups in all four conditions (all p's > 0.05; see Fig. 9B).

Table 3
ANOVA results on late waveforms amplitude, FB competence grouped by performance on the behavioral test questions in the ERP belief task.

Factor	$F_{(df=1,34)}$	p	η_p^2
Group	0.30	.587	.01
Belief Condition	0.81	.375	.02
Electrode Cluster**	10.44	.003	.24
Group × Belief Condition[a]	3.31	.078	.09
Group × Electrode Cluster	0.64	.431	.02
Condition × Electrode Cluster***	20.88	< .001	.38
Group × Belief Condition × Electrode Cluster[a]	3.19	.083	.09

Note: [a] $p < .10$; * $p < .05$; ** $p < .01$; *** $p < .001$.

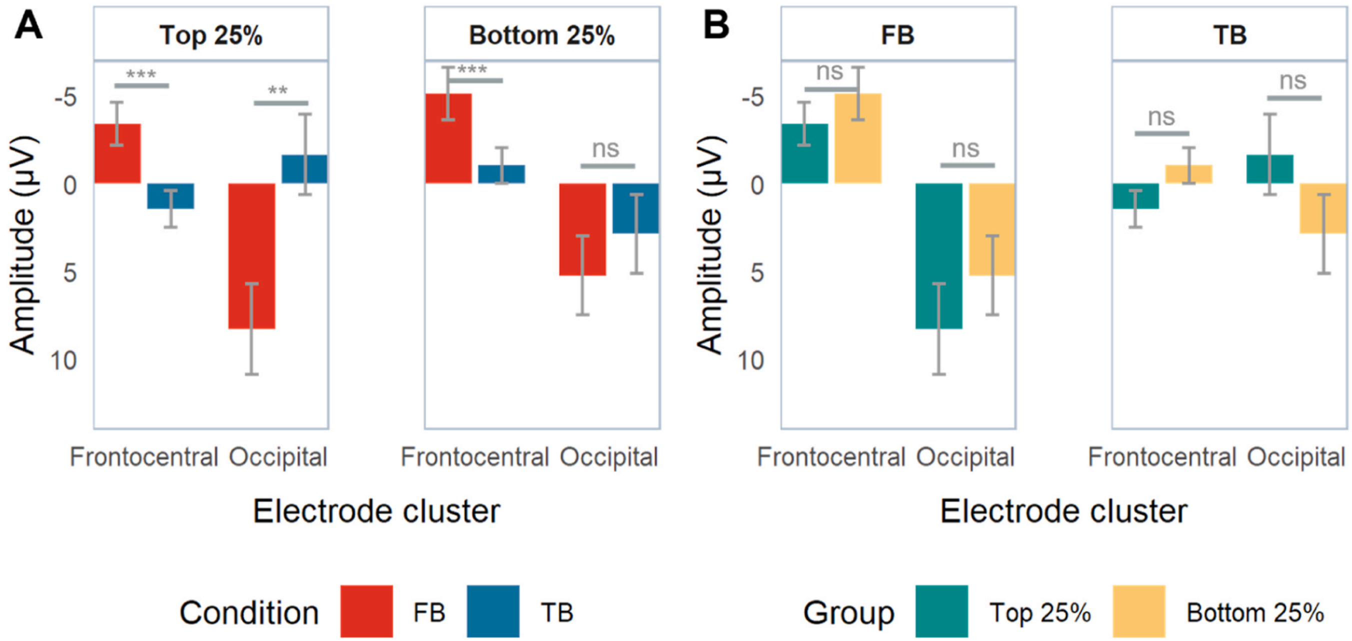

Fig. 9. (A) A late positive waveform over the occipital electrode sites distinguished between the FB and TB conditions only in children with top 25 % FB accuracy in the ERP belief task, while a late negative waveform over the frontocentral electrode sites consistently distinguished between the FB and TB conditions regardless of FB accuracy in the ERP belief task. (B) Compared with children with bottom 25 % FB accuracy in the ERP belief task, children with top 25 % FB accuracy in the ERP belief task responded with a higher amplitude late waveform in the FB condition over occipital electrode sites. Data are expressed as mean ± SE. Note that, in (A), the SE refers to the standard error of the pairwise difference between the 2 compared sub-conditions; in (B), the SE refers to the standard error of the difference between the 2 independent means. ns: not significant; * $p < .05$; ** $p < .01$; *** $p < .001$.

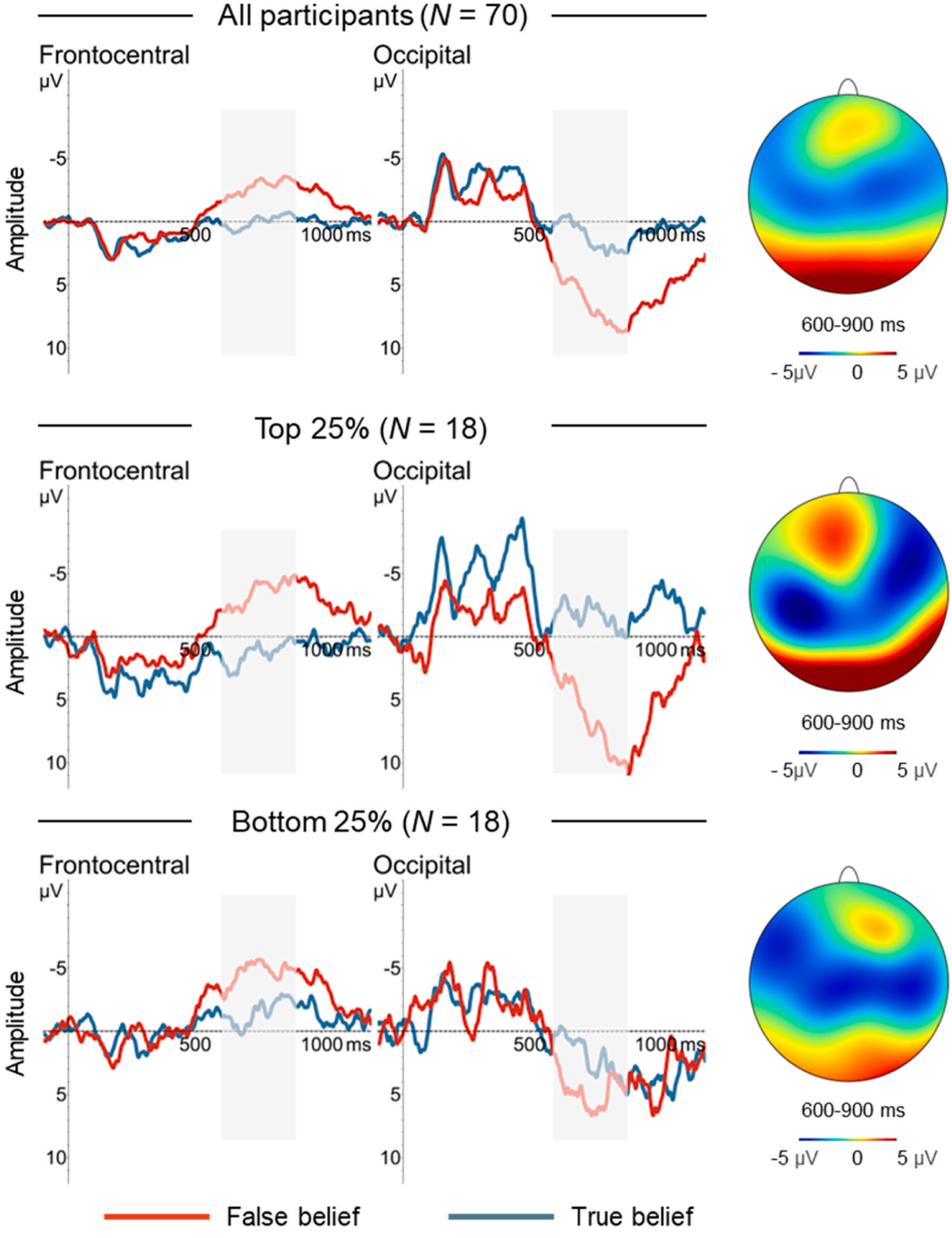

Fig. 10. ERP waveforms separated for "condition" and "group" (children with top 25 % and bottom 25 % FB accuracy in the ERP belief task) plotted over the averaged frontocentral and occipital electrode sites. Red line: ERP waveforms in the FB condition; blue line: ERP waveforms in the TB condition. Topographic maps showed mean amplitude differences between ERPs of the TB condition subtracted from the FB condition.

The analytical approach and pattern of results presented here closely parallel those from the independent behavioral FB task described in Section 3.2.1, thereby strengthening the evidence for neural correlates of FBU in infants. However, these findings should be considered supplementary, given the relatively low accuracy on the ERP task's behavioral questions and the smaller sample sizes in the top and bottom 25 % groups. The low-demands behavioral FB task remains essential, as it offers a clearer performance distinction for categorizing infants younger than 3 years into FB passers and failers.

4. Discussion

The present study examined the neural correlates of explicit FBU in infants aged 33–36 months. Recent behavioral research has shown that infants younger than 3 years can succeed in low-demands explicit FB tasks (Grosso et al., 2019; Scott et al., 2020; Setoh et al., 2016). However, to date, no research has investigated the neural correlates of explicit FBU in such young children. The present study found that early competence in a low-demands FB task is paralleled by distinctive neural response patterns associated with FB processing.

Infants aged 33–36 months exhibited late waveforms with distinct patterns in the FB and TB conditions across frontocentral and occipital electrode sites. In line with previous developmental cognitive neuroscience research, the present finding of a more diffuse and less lateralized distribution of late waveforms in infants who processed false beliefs aligned with reports of more diffuse and bilateral brain activation in older children compared to adults performing the same ToM tasks (e.g., Kühn-Popp et al., 2013; Liu et al., 2004, 2009b; Meinhardt et al., 2011, 2012; Sabbagh & Taylor, 2000). We tentatively associated the late waveforms observed in infants with those found in older children and adults, suggesting a potential continuity in the neural processing of false belief across development.

Following the approach by Liu et al. (2009b) in older children, this study grouped 33- to 36-month-old infants into passers and failers based on their performance in the low-demands behavioral FB task by Setoh et al. (2016). For all participants, the amplitude differentiation of late waveforms was observed over the frontocentral electrode sites. However, the amplitude differentiation of late waveforms between the FB and TB conditions over the occipital electrode sites was observed only in passers, showing a connection to their behavioral FB competence. This brain-behavior connection associated with FBU expands on Liu et al.'s (2009b) findings, indicating a close relationship between behavioral FB competence and a neural-level distinction between the FB and TB conditions. Our study directly contrasts FB with TB conditions, underscoring the neural sensitivity of FB reasoning over general mental state reasoning. It can be inferred that a neural system of belief-based processing is functional even before the third birthday.

4.1. Interpreting neural correlates of false belief understanding across development

While both Liu et al. (2009b) and the present study revealed neural sensitivity for FBU in young children, they identified distinct brain regions engaged in belief reasoning. Specifically, we found engagement of occipital electrode sites in infants associated with behavioral FB competence, contrasting with Liu et al.'s (2009b) identification of frontal sites involvement in children aged 4–6 years with behavioral FB competence. These discrepancies may reflect developmental progressions in the neural ToM network but may also result from distinct effects of task configuration on neural responses.

One possibility is that this difference may be due to the developmental maturation timeline. Specifically, the occipital regions mature earlier and undergo significant development in early childhood, while frontal regions show marked maturation after three years (Deoni et al., 2015). Such asynchronous maturation patterns hint at the posterior regions' earlier functional readiness for social cognition tasks, including processing belief-related information, compared to the anterior regions. However, given the cross-sectional nature of our comparison, which spans studies conducted in different countries with different tasks, coupled with the lack of precise localization in ERP studies, these interpretations should be considered preliminary. A nuanced understanding calls for further research to elucidate the developmental trajectory of neural mechanisms underlying FBU and clarify how these mechanisms are refined with age.

Besides developmental brain maturation, task differences may also impact the observed late waveform patterns between our study and Liu et al. (2009b). The two studies differed in ERP eliciting event configurations. In Liu et al. (2009b) study, the presentation of a story scenario was followed by a "think" and a "reality" question. The ERPs for the "think" and the "reality" conditions were time-locked to the "think" and "reality" events which immediately followed the respective behavioral questions. Thus, Liu et al. (2009b) assessed the neural correlates of children's explicit verbal reasoning about false and true beliefs in comparison to reality. In contrast, our ERP eliciting events were activated by the auditory presentation of the last word of the belief information (e.g., "Leo thinks the ball is in the ***box***") without explicit belief reasoning instructions. Explicit belief reasoning instructions might engage neurocognitive processes differently than passive exposure to belief information, potentially tapping into a spontaneous representational understanding of beliefs (Aichhorn et al., 2009).

Our findings were comparable with those obtained in studies of adults and older children (6–12 years) (e.g., Kühn-Popp et al., 2013; Liu et al., 2004, 2009b; Meinhardt et al., 2011, 2012; Sabbagh & Taylor, 2000), which also observed two distinct late waveforms, suggesting that these ERPs represent common neural responses in belief reasoning. Besides the late waveforms over the frontal sites, prior studies highlighted the presence of late waveforms over the parietal or parieto-occipital regions during belief reasoning tasks (Bowman et al., 2012; Guan et al., 2020; Kühn-Popp et al., 2013; Meinhardt et al., 2011). Our study corroborates this finding by detecting late positive waveforms in the posterior region, particularly towards the occipital electrode sites, reflecting broader and more delayed neural responses in infants compared to adults, supporting the notion of age-related changes in ERP latency (DeBoer et al., 2007; Taylor & Baldeweg, 2002) and the gradual enhancement of neural processing efficiency throughout childhood (Kail, 1991; Meinhardt et al., 2011).

The association of only one of the two late waveforms with behavioral FB competence in our study provides a nuanced perspective on their role in belief reasoning. Our results thus tentatively support a dual-process model for interpreting neural responses to FB compared to TB information. Specifically, late negative waveforms independent of behavioral FBU competence were observed over the frontocentral electrode sites. One interpretation of this result is that the frontal neural response primarily engages with the match or mismatch detection between Leo's belief and the state of reality rather than with the attribution of mental states. However, mismatch detection processes typically peak early, around 100 ms, reflecting a largely automatic process (Friederici et al., 2002; Nelson & McCleery, 2008). Since the present task required infants to process a complex sentence containing a sentential complement, a more delayed mismatch detection may be possible.

An alternative interpretation of the findings is that two mentalistic response processes may be elicited almost simultaneously by the spontaneous response ERP task, a non-representational one over the frontocentral electrode sites and a representational one over the occipital electrode sites. FBU involves a representational understanding of the mind, that is, an understanding that another person may misrepresent a state of the world, thereby seriously holding a claim to be true that the participant knows to be false. In early childhood development, non-representational, but nonetheless mentalistic ways of handling falsity can also be observed. One prominent example is pretend play: The children who pretend to drink from an empty cup behave as if there was tea in the cup but do not entertain this thought as a claim about the truth. A cognitive theory by Perner (1991, Chapter 8) distinguishes between "thinking of" (non-representational processing akin to desires or preferences) and "thinking that" (representational belief reasoning). The child who conceives of an agent as "thinking of" a state of the world (e.g., Leo thinks of the ball as being in the box) will recognize the discrepancy between Leo's thought and the real state of the world without representing Leo's thought as a misrepresentation of reality. Thus, the frontocentral neural responses to belief information may reflect the recognition of a discrepancy (as opposed to a correspondence) between a belief and a state of the world at a non-representational level.

In contrast, late waveforms observed over the occipital electrode sites may appear to reflect participants' reasoning about beliefs as claims about the truth ("thinking that"). This kind of reasoning not only conceives of an agent as mentally connected to a state of the world but as correctly or falsely representing the state of the world. Thus, at this level, infants not only distinguish between mental states and states of the world but also understand the representational relation between them, which is equivalent to a representation of perspectives. This process of perspective representation is evidenced by late positive waveforms over the occipital electrode sites, which differentiated belief conditions and were observed only in children who passed the behavioral FB task. These results align with findings from Bowman et al. (2012), who identified selective posterior neural responses associated solely with belief reasoning in children who successfully answered the behavioral test questions. Similarly, contrasting FB tasks with non-mental tasks involving misinformation (e.g., the false sign task) revealed neural sensitivity to belief representation, particularly over posterior regions (Aichhorn et al., 2009; Perner et al., 2006; Wysocka et al., 2020; Zhang et al., 2013). However, the inherent limitations in the spatial resolution of ERP data preclude definitive identification of involved cortical structures. Further research is needed to dissect the complex neural mechanisms supporting FBU.

4.2. Theoretical implications of the present findings

Recent debates in the ToM literature revolved around whether infants and young children undergo a conceptual reorganization in their understanding of the mind (i.e., the "conceptual change" view) or whether even infants possess a conceptual framework for representing beliefs that remains stable over development (i.e., the "conceptual continuity" view). According to conceptual change accounts, children initially lack genuine belief representations and only come to acquire them through a qualitative developmental reorganization around age 4 or 5 (e.g., Gopnik & Astington, 1988; Perner, 1991; Wellman, 2014). In contrast, conceptual continuity perspectives maintain that infants and very young children are able to represent beliefs when tested under optimal conditions (low memory, response generation, and executive demands) (e.g., Baillargeon et al., 2010, 2016; Leslie et al., 2004).

The brain-behavior relations observed in the present study support the conceptual continuity account of FBU development. Children between 33 and 36 months of age exhibited neural activity specifically associated with FB processing, differentiating between FB and TB conditions at frontocentral and occipital sites. Most importantly, a brain-behavior correlation in FB processing was found with behavioral passers exhibiting distinct responses to FB versus TB information at occipital sites. These results were very similar to findings reported by Liu et al. (2009b) in 4- to 6-year-old children, indicating that continuity in FB processing in the brain is reflected on the behavioral level when task demands are appropriately reduced. This pattern also aligned with previous studies that showed brain-behavior relations in 3- to 5-year-old children and found that passers and failers on standard explicit FB tasks differed in their neural responses to the passive viewing of FB events (Bowman & Brandone, 2024). It is possible that a developmental shift in FB processing occurred from posterior to frontal brain regions between infancy and preschool years; however, this remained difficult to determine based on existing studies and warrants further exploration. It is also possible that, early in development, dual processing of belief-related information may take place in the brain, although it remains unclear to what extent the two processes observed in the present study were task-specific. In any case, there is evidence in both 33- to 36-month-old infants and 4- to 6-year-olds children for distinct neural responses to FB and TB information that are associated with the behavioral mastery of FB tasks. These findings support substantive continuity in brain-behavior relations in FB processing.

Future research needs to investigate brain-behavior relations in FBU over a broader age range in tasks varying in domain-general demands to determine the relation of developmental changes in the neural ToM network and behavioral FB competence. It should be noted that in the present study domain-general task demands, such as memory, inhibition, or response generation, may have contributed to an underestimation of infants' FBU in both the ERP and behavioral tasks. Although conceptual continuity theory proposes that competence in FBU is continuous from infancy to adulthood, performance accuracy in the present behavioral and ERP tasks did not approach ceiling levels. Thus, further research is necessary to determine whether performance can be improved by reducing specific task-related processing demands. Moreover, research efforts are needed to connect explicit FBU at 33 months with implicit FBU in the first and second years of life. Based on findings by Hyde et al., (2015, 2018), there is evidence of similarities between infants' and adults' neural responses to passively viewing FB versus control scenarios. Similar neural patterns are expected when comparing young infants with 2- to 3-year-old children.

From a clinical perspective, identifying the early neural correlates of FBU in typically developing infants may offer valuable insights into disorders characterized by challenges in social cognition, such as autism spectrum disorder (Andreou & Skrimpa, 2020; Baron-Cohen, 1997, 2001). Early detection of atypical neural patterns underlying FB reasoning could inform diagnostic approaches and targeted interventions, potentially improving developmental trajectories for children at risk. Furthermore, investigating these neural markers could shed further light on how social-cognitive deficits emerge and persist, providing a foundation for refining therapeutic strategies in clinical settings.

4.3. Strengths and limitations of the study

A notable strength of our method is using independent tasks to assess FBU on both neural and behavioral levels. The behavioral FB task, designed with decreased response-generation and inhibitory-control demands, assesses infants' ability to infer FBs within a traditional paradigm, while the ERP task tracks the real-time neural signatures of processing false beliefs and their causal impact on an agent's actions. Because these tasks rely on different skill sets and each task targets unique yet complementary dimensions of FB reasoning, the likelihood that children rely on the same superficial strategies or cues across both measures is substantially reduced.

Despite these strengths, our study also has limitations. First, due to task-specific characteristics, further research is needed to clarify the extent to which neural correlates of FBU are independent of task demands. Second, the narrow age range of 33–36 months limits the generalizability of our findings; including a broader age range in future studies would help elucidate developmental patterns. Finally, infants' limited attention spans and behavioral variability constrained the number of ERP trials. In ERP research involving young children, there needs to be more certainty about the specific criteria governing the number or the proportion of trials necessary for stable ERP estimates. Previous work conducted a comprehensive review of ERP studies involving young children concerning infant ERP data for cognitive research, suggesting a minimum of five usable trials, with an average of eight trials for analysis (Brooker et al., 2020; Stets et al., 2012). Nonetheless, given the challenges of ERP research with this age group, our study offers an important early step in investigating the neural basis of FBU in early childhood. Crucially, recent EEG research on infant social cognition (Filippi et al., 2020; Southgate & Vernetti, 2014) has demonstrated that meaningful conclusions about belief-based action prediction and neural correlates of infant action processing related to ToM can indeed be drawn from a small number of artifact-free trials. This methodological parallel underscore the value of limited trial datasets in revealing early cognitive processes and cautiously supports the potential contribution of our findings to the emerging understanding of the neural basis of FBU, while underscoring the need for further research.

4.4. Conclusion

In summary, our study integrated a low-demands behavioral FB task with a novel ERP paradigm to elucidate the brain-behavior connections underlying FBU in infants under three years of age. Identifying one of two late waveforms associated with behavioral FB competence indicated an early sensitive neural system supporting FBU. We observed late negative waveforms over the frontocentral electrode sites in both passers and failers. Crucially, late positive waveforms over the occipital electrode sites—observed exclusively in children who demonstrated behavioral FB competence—appear to reflect belief representation on the neural level in infants. These findings suggest the possibility of early sensitivity in neural systems that support FBU. Further rigorous experiments with large sample sizes are essential to validate and expand upon the current findings. Such studies will be crucial for refining our understanding of the cognitive and neural architecture of ToM from a developmental perspective.

Ethics statement

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

CRediT authorship contribution statement

Shuting Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Jörg Meinhardt:** Writing – review & editing, Supervision, Resources, Project administration, Methodology. **Beate Sodian:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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 (DFG) to the last author [grant numbers SO 213/33–1, SO 213/33–2] and the China Scholarship Council (CSC) to the first author [grant number CSC202006040034]. The project is part of the research group "Crossing the Borders: The Interplay of Language, Cognition, and the Brain in Early Human Development." We thank the children, parents, and students who participated in this study. We are grateful to Barbara C.N. Müller, to Josef Perner, and to Qiaoyue Ren for comments on an earlier version of this manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.infbeh.2025.102106.

Data and code availability statement

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

References

Aichhorn, M., Perner, J., Weiss, B., Kronbichler, M., Staffen, W., & Ladurner, G. (2009). Temporo-parietal junction activity in theory-of-mind tasks: falseness, beliefs, or attention. *Journal of Cognitive Neuroscience, 21*(6), 1179–1192. https://doi.org/10.1162/jocn.2009.21082

Andreou, M., & Skrimpa, V. (2020). Theory of mind deficits and neurophysiological operations in autism spectrum disorders: a review. Article 6. *Brain Sciences, 10*(6). https://doi.org/10.3390/brainsci10060393

Bailey, K., Mlynarczyk, G., & West, R. (2016). Slow wave activity related to working memory maintenance in the N-back task. *Journal of Psychophysiology, 30*(4), 141–154. https://doi.org/10.1027/0269-8803/a000164

Baillargeon, R., Scott, R. M., & Bian, L. (2016). Psychological reasoning in infancy. *Annual Review of Psychology, 67*(1), 159–186. https://doi.org/10.1146/annurev-psych-010213-115033

Baillargeon, R., Scott, R. M., & He, Z. (2010). False-belief understanding in infants. *Trends in Cognitive Sciences, 14*(3), 110–118. https://doi.org/10.1016/j.tics.2009.12.006

Baron-Cohen, S. (1997). *Mindblindness: An Essay on Autism and Theory of Mind*. MIT Press.

Baron-Cohen, S. (2001). Theory of mind in normal development and autism. *Prisme, 34*.

Barone, P., Corradi, G., & Gomila, A. (2019). Infants' performance in spontaneous-response false belief tasks: a review and meta-analysis. *Infant Behavior and Development, 57*, Article 101350. https://doi.org/10.1016/j.infbeh.2019.101350

Barriga-Paulino, C. I., Rodríguez-Martínez, E. I., Rojas-Benjumea, M.Á., & Gómez, C. M. (2014). Slow wave maturation on a visual working memory task. *Brain and Cognition, 88*, 43–54. https://doi.org/10.1016/j.bandc.2014.04.003

Bowman, L. C., & Brandone, A. C. (2024). Neural correlates of preschoolers' passive-viewing false belief: insights into continuity and change and the function of right temporoparietal activity in theory of mind development. *Developmental Science, 27*(6), Article e13530. https://doi.org/10.1111/desc.13530

Bowman, L. C., Liu, D., Meltzoff, A. N., & Wellman, H. M. (2012). Neural correlates of belief- and desire-reasoning in 7- and 8-year-old children: an event-related potential study. *Developmental Science, 15*(5), 618–632. https://doi.org/10.1111/j.1467-7687.2012.01158.x

Brooker, R. J., Bates, J. E., Buss, K. A., Canen, M. J., Dennis-Tiwary, T. A., Gatzke-Kopp, L. M., Hoyniak, C., Klein, D. N, Kujawa, A., Lahat, A., Lamm, C., Moser, J. S., Petersen, I. T., Tang, A., Woltering, S., & Schmidt, L. A. (2020). Conducting event-related potential (ERP) research with young children: A review of components, special considerations, and recommendations for research on cognition and emotion. *J. Psychophysiol., 34*(3), 137–158. https://doi.org/10.1027/0269-8803/a000243

Buttelmann, D., Carpenter, M., & Tomasello, M. (2009). Eighteen-month-old infants show false belief understanding in an active helping paradigm. *Cognition, 112*(2), 337–342. https://doi.org/10.1016/j.cognition.2009.05.006

Buttelmann, D., Over, H., Carpenter, M., & Tomasello, M. (2014). Eighteen-month-olds understand false beliefs in an unexpected-contents task. *Journal of Experimental Child Psychology, 119*, 120–126.

Chen, L., Cheung, H., Szeto, C.-Y., Zhu, Z., & Wang, S. (2012). Do false belief and verb non-factivity share similar neural circuits? *Neuroscience Letters, 510*(1), 38–42. https://doi.org/10.1016/j.neulet.2011.12.065

Clements, W. A., & Perner, J. (1994). Implicit understanding of belief. *Cognitive Development, 9*(4), 377–395. https://doi.org/10.1016/0885-2014(94)90012-4

DeBoer, T., Scott, L. S., & Nelson, C. A. (2007). Methods for acquiring and analyzing infant event-related potentials. In M. de Haan (Ed.), *Infant EEG and Event-related Potentials* (pp. 5–37). Psychology Press.

Deoni, S. C. L., Dean, D. C., Remer, J., Dirks, H., & O'Muircheartaigh, J. (2015). Cortical maturation and myelination in healthy toddlers and young children. *NeuroImage, 115*, 147–161. https://doi.org/10.1016/j.neuroimage.2015.04.058

Dien, J. (1998). Issues in the application of the average reference: review, critiques, and recommendations. *Behavior Research Methods, Instruments, Computers, 30*(1), 34–43. https://doi.org/10.3758/BF03209414

Döhnel, K., Schuwerk, T., Meinhardt, J., Sodian, B., Hajak, G., & Sommer, M. (2012). Functional activity of the right temporo-parietal junction and of the medial prefrontal cortex associated with true and false belief reasoning. *NeuroImage, 60*(3), 1652–1661. https://doi.org/10.1016/j.neuroimage.2012.01.073

Elsner, B., Jeschonek, S., & Pauen, S. (2013). Event-related potentials for 7-month-olds' processing of animals and furniture items. *Developmental Cognitive Neuroscience, 3*, 53–60. https://doi.org/10.1016/j.dcn.2012.09.002

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Filippi, C., Choi, Y. B., Fox, N. A., & Woodward, A. L. (2020). Neural correlates of infant action processing relate to theory of mind in early childhood. *Dev. Sci., 23*(2). https://doi.org/10.1111/desc.12876

Friederici, A. D., Friedrich, M., & Weber, C. (2002). Neural manifestation of cognitive and precognitive mismatch detection in early infancy. *Neuroreport, 13*(10), 1251–1254. https://doi.org/10.1097/00001756-200207190-00006

Geangu, E., Gibson, A., Kaduk, K., & Reid, V. M. (2013). The neural correlates of passively viewed sequences of true and false beliefs. *Social Cognitive and Affective Neuroscience, 8*(4), 432–437. https://doi.org/10.1093/scan/nss015

Gopnik, A., & Astington, J. W. (1988). Children's understanding of representational change and its relation to the understanding of false belief and the appearance-reality distinction. *Child Development, 59*(1), 26–37. https://doi.org/10.1111/j.1467-8624.1988.tb03192.x

Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology, 55*(4), 468–484. https://doi.org/10.1016/0013-4694(83)90135-9

Grimm, H., Aktaş, M., & Frevert, S. (2015). *Sprachentwicklungstest für drei- bis fünfjährige Kinder*. Hogrefe.

Grosse Wiesmann, C., Friederici, A. D., Singer, T., & Steinbeis, N. (2020). Two systems for thinking about others' thoughts in the developing brain. *Proceedings of the National Academy of Sciences, 117*(12), 6928–6935. https://doi.org/10.1073/pnas.1916725117

Grosse Wiesmann, C., Schreiber, J., Singer, T., Steinbeis, N., & Friederici, A. D. (2017b). White matter maturation is associated with the emergence of theory of mind in early childhood. *Nature Communications, 8*(1), Article 14692. https://doi.org/10.1038/ncomms14692

Grosso, S. S., Schuwerk, T., Kaltefleiter, L. J., & Sodian, B. (2019). 33-month-old children succeed in a false belief task with reduced processing demands: A replication of Setoh et al. (2016). *Infant Behavior and Development, 54*, 151–155. https://doi.org/10.1016/j.infbeh.2018.09.012

Guan, Y., Keil, A., & Farrar, M. J. (2020). Electrophysiological dynamics of false belief understanding and complementation syntax in school-aged children: oscillatory brain activity and event-related potentials. *Journal of Experimental Child Psychology, 198*, Article 104905. https://doi.org/10.1016/j.jecp.2020.104905

Hoehl, S., & Wahl, S. (2012). Recording infant ERP data for cognitive research. *Developmental Neuropsychology, 37*(3), 187–209. https://doi.org/10.1080/87565641.2011.627958

Hyde, D. C., Aparicio Betancourt, M., & Simon, C. E. (2015). Human temporal-parietal junction spontaneously tracks others' beliefs: a functional near-infrared spectroscopy study. *Human Brain Mapping, 36*(12), 4831–4846. https://doi.org/10.1002/hbm.22953

Hyde, D. C., Simon, C. E., Ting, F., & Nikolaeva, J. I. (2018). Functional organization of the temporal-parietal junction for theory of mind in preverbal infants: a near-infrared spectroscopy study. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 38*(18), 4264–4274. https://doi.org/10.1523/JNEUROSCI.0264-17.2018

IBM Corp. (2023). *IBM SPSS Statistics for Windows, Version 29.0.2.0 (Version 29.0.2.0) [Computer software]*. IBM Corp.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin, 109*(3), 490–501. https://doi.org/10.1037/0033-2909.109.3.490

Kaltefleiter, L. J., Schuwerk, T., Wiesmann, C. G., Kristen-Antonow, S., Jarvers, I., & Sodian, B. (2022). Evidence for goal- and mixed evidence for false belief-based action prediction in 2- to 4-year-old children: a large-scale longitudinal anticipatory looking replication study. *Developmental Science, 25*(4). https://doi.org/10.1111/desc.13224

Knudsen, B., & Liszkowski, U. (2012). 18-month-olds predict specific action mistakes through attribution of false belief, not ignorance, and intervene accordingly. *Infancy, 17*(6), 672–691.

Kobayashi, C., Glover, G. H., & Temple, E. (2007). Children's and adults' neural bases of verbal and nonverbal 'theory of mind. *Neuropsychologia, 45*(7), 1522–1532. https://doi.org/10.1016/j.neuropsychologia.2006.11.017

Kovács, Á. M., Téglás, E., & Endress, A. D. (2010). The social sense: Susceptibility to others' beliefs in human infants and adults. *Science, 330*(6012), 1830–1834. https://doi.org/10.1126/science.1190792

Kühn-Popp, N., Sodian, B., Sommer, M., Döhnel, K., & Meinhardt, J. (2013). Same or different? ERP correlates of pretense and false belief reasoning in children. *Neuroscience, 248*, 488–498. https://doi.org/10.1016/j.neuroscience.2013.06.017

Le Petit, M., Eustache, F., Perrier, J., de La Sayette, V., Desgranges, B., & Laisney, M. (2022). Functional connectivity of the medial prefrontal cortex related to mindreading abilities. *Cerebral Cortex Communications, 3*, 1–13. https://doi.org/10.1093/texcom/tgac032

Leslie, A. M., Friedman, O., & German, T. P. (2004). Core mechanisms in 'theory of mind. *Trends in Cognitive Sciences, 8*(12), 528–533. https://doi.org/10.1016/j.tics.2004.10.001

Li, S., Meinhardt, J., & Sodian, B. (2023). Neural correlates of theory of mind development in young children. *International Journal on Neuropsychology and Behavioural Sciences, 4*(1), 1–2.

Li, S., Müller, B. C. N., Meinhardt, J., & Sodian, B. (2025). Resting-state EEG alpha asymmetry predicts false belief understanding during early childhood: An exploratory longitudinal study. *Brain Research.* , Article 149523. https://doi.org/10.1016/j.brainres.2025.149523

Liu, D., Meltzoff, A. N., & Wellman, H. M. (2009a). Neural correlates of belief- and desire-reasoning. *Child Development, 80*(4), 1163–1171. https://doi.org/10.1111/j.1467-8624.2009.01323.x

Liu, D., Sabbagh, M. A., Gehring, W. J., & Wellman, H. M. (2004). Decoupling beliefs from reality in the brain: an ERP study of theory of mind. *NeuroReport, 15*(6), 991–995. https://doi.org/10.1097/01.wnr.0000123388.87650.06

Liu, D., Sabbagh, M. A., Gehring, W. J., & Wellman, H. M. (2009b). Neural correlates of children's theory of mind development. *Child Development, 80*(2), 318–326. https://doi.org/10.1111/j.1467-8624.2009.01262.x

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Meinhardt, J., Kühn-Popp, N., Sommer, M., & Sodian, B. (2012). Distinct neural correlates underlying pretense and false belief reasoning: evidence from ERPs. *NeuroImage, 63*(2), 623–631. https://doi.org/10.1016/j.neuroimage.2012.07.019

Meinhardt, J., Sodian, B., Thoermer, C., Döhnel, K., & Sommer, M. (2011). True- and false-belief reasoning in children and adults: an event-related potential study of theory of mind. *Developmental Cognitive Neuroscience, 1*(1), 67–76. https://doi.org/10.1016/j.dcn.2010.08.001

Melchers, P., & Melchers, M. (2015). *Kaufman Assessment Battery for Children, Second Edition (KABC-II). (Deutschsprachige Fassung)*. NCS Pearson Inc.

Nelson, C. A., & McCleery, J. P. (2008). Use of event-related potentials in the study of typical and atypical development. *Journal of the American Academy of Child Adolescent Psychiatry, 47*(11), 1252–1261. https://doi.org/10.1097/CHI.0b013e318185a6d8

Onishi, K. H., & Baillargeon, R. (2005). Do 15-month-old infants understand false beliefs? *Science, 308*(5719), 255–258. https://doi.org/10.1126/science.1107621

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2010). Fieldtrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience, 2011*, Article e156869. https://doi.org/10.1155/2011/156869

Perner, J. (1991). *Understanding the Representational Mind*. The MIT Press.

Perner, J., Aichhorn, M., Kronbichler, M., Staffen, W., & Ladurner, G. (2006). Thinking of mental and other representations: the roles of left and right temporo-parietal junction. *Social Neuroscience, 1*(3–4), 245–258. https://doi.org/10.1080/17470910600989896

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., Miller, G. A., Ritter, W., Ruchkin, D. S., Rugg, M. D., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology, 37*(2), 127–152. https://doi.org/10.1111/1469-8986.3720127

Richardson, H., Lisandrelli, G., Riobueno-Naylor, A., & Saxe, R. (2018). Development of the social brain from age three to twelve years. *Nature Communications, 9*(1), 1027. https://doi.org/10.1038/s41467-018-03399-2

Richardson, H., & Saxe, R. (2020). Chapter 21—early signatures of and developmental change in brain regions for theory of mind. In J. Rubenstein, P. Rakic, B. Chen, & K. Y. Kwan (Eds.), *Neural Circuit and Cognitive Development (Second Edition)* (pp. 467–484). Academic Press. https://doi.org/10.1016/B978-0-12-814411-4.00021-4.

Robinson, E. J., & Mitchell, P. (1995). Masking of children's early understanding of the representational mind: Backwards explanation versus prediction. *Child Development, 66*(4), 1022–1039. https://doi.org/10.2307/1131796

Rösler, F., Heil, M., & Röder, B. (1997). Slow negative brain potentials as reflections of specific modular resources of cognition. *Biological Psychology, 45*(1), 109–141. https://doi.org/10.1016/S0301-0511(96)05225-8

RStudio Team. (2024). [Computer software] (Version 2024.09.0+375). 〈http://www.rstudio.com/〉.

Sabbagh, M. A. (2013). Brain electrophysiological studies of theory of mind. In S. Baron-Cohen, H. Tager–Flusberg, & M. V. Lombardo (Eds.), *Understanding Other Minds: Perspectives from Developmental Social Neuroscience*. Oxford University Press.

Sabbagh, M. A., & Taylor, M. (2000). Neural correlates of theory-of-mind reasoning: An event-related potential study. *Psychological Science, 11*(1), 46–50. https://doi.org/10.1111/1467-9280.00213

Saxe, R. (2009). Theory of mind (neural basis). In W. P. Banks (Ed.), *Encyclopedia of Consciousness* (pp. 401–409). Elsevier. https://doi.org/10.1016/B978-012373873-8.00078-5.

Saxe, R., Carey, S., & Kanwisher, N. (2004a). Understanding other minds: linking developmental psychology and functional neuroimaging. *Annual Review of Psychology, 55*(1), 87–124. https://doi.org/10.1146/annurev.psych.55.090902.142044

Saxe, R., Whitfield-Gabrieli, S., Scholz, J., & Pelphrey, K. A. (2009). Brain regions for perceiving and reasoning about other people in school-aged children. *Child Development, 80*(4), 1197–1209. https://doi.org/10.1111/j.1467-8624.2009.01325.x

Schneider, D., Bayliss, A. P., Becker, S. I., & Dux, P. E. (2012). Eye movements reveal sustained implicit processing of others' mental states. *Journal of Experimental Psychology: General, 141*(3), 433–438. https://doi.org/10.1037/a0025458

Schuwerk, T., Grosso, S. S., & Taylor, P. C. J. (2021). The influence of TMS of the rTPJ on attentional control and mentalizing. *Neuropsychologia, 162*, Article 108054. https://doi.org/10.1016/j.neuropsychologia.2021.108054

Schuwerk, T., Kampis, D., Baillargeon, R., Biro, S., Bohn, M., Byers-Heinlein, K., Dörrenberg, S., Fisher, C., Franchin, L., & Fulcher, T. (2024). Action anticipation based on an agent's epistemic state in toddlers and adults [Registered Report](Version posted online February 13, 2024).

Schuwerk, T., Priewasser, B., Sodian, B., & Perner, J. (2018). The robustness and generalizability of findings on spontaneous false belief sensitivity: a replication attempt. *Royal Society Open Science, 5*(5), Article 172273. https://doi.org/10.1098/rsos.172273

Scott, R. M., & Baillargeon, R. (2009). Which penguin is this? Attributing false beliefs about object identity at 18 months. *Child Development, 80*(4), 1172–1196. https://doi.org/10.1111/j.1467-8624.2009.01324.x

Scott, R. M., & Baillargeon, R. (2017). Early false-belief understanding. *Trends in Cognitive Sciences, 21*(4), 237–249. https://doi.org/10.1016/j.tics.2017.01.012

Scott, R. M., He, Z., Baillargeon, R., & Cummins, D. (2012). False-belief understanding in 2.5-year-olds: evidence from two novel verbal spontaneous-response tasks. *Developmental Science, 15*(2), 181–193.

Scott, R. M., Roby, E., & Baillargeon, R. (2022). How sophisticated is infants' theory of mind? In O. Houdé, & G. Borst (Eds.), *The Cambridge Handbook of Cognitive Development* (1st ed., pp. 242–268). Cambridge University Press. https://doi.org/10.1017/9781108399838.015.

Scott, R. M., Roby, E., & Setoh, P. (2020). 2.5-year-olds succeed in identity and location elicited-response false-belief tasks with adequate response practice. *Journal of Experimental Child Psychology, 198*, Article 104890. https://doi.org/10.1016/j.jecp.2020.104890

Senju, A., Southgate, V., Snape, C., Leonard, M., & Csibra, G. (2011). Do 18-month-olds really attribute mental states to others?: A critical test. *Psychological Science, 22*(7), 878–880. https://doi.org/10.1177/0956797611411584

Setoh, P., Scott, R. M., & Baillargeon, R. (2016). Two-and-a-half-year-olds succeed at a traditional false-belief task with reduced processing demands. *Proceedings of the National Academy of Sciences, 113*(47), 13360–13365. https://doi.org/10.1073/pnas.1609203113

Sodian, B., Kaltefleiter, L. J., Schuwerk, T., & Kloo, D. (2024). Continuity in false belief understanding from 33 to 52 months of age. *Journal of Experimental Child Psychology, 247*, Article 106039. https://doi.org/10.1016/j.jecp.2024.106039

Sommer, M., Döhnel, K., Sodian, B., Meinhardt, J., Thoermer, C., & Hajak, G. (2007). Neural correlates of true and false belief reasoning. *NeuroImage, 35*(3), 1378–1384. https://doi.org/10.1016/j.neuroimage.2007.01.042

Sommer, M., Meinhardt, J., Eichenmüller, K., Sodian, B., Döhnel, K., & Hajak, G. (2010). Modulation of the cortical false belief network during development. *Brain Research, 1354*, 123–131. https://doi.org/10.1016/j.brainres.2010.07.057

Southgate, V., Chevallier, C., & Csibra, G. (2010). Seventeen-month-olds appeal to false beliefs to interpret others' referential communication. *Developmental Science, 13*(6), 907–912. https://doi.org/10.1111/j.1467-7687.2009.00946.x

Southgate, V., & Vernetti, A. (2014). Belief-based action prediction in preverbal infants. *Cognition, 130*(1), 1–10. https://doi.org/10.1016/j.cognition.2013.08.008

Southgate, V., Senju, A., & Csibra, G. (2007). Action anticipation through attribution of false belief by 2-year-olds. *Psychological Science, 18*(7), 587–592. https://doi.org/10.1111/j.1467-9280.2007.01944.x

Stets, M., & Reid, V. M. (2011). Infant ERP amplitudes change over the course of an experimental session: Implications for cognitive processes and methodology. *Brain and Development, 33*(7), 558–568. https://doi.org/10.1016/j.braindev.2010.10.008

Stets, M., Stahl, D., & Reid, V. M. (2012). A meta-analysis investigating factors underlying attrition rates in infant ERP studies. *Developmental Neuropsychology, 37*(3), 226–252. https://doi.org/10.1080/87565641.2012.654867

Surian, L., Caldi, S., & Sperber, D. (2007). Attribution of beliefs by 13-month-old infants. *Psychological Science, 18*(7), 580–586.

Surian, L., & Geraci, A. (2012). Where will the triangle look for it? Attributing false beliefs to a geometric shape at 17 months. *British Journal of Developmental Psychology, 30*(1), 30–44. https://doi.org/10.1111/j.2044-835X.2011.02046.x

Taylor, M. J., & Baldeweg, T. (2002). Application of EEG, ERP and intracranial recordings to the investigation of cognitive functions in children. *Developmental Science, 5*(3), 318–334. https://doi.org/10.1111/1467-7687.00372

Thoermer, C., Sodian, B., Vuori, M., Perst, H., & Kristen, S. (2012). Continuity from an implicit to an explicit understanding of false belief from infancy to preschool age. *British Journal of Developmental Psychology, 30*(1), 172–187. https://doi.org/10.1111/j.2044-835X.2011.02067.x

Tomasello, M. (2018). How children come to understand false beliefs: A shared intentionality account. *Proceedings of the National Academy of Sciences, 115*(34), 8491–8498. https://doi.org/10.1073/pnas.1804761115

Wellman, H. M. (2014). *Making Minds: How Theory of Mind Develops*. Oxford University Press.

Wellman, H. M., & Bartsch, K. (1988). Young children's reasoning about beliefs. *Cognition, 30*(3), 239–277. https://doi.org/10.1016/0010-0277(88)90021-2

Wellman, H. M., Cross, D., & Watson, J. (2001). Meta-analysis of theory-of-mind development: the truth about false belief. *Child Development, 72*(3), 655–684. https://doi.org/10.1111/1467-8624.00304

Wellman, H. M., & Liu, D. (2004). Scaling of theory-of-mind tasks. *Child Development, 75*(2), 523–541. https://doi.org/10.1111/j.1467-8624.2004.00691.x

Wimmer, H., & Perner, J. (1983). Beliefs about beliefs: Representation and constraining function of wrong beliefs in young children's understanding of deception. *Cognition, 13*(1), 103–128. https://doi.org/10.1016/0010-0277(83)90004-5

Wysocka, J., Golec, K., Haman, M., Wolak, T., Kochański, B., & Pluta, A. (2020). Processing false beliefs in preschool children and adults: developing a set of custom tasks to test the theory of mind in neuroimaging and behavioral research. *Frontiers in Human Neuroscience, 14*, 119. https://doi.org/10.3389/fnhum.2020.00119

Yott, J., & Poulin-Dubois, D. (2012). Breaking the rules: Do infants have a true understanding of false belief? *British Journal of Developmental Psychology, 30*(1), 156–171.

Zhang, T., Zhang, Q., Li, Y., Long, C., & Li, H. (2013). Belief and sign, true and false: the unique of false belief reasoning. *Experimental Brain Research, 231*(1), 27–36. https://doi.org/10.1007/s00221-013-3661-7