BETA EEG AS A CORRELATE OF BELIEF-REASONING IN PRESCHOOLERS

by

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Abstract

Reasoning about beliefs is difficult, especially when others have conflicting beliefs from one's own. A milestone in Theory of Mind (ToM) development is the understanding of false beliefs: the realization that others may hold subjective and distinct representations of reality (Wellman & Cross, 2001). This understanding is typically assessed in children using the False Belief (FB) task in which they must judge a story protagonist's outdated beliefs about a target object's location (Wimmer & Perner, 1983). While improvements in children's performance in the FB task over preschool years are well-documented, the neurocognitive factors contributing to their success remains unclear.

Building on research into the neural basis of ToM, our work takes a novel approach by focusing on the dynamics of how belief representations are managed over time. Measures of beta-band (13–30 Hz) electroencephalographic (EEG) activity are particularly well suited to this question as its modulations have been linked to how people *maintain* or *update* mental representations—key operations in belief-reasoning (Payumo, 2021). Enhancement in beta power is argued to index cognitive maintenance, whereas suppression in beta power is thought to index cognitive updating (Engel & Fries, 2010; Kilavik et al., 2013; Schmidt et al., 2019). Differences in these processes between children who pass and fail the FB task may provide insight into the mechanisms underlying ToM development.

In our first study, we examined EEG in preschoolers (ages 3–6, n= 39) as they completed a FB task. Beta EEG was analyzed during the *location-change event,* a critical moment in the FB task when the target object (i.e., a pet animal) switches locations and representations are formed about the protagonist's beliefs. We found that failers showed beta suppression over the posterior parietal site, indicating inappropriate updates to their representations of the protagonist's beliefs that the object is in the new location. In contrast, passers exhibited some evidence of beta enhancement, suggesting that they withheld updates

to their belief representations. These findings suggest that failers fail because they misrepresent the protagonist's beliefs as aligned with reality, contributing to the argument that preschoolers do not yet conceive that others' beliefs are distinct representations from their own (Wellman & Cross, 2001; Gopnik & Wellman, 1994).

In our second study, we recruited a new group of preschoolers (ages 3–7, *n*= 35) to complete two EEG tasks: the Standard False Belief (FB) task and an Ignorant FB task—a version in which children typically perform better because they are unaware of the animal's final location (Birch & Bloom, 2003; Wellman & Bartsch, 1988). This study replicated our previous findings by again demonstrating group differences in beta activity over the posterior parietal region: failers exhibited suppression indicative of updating, while passers showed enhancement suggesting maintenance. It also extended our investigation by examining how children responded to the Ignorant FB condition. While there were no group differences in Ignorant FB, children who failed displayed greater beta enhancement over right temporo-parietal in the Ignorant FB than in the Standard FB. Although failers' performance did not improve in Ignorant FB, beta differences suggest that failers differentiated knowledge conditions at the neural level. These findings shed light on how knowledge affects belief-reasoning in young children and highlight dissociations between brain responses and behaviour.

Together, these studies offer novel neural evidence linking beta oscillatory dynamics to belief-reasoning. By identifying distinct neural patterns associated with cognitive maintenance and updating in young children, our findings suggest that failures in FB tasks may reflect deeper conceptual limitations in belief representation. These results contribute to theoretical accounts of ToM development, highlighting the changes in behavioural and neural correlates of belief-reasoning over the preschool years.

Co-Authorship

Mark Payumo wrote the four chapters that make up this dissertation, collected the data, and conducted the main data analyses and interpretation for the studies described in Chapters 2 and 3. This work was completed under the supervision of Dr. Mark Sabbagh. The authors made the following contributions:

Chapter 2

- Study Design: Mark Payumo & Mark Sabbagh
- Data Analysis: Mark Payumo & Mark Sabbagh
- Editing: Mark Payumo & Mark Sabbagh

Chapter 3

- Study Design: Mark Payumo, En Ze Pei, Mark Sabbagh
- Data Collection: Mark Payumo & En Ze Pei
- Data Analysis: Mark Payumo, Mark Sabbagh, En Ze Pei, Taylor Vilardo
- Editing: Mark Payumo & Mark Sabbagh

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List of Abbreviations

dmPFC……. Dorsomedial Prefrontal Cortex

EEG……. Electroencephalography

ERP……...Event-Related Potential

ERSP…… Event-Related Spectral Perturbation

FB……. False Belief

ToM……...Theory of Mind

TB……. True Belief

TPJ…… Temporo-Parietal Junction

Chapter 1

General Introduction

1.1 Theory of Mind

Successful navigation of the social world relies in part on our Theory of Mind (ToM): the conceptual framework that we use to infer and predict others' mental states, such as their intentions, desires, and beliefs (Wellman, 1992). For adults, these mental states are understood as idiosyncratic representations of the world that are critically dependent on one's unique history, context, and experience. An entailment of this understanding is that someone else's beliefs might be different from one's own, or even from reality (Wellman, Cross, & Watson, 2001). For example, if you find out that a friend has not been informed an event has been rescheduled to an earlier time, you might expect them to arrive late. To accurately anticipate their behaviour, you must recognize that their actions are guided by their beliefs, even though it differs from reality or your own beliefs. This understanding that beliefs are rather subjective representations of the world appears to not come so easily for young children. This is evidenced by their performance on "False Belief (FB)" tasks, which assess belief-reasoning in situations where another person's beliefs conflict with one's own.

1.1.1 The False Belief Task

In the "location change" version of the FB task (Wimmer & Perner, 1983), children are presented with a scenario of a story character placing an object in one of two locations. Then, the character leaves the scene and during their absence, the object is moved to the other location. While children who saw the object move know about its true location, the character should still believe *falsely* that it is still in its original place. When asked where the character will look for the object when they come back, 3-year-olds tend to incorrectly judge that the character will look in the new location despite not having seen the location-change event occur. It is not until the age of 5 that children are able to answer correctly that the character

will look for the object in its original location. This demonstrates 5-year-olds' ability to correctly reason that the character has a false belief that the object is in the original location because they did not see it be moved. This change in children's performance on the FB task can be observed universally, across different versions of the task, with most children passing by age 5 (Wellman et al., 2001; Callaghan et al., 2005). A critical question concerns the cognitive mechanisms required to pass the FB task over preschool years.

To contextualize the unique challenge of FB reasoning, researchers use True Belief (TB) tasks as a comparison. TB scenarios are structurally similar to FB ones: a protagonist places an object in one of two hiding places and leaves the scene. However, in TB tasks, the protagonist returns in time to witness the object's relocation. As a result, their belief of the object's whereabouts is aligned with the participants'– they both know it is now in the other hiding place. Studies show that 3-year-olds, who typically fail FB tasks, can correctly judge here that the protagonist will look for the object in the new location (Wellman et al., 2001). The TB task thus serves as a useful baseline, highlighting the demands of FB reasoning.

One idea is that children's difficulty with FB tasks arises from the interference of their own knowledge with their ability to represent another's belief. In demonstrating this, Wellman & Bartsch (1988) designed "Ignorant" FB scenarios where participants themselves were unaware of the object's true location, thus eliminating any influences from their own knowledge. These tasks took the form of stories involving a character wanting to find some target object (e.g., toy, candy). In some trials children were informed of the object's actual location, and in others they were left ignorant. When asked where the protagonist will look for the object, 3-year-olds performed at chance in Standard FB conditions but above chance in Ignorant FB conditions. These findings, replicated in more recent studies (Birch & Bloom, 2003; Ghrear et al., 2016), suggest that belief-reasoning is especially difficult when children must suppress what they know to be true. By removing this confound, Ignorant FB tasks

show how factors, such as the level of conflict between knowledge states, influence belief-reasoning.

To understand the mechanisms driving ToM performance, we can examine children's reasoning across different belief scenarios and link those behaviours to neural activity. By comparing the neural and cognitive profiles of children who pass the FB task versus those who fail, we can specify what factors support success in belief-reasoning and how such capacities emerge over time. To better understand what these factors are, and how they might develop, we can turn to theoretical models that specify the cognitive mechanisms supporting ToM.

1.2 Cognitive Models of Theory of Mind

There are several theoretical accounts as to what mechanisms are recruited to pass ToM tasks. This dissertation will examine two: representational monitoring and shared-beliefs heuristic. After describing both, I will argue that they can be distinguished by the ways in which they each rely on the cognitive processes of updating and maintenance. Cognitive updating involves modifying mental representations by either discarding outdated models or integrating new information (Lenartowicz et al., 2021). In contrast, cognitive maintenance stabilizes existing representations, enabling the retention of relevant information over time (Compte et al., 2000; Lisman & Idiart, 1995). These mechanisms are thought to engage distinct neural processes, potentially reflected in different patterns of brain activity (Nir-Cohen, Egner, & Kessler, 2023). The goal of my research will be to leverage EEG measures of updating and maintenance to distinguish the two broader theoretical accounts of the development of FB understanding.

1.2.1 Representational Monitoring

One account, which we are calling the "representational monitoring" hypothesis, proposes that we continuously track the mental states of others. Whenever we observe that

others have some experience that might cause them to change their beliefs, we must then update our own representations of the contents of their beliefs in a manner that is consistent with their experiences.

This hypothesis aligns with the dual-systems account proposed by Apperly and Butterfill (2009), who argue that belief reasoning is supported by two cognitive systems. The early-developing system is automatic, fast, and efficient, allowing infants to track belief-like states without representing them as full propositional attitudes. However, it is limited in flexibility and cannot accommodate the demands of FB reasoning. In contrast, the later-developing, deliberative system emerges over the preschool years and is capable of representing beliefs explicitly as mental states. This system is cognitively demanding and necessary for success in FB tasks, allowing children to inhibit their own knowledge and maintain a separate representation of another's beliefs. Developmental improvements in executive functions, such as working memory and cognitive flexibility, contribute to the maturation of this representational monitoring system.

A related view comes from Leslie and colleagues (1994, 2004) who propose a Theory of Mind Mechanism (ToMM), an innate domain-specific cognitive system specialized for representing mental states. It provides a representational architecture for understanding that others act based on their own subjective perspectives, even when these differ from one's own experiences. According to Leslie, ToMM is available early in life, but its full deployment in FB tasks is limited by the development of a selection processor that is responsible for inhibiting prepotent responses and selecting the appropriate representation. Thus, while ToMM generates belief representations, successful task performance also requires coordination with domain-general executive processes.

Together, these accounts emphasize that passing FB tasks requires not only a capacity for monitoring representations, but also the ability to flexibly manage these representations

through accurate updating and maintenance. These processes can be illustrated through specific ToM scenarios. For instance, in the TB scenario, we observe that the protagonist sees the item transfer from its original location to the new location. Because of this new information, we must update our representation of the protagonist's beliefs to comport with our understanding of those experiences. In the contrasting FB version of the task, because the protagonist does not see the displacement, there is no reason for us to update our representation of the protagonist's beliefs. We may then instead engage in cognitive maintenance, actively stabilizing our representations of others' beliefs when it diverges from our own or reality. By comparison, children who fail may inappropriately update their representations of the protagonist's beliefs in line with their own. Figures 1A depicts a timeline of successful representational monitoring in the FB task.

The representational monitoring account has been invoked to explain how infants pass FB tasks (Southgate et al., 2007; Kovács et al., 2010). Violation-of-expectation paradigms demonstrate that even infants expect an agent to act in accordance with their false beliefs. In these tasks, an actor places an object in one location and leaves, the object is then moved to a different location in their absence. When the actor returns, infants exhibit longer looking times if the actor searches for the object in the new location rather than in its original location. This indicates surprise and an expectation that the actor should hold a false belief about the object's whereabouts (Onishi & Baillargeon, 2005; Southgate et al., 2007). These findings suggest that from infancy, children may already possess the ability to track others' mental states (Carruthers, 2013). This has led to one influential view that the capacity to represent others' beliefs, including false ones, is an early-emerging, perhaps innate, feature of human cognition (Onishi & Baillargeon, 2005; Southgate et al., 2007).

In contrast, the conceptual change account, also known as the "theory theory", argues that children undergo a developmental shift in their understanding of beliefs over preschool

years (Wellman & Cross, 2001; Gopnik & Wellman, 1994). That is, before age 5, children may not fully grasp that beliefs are independent representations of reality. Instead, they might assume that others' beliefs mirror the true state of the world (Helming et al., 2014). For example, if a child sees the object being moved in the FB task, they might mistakenly update their representation of the protagonist's belief, even if the protagonist is not present. This would suggest a failure at the stage of belief formation, not just during response selection. This highlights the importance of examining the belief-formation stage itself, rather than focusing solely on children's final responses. By investigating the processes engaged as belief representations are initially constructed, we can assess whether children are accurately monitoring others' beliefs. This approach helps to clarify whether ToM develops through conceptual change during preschool years or is already present from infancy.

1.2.2 Shared-Beliefs Heuristic

The shared-beliefs heuristic hypothesis proposes that, instead of actively and continuously keeping track of the mental states of others, we reason first based on a simple heuristic that other people likely share our same beliefs. This strategy is typically adaptive, given that in many real-world interactions, shared experiences do lead to shared mental states. We would only need to abandon this simple heuristic on the relatively rare occasions we realize, either through immediate feedback, or through prior contextual experience, that the heuristic has led, or will lead, to an error (Keysar, Lin, & Barr, 2003). This notion is supported by work from Epley, Morewedge, and Keysar (2004), who argue that reasoning about others' mental states is anchored in one's own perspective. According to their model, perspective-taking is a two-step process: individuals begin with an egocentric default and assume others know what they know, and only later and with cognitive effort, they adjust their attributions to account for differing mental states. Their research suggests that preschoolers, due to their less developed executive function, may be more prone to ToM

errors as they are unable to correct their egocentric assumptions. This framing supports the view that belief reasoning often begins with a shared-belief assumption**,** which must be actively overridden in situations like FB tasks.

Nickerson (1999) similarly highlights the pervasive difficulty of separating one's own knowledge from inferences about what others know, a bias commonly known in the ToM literature as the "curse of knowledge" (Birch & Bloom, 2007). These accounts propose that once individuals acquire a piece of information, it becomes difficult for them to imagine a state of ignorance or a belief system that lacks that information. As a result, people tend to project their own knowledge onto others, assuming that others know what they know, unless given explicit reason to do otherwise. This aligns closely with the shared-beliefs heuristic, which posits that individuals initially assume belief alignment. In the context of the FB task, successful reasoning about false beliefs would require overcoming this curse of knowledge. However, preschoolers, lacking the executive control to do so, may instead continue to incorrectly rely on their biases of shared beliefs.

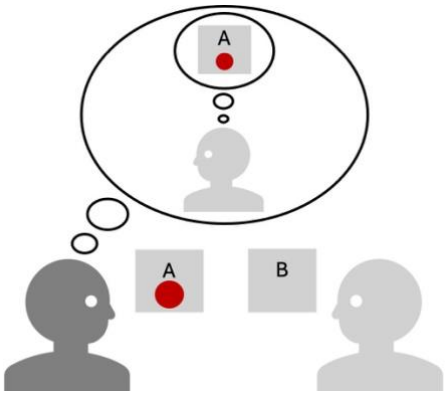
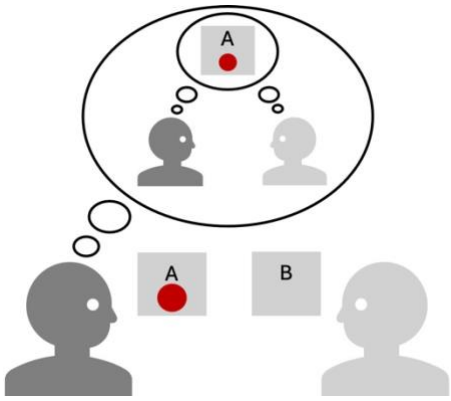
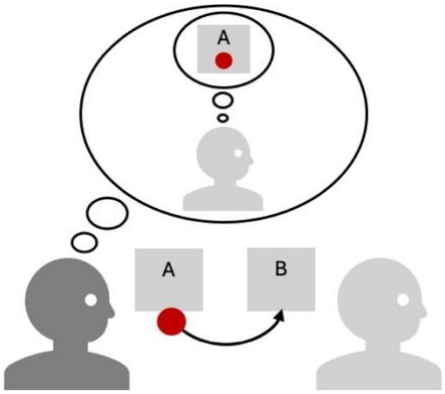
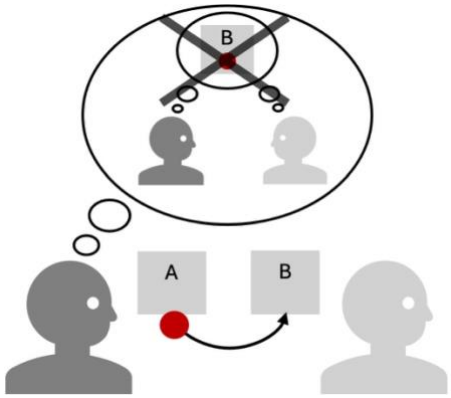
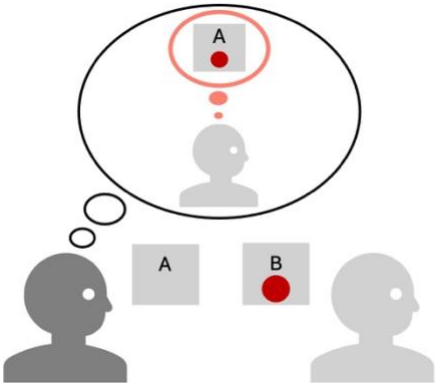
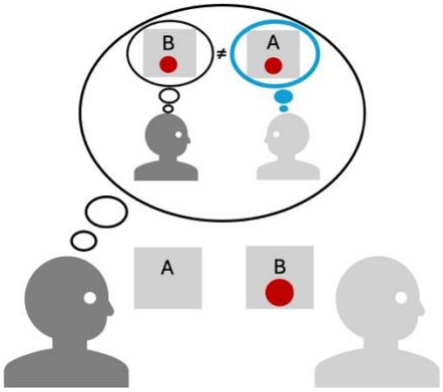
Taken together, these perspectives support the theoretical claim that belief-reasoning is initially anchored in the self, and that adjustments to account for others' differing mental states are effortful and dependent on executive function (Carlson & Moses, 2001; Perner & Lang, 1999). If children's reasoning is indeed guided by a shared-belief heuristic, we would expect distinct mechanisms depending on the ToM scenario. In the TB scenario described above, one can arrive at the correct answer by relying on the shared-beliefs heuristic; after all, because of their similar perceptual experiences, one's beliefs about the location of the object are the same as the protagonists. In the FB scenario, however, the shared-beliefs heuristic must be overridden. Successful reasoning requires shifting away from one's default assumptions. From this perspective, 3-year-olds may fail FB tasks because they fail to override their reliance on the shared-belief heuristic and instead maintain it.

The current study focuses on the processes of updating and maintenance— domain-general mechanisms that promote change and maintain stability within cognitive systems. Our goal was to examine how these processes are engaged differently between passers and failers in the FB task. While both the representational monitoring and shared-beliefs heuristic accounts suggest that basic processes of maintenance and updating support ToM reasoning, the role that maintenance and updating are proposed to play are different in each case. According to the shared-beliefs heuristic account, observers relying on a shared-beliefs heuristic would need to update or override their use of this strategy in the FB condition. Because the protagonist is not present with the observer when the object moves, the observer can no longer assume that knowledge is shared. In this case, we would expect FB reasoning to be associated with processes that reflect updating or overriding their use of that bias (see Figure 1B). A very different pattern is expected on the representational monitoring account. According to this hypothesis, we need to maintain our representation of the protagonists' belief in FB scenarios, because they are not present to see the object moving and thus have no reason to know about the object's true location (see Figure 1A).

The current dissertation will focus on the cognitive processes involved in forming belief representations during the FB task, before any explicit decision is required. By examining neural correlates of updating and maintenance across different ToM conditions, this work aims to test whether young children fail FB tasks because they inappropriately update their representations of others' beliefs in line with reality or are unable to override their shared-beliefs heuristic. In contrast, children who succeed may be distinguished by their ability to maintain others' outdated beliefs despite knowing the true state of the world, or their ability to overcome their initial shared belief assumptions. Comparing the neural profiles of passers and failers may therefore provide insight into the cognitive mechanisms that support successful belief-reasoning.

Figure 1

*Depiction of successful reasoning in the **False Belief** scenario*

A. Representational Monitoring	B. Shared Beliefs Heuristic
	
1. Observer's (dark grey) initial representation of protagonist's (light grey) beliefs that the object (red ball) is in Location A.	1. Observer initially holds a heuristic that protagonist shares the same belief that the object is in Location A.
	
2. While protagonist is turned away, object moves to Location B.	2. While protagonist is turned away, object moves to Location B. Observer recognizes that protagonist no longer shares same beliefs.
	
3. Observer maintains their representation of protagonist's beliefs that they still believe object is in Location A.	3. Observer updates their belief heuristic in acknowledging protagonist's unshared beliefs.

1.3 Beta EEG as a Correlate of Belief-Reasoning

Research using fMRI has shown that ToM judgments elicit neural activity from a set of brain regions referred to as the "Theory of Mind brain network" (Carrington & Bailey, 2009). It includes, among other regions, the dorsomedial prefrontal cortex (dmPFC) and the temporo-parietal junctions (TPJ). These regions are believed to work together in forming our representations of others' mental states and in attributing beliefs in particular (Saxe, 2006; Mahy et al., 2014). Although this has been shown most extensively in adults (Saxe & Kanwisher, 2003; Saxe & Powell, 2006), it appears to be true for young children as well (Sabbagh et al., 2009; Saxe et al., 2009; Gweon et al., 2012).

In addition to fMRI, some researchers have used electroencephalography (EEG) measures and come to similar conclusions. For instance, research on event-related potentials (ERPs) provide evidence that making ToM judgements elicits a late slow wave component over frontal and parietal sites (Liu et al., 2004, 2009; Sabbagh & Taylor, 2000). Because EEG capture these temporally precise neural responses, a main advantage is that it can be easily and non-invasively used in preschool-aged children. Indeed, work has shown that the late slow wave ERP activity associated with FB performance is comparable in adults and children who are good at solving FB tasks (Liu et al., 2009; Meinhardt et al., 2011). These findings provide confidence that EEG measures can be used to index the neural systems that are critical for ToM development in preschool aged children.

A central issue in our research is how the cognitive processes of "maintenance" and "updating" can be indexed in a belief-reasoning task. While ERP analysis has been the dominant EEG framework in ToM research, it primarily captures brain responses that are tightly time-locked to specific events—meaning the same pattern of activity occurs at the same time across trials. This approach, however, may miss other types of neural activity that unfold more flexibly and vary from trial to trial. As an alternative, event-related spectral

perturbation (ERSP) analysis provides a complementary perspective by examining real-time modulations in EEG power across different frequency bands (e.g., alpha, beta, gamma) in response to ongoing experimental events. This will allow us to track how cognitive processes unfold in FB tasks in real time. ERSPs measure the changes in spectral power relative to a baseline period, allowing researchers to track event-related enhancement (increases in power) or suppression (decreases in power) in oscillatory activity (Makeig, 1993; Pfurtscheller & Lopes da Silva, 1999). The direction and magnitude of these spectral changes provide insight into underlying neural computations.

For this dissertation, we will focus on ERSP measures of beta frequencies (13-30 Hz). Beta oscillations (13–30 Hz) have long been recognized as a prominent neural rhythm in EEG research, originally linked to states of active wakefulness and alertness (Adrian & Matthews, 1934). Early work emphasized their role in the motor system, showing that beta power increases during the maintenance of stable motor states and decreases during movement initiation or adaptation (Pfurtscheller, Stancák, & Neuper, 1996). More recently, research has extended the role of beta activity beyond motor domains to higher-level cognition (Engel & Fries, 2010; Kilavik et al., 2013). There is evidence that stimulus-related *increases* in beta power (enhancement) may be observed when a given task demands the *maintenance* of cognitive representations. In contrast, beta power *decreases* (suppression) index *updates* to current representations. These distinct functions make beta EEG a promising candidate for indexing the cognitive operations involved in belief reasoning. By examining the time course of beta modulation across belief conditions, we can test whether and when belief maintenance or updating processes are differentially engaged between passers and failers of the FB task.

1.3.1 Beta EEG and Cognitive Maintenance and Updating

Recent theoretical accounts have suggested a role for beta EEG in maintaining the existing motor and cognitive state, or the "status quo" of the system (Engel & Fries, 2010; Spitzer & Haegens, 2017). This hypothesis is mainly supported by early observations of beta's association with sensorimotor processing (Alegre et al., 2004; Pfurtscheller et al., 1996). In these studies, participants' EEG was examined over frontal and central regions as they performed motor "Go/No Go" tasks in which they must either execute (Go) or withhold (No Go) a motor action in response to a stimulus cue. In Go trials, beta power is enhanced temporarily once the "Go" signal to start moving is presented. On No Go trials, however, when participants are presented with a "No Go" signal and the prepared movement is not performed, beta power exhibits a rapid enhancement instead of a suppression. Once the movement is terminated, beta power once again exhibits an enhancement– a "post-movement beta rebound" that marks the reversion back to a stable position (Pfurtscheller et al., 1996).

Based on these findings, which have been replicated consistently (for review, see Kilavik et al., 2013), beta enhancement has been linked to motor maintenance, such as in events that require postural holds and stable positioning. In contrast, suppression in beta power is associated with motor action changes in which movement is executed (Zaepffel et al., 2013), but also during action observation (Koelewijn et al., 2008) and passive movement (Keinrath et al., 2006) where change is simply experienced. Moreover, beta oscillations in the medial prefrontal cortex have been observed to become suppressed relative to baseline in Go trials of Go/No Go tasks when a conflict arises (e.g., a red arrow pointing right while the correct response is to press the left button), particularly when individuals successfully adjust their responses (Zavala et al., 2018). This suggests that suppression in beta power may be associated with adaptive behavioural adjustments. Together, these findings support the view

that beta suppression signals a readiness to transition from the current state, highlighting its broader role in facilitating flexibility and adaptation in response to changing task demands.

Although most research on beta has focused on its role in movement, recent studies have highlighted its involvement in cognitive functions, such as working memory (for review, see Schmidt et al., 2019). Initial studies by Lundqvist et al. (2016, 2018) recorded EEG in the prefrontal cortex of monkeys as they performed a match-to-sample task, in which they were required to remember a sample sequence of images of objects (e.g., flower, boat) and determine whether a testing sequence matches. The authors found that upon the onset of each new image within the sample sequence, beta was suppressed. They argued that this suppression in beta may be associated with encoding new items into working memory. More broadly, such beta suppression can be thought of as an index of cognitive updating – revising mental representations in response to new information. They also found beta to be enhanced during the delay periods between stimuli presentation, suggesting that enhancement reflects the maintenance of presented items in working memory (Schmidt et al., 2019).

This pattern has been replicated in human samples as well. Hall et al. (2024) recorded EEG as participants engaged in a working memory task involving encoding, maintenance, and retrieval phases. In the encoding phase, participants were presented with a grid of four letters to memorize. Then during the maintenance phase, participants were presented with distractor stimuli in the form of letters (high-distraction) or pound signs (low-distraction) for 2.5s. Finally in the retrieval phase, a probe letter appeared, and participants were instructed to respond with a button as to whether the probe letter was present or absent in the initial encoding set of four letters. Researchers found that during encoding, beta (14-23 Hz) power decreased relative to baseline, starting from bilateral occipital cortex and spreading to the temporoparietal and frontal cortices. Moreover, low beta (12-18 Hz) power increased briefly

relative to baseline during early maintenance. They also found that high-distractor trials elicited stronger beta oscillations during maintenance in prefrontal regions.

Beta's ERSP patterns can also be observed in human studies of executive control, such as in tasks that require stopping a thought. For instance, in "Think/No Think" paradigms, participants are presented with word pairs (e.g., "oil"– "pump") to learn. Thereafter, participants' EEG is recorded as they perform trials in which they receive a reminder word from the learnt pair, presented either in green (cuing them to think about the associated word– "Think"), or in red (cuing them to stop retrieval– "No Think"). While Think trials require cognitive updating to switch to the associated word, the No Think trials demand cognitive maintenance as participants must avoid any disruption to their current thoughts. Similar to the EEG results of Go/No Go tasks, researchers found greater beta activity during No Think trials compared to Think trials, highlighting beta's influence on cognitive control (Castiglione et al., 2019).

This connection between increased beta power and cognitive maintenance and updating is further supported by clinical research on Parkinson's disease, a neurodegenerative disorder caused by the degeneration of dopaminergic neurons. Patients exhibit a deterioration of behavioural and cognitive flexibility, manifesting as difficulties in movement execution and in adapting to changing events. Researchers have linked these symptoms to a pathophysiological enhancement of beta EEG in the basal ganglia and subthamalic nucleus (Brown, 2003; Chen et al., 2010; Engel & Fries, 2010). Treatments (e.g., dopamine agonists, brain stimulation) that are often effective at alleviating the symptoms of Parkinson's, including those associated with cognitive perseveration, are shown to lead to relevant reductions in beta power (Kühn et al., 2008; Little & Brown, 2014). Taken together, the above findings converge on the conclusion that beta enhancement may be strongly linked with context-appropriate representational maintenance in healthy individuals, and in the more

extreme case of Parkinson's disease, pathologically inappropriate representational maintenance. It additionally suggests that beta suppression (as induced by treatments) can promote motor and cognitive flexibility, allowing for representational updating and change.

These findings show how beta oscillatory activity is involved many higher order cognitive processes, including working memory and cognitive control (Hall et al., 2024; Lundqvist et al., 2024; Zavala et al., 2018). At a broader level, they illustrate how patterns of beta activation are sensitive to the dynamic regulation of cognitive states, including online cognitive updating (via suppression) and maintenance (enhancement) This highlights how beta is engaged not only in motor programming, but also in the shaping of internal mental representations.

1.3.2 Beta EEG in Preschoolers

While beta oscillations have been extensively studied in adults, growing evidence suggests they play a crucial role in cognitive processes across development, including in young children. Researchers have argued that the neurodevelopmental trajectory of beta oscillations may underpin behavioural milestones, particularly those related to cognitive control and working memory. Understanding these developmental changes is essential not only for clarifying beta's role in cognitive updating and maintenance but also for establishing its reliability as a measurable neural correlate in preschoolers.

Studies investigating sensorimotor beta rhythms provide insights into how beta oscillations evolve with age. Gaetz et al. (2010) used magnetoencephalography (MEG) to examine sensorimotor beta oscillations in young children (ages 4–6), adolescents (11–13), and adults during a simple motor task in which they were instructed to perform finger abductions in response to a visual cue—a white fixation cross turning green. They found characteristic beta (16–24 Hz) suppression during movement across all ages. This was followed by a post-movement beta rebound, which increased in magnitude with age. This

pattern suggests that beta suppression is involved in preschoolers' motor movement and that greater post-movement beta rebound may reflect maturational changes in motor control.

Beyond motor function, beta oscillations have been implicated in higher-order cognitive processes such as response inhibition. Lo et al. (2013) administered a Go/No Go task to 5- and 6-year-old children, in which they were instructed to respond to certain stimuli (i.e., image of a sheep) by pressing a button and to withhold their response to other stimuli (i.e., red X). Analysis of EEG revealed a significant increase in beta band power in the right frontal region during No Go trials for 6-year-olds compared to 5-year-olds. This suggests that beta oscillations are functionally relevant for the development of inhibitory control in early childhood. As the magnitude of beta enhancement was associated with better response inhibition in No Go trials, this finding further reinforces beta's role in emerging executive function.

Building on these findings, more recent work has linked beta oscillations to working memory processes in children. Gómez et al. (2023) recorded EEG in participants aged 6–29 years during a delayed match-to-sample task, where they had to encode, maintain, and retrieve visual stimuli. At encoding, after a transient beta burst, a sustained beta suppression was observed over the occipital region, suggesting that beta suppression may facilitate the initial encoding of information. During the retention phase, beta power increased at both frontal and occipital sites, supporting its role in maintaining working memory representations.

Together, these findings suggest that beta oscillations are not only measurable in children but also play a critical role in updating and maintenance, in both motor and cognitive programs. These findings highlight beta oscillations as a promising neural correlate for studying cognitive development and suggest that its maturation may underpin key cognitive abilities in early childhood.

1.3.3 Beta EEG and Theory of Mind

Given what we know about beta EEG, it shows promise as an index of the cognitive mechanisms underlying belief-reasoning. Looking at ERSPs of beta during belief-reasoning tasks may offer valuable insights into the real-time dynamics of our ToM. Importantly, the two ToM accounts make distinct predictions about the patterns of beta enhancement and suppression depending on belief condition. According to the representational monitoring account, children who succeed on FB tasks would be expected to show enhancement in beta power, reflecting the active maintenance of their representations of the protagonist's beliefs. The shared-beliefs heuristic account suggests a different pattern: we would expect to see beta suppression in FB tasks, indicating a shift away from this default heuristic. Therefore, beta ERSPs may serve as a useful neurophysiological index for distinguishing between the two ToM accounts – shedding light on whether children rely on heuristics or engage in representational monitoring.

Our lab's latest study provides some initial evidence that adults exhibit beta EEG patterns in line with the shared-beliefs heuristic account (Payumo, 2021). Using an animated location-change task, adult participants judged story protagonists' beliefs about a pet animal's location. EEG was recorded during the critical moment in the task—the location-change event—when the animal moved from one location to another. This moment is key, as participants can begin to form representations of the protagonist's belief based on their absence during the animal's move. The goal of the study was to identify the neural mechanisms engaged during belief-reasoning in adults. This is helpful in establishing a reference point for developmental comparisons with children. By characterizing beta changes that accompany this transition event, we can gain insight into whether children are either maintaining their representation of the protagonist's beliefs or updating their use of the shared-belief heuristic.

We found that in the FB condition, beta suppression was sustained throughout the entire location-change event, over frontal and temporoparietal regions. Since adults are generally successful at FB tasks, they may not engage in representational updates as doing so would lead to incorrect judgments. Instead, this sustained beta suppression may reflect cognitive shifts away from the shared-beliefs heuristic as observers recognize the divergence between their own beliefs and those of the protagonist. This demonstrates how adults may rely on the shared-beliefs heuristic as a strategy for ToM reasoning. Whether children engage in the same reasoning strategy remains unclear. The current study aimed to extend this investigation to preschoolers in order to determine the neurobiological factors of ToM development.

In children who passed the FB task, we expected to observe beta suppression during the FB condition, reflecting a shift away from the shared-beliefs heuristic—similar to patterns observed in adults. Under an alternative account, we instead predicted beta enhancement, consistent with representational maintenance of the protagonist's belief. Conversely, for children who failed the FB task, we anticipated that their beta EEG profiles would diverge from both passers and adults in terms of modulation. One possibility was that failers would show no sustained beta suppression in the FB condition, reflecting continued reliance on shared-belief heuristics when such biases should be overridden. Alternatively, failers might exhibit beta suppression, indicating representational updating when they should be maintaining. These neural differences between passers and failers were expected to reflect distinct cognitive processes engaged during FB reasoning.

1.4 The Current Thesis

This dissertation used EEG to examine preschoolers' belief-reasoning in ToM tasks. Beta EEG is believed to be associated with processes relevant for belief-reasoning. We argue

that by analyzing modulations in beta activity during critical moments in the location-change task, we can determine what processes contribute to ToM reasoning.

In Chapter 2, we recorded EEG from children ages 3 to 6 years old during FB and TB scenarios. Beta activity was analyzed during the location-change event, when the target object (i.e., pet animal) departs from one location and arrives at the second location. Beta EEG was compared between children who passed and those who failed to see what mechanisms contribute to children's ToM development.

The goal of Chapter 3 was to replicate and extend the findings of Chapter 2 by using Ignorant FB and TB conditions, in which participants do not see where the animal goes. By comparing beta EEG between passers and failers across Standard and Ignorant ToM conditions, we aimed to examine the processes behind preschoolers' distinct ToM task performances.

Together, these studies have theoretical implications for our understanding of ToM by revealing how beta oscillations may index cognitive processes underlying belief-reasoning in preschoolers. By examining beta EEG modulations during critical moments of the ToM task, we provide insight into how neural activity differentiates successful and unsuccessful ToM reasoning. Moreover, by extending this investigation to Ignorant ToM conditions, we test whether beta activity index mechanisms associated with young children's improved performance. These findings contribute to the growing literature on the neural mechanisms of early social cognition and provide initial evidence that beta oscillations can serve as a neural correlate of belief-reasoning in young children.

Chapter 2 – Study 1

Beta EEG and Belief-Reasoning in Preschoolers

2.1 Introduction

A central question in ToM research concerns the neurocognitive factors that contribute to the development of children's belief-reasoning. Competing theoretical accounts propose distinct explanations for why preschoolers fail FB tasks, particularly around age 3, while succeeding more reliably by age 5. These accounts differ in the type of mental operation they assume (see Table 1).

According to the shared-beliefs heuristic account, children tend to assume that others share the same beliefs they do (Epley et al., 2004; Nickerson, 1999). This heuristic is adaptive in most social contexts, where people often do have similar experiences and shared knowledge. However, it leads to systematic errors when others have divergent perspectives. In FB tasks, children must override this default assumption and update their reasoning to account for the protagonist's unique, and now outdated, experience. Children's failures on FB tasks may therefore reflect their difficulty disengaging from this shared-beliefs heuristic and replacing it with a belief state that is not aligned with their own.

By contrast, the representational monitoring account (Apperly & Butterfill, 2009; Leslie et al., 2004) suggests that successful ToM performance depends on the ability to accurately track others' beliefs as distinct representations. This means updating belief representations when new information is encountered that would lead others to change their beliefs, and as well, maintaining belief representations when no change is warranted. On this view, the challenge of FB tasks lies in preserving a belief representation that is no longer aligned with current reality– a process that requires cognitive maintenance. Failures in FB reasoning may therefore indicate a problem at the level of forming or maintaining distinct belief representations, not just overriding a heuristic.

To determine which ToM account can be supported, some insight may be gleaned by comparing neural activity associated with belief-reasoning in children who succeed (passers) versus those who fail (failers) on FB tasks. In this study, we investigated the neurocognitive bases of belief-reasoning by examining modulations in beta EEG as children aged 3 to 6 years completed FB and TB tasks. Modulations in beta EEG have been associated with processes of cognitive maintenance and updating (Engel & Fries, 2010; Kilavik et al., 2013; Schmidt et al., 2019). Beta suppression (decrease in power) is thought to index cognitive updating, while beta enhancement (increase in power). By examining how beta is modulated in passers and failers, we can determine differences in how they reason about beliefs.

The following sections will outline the rationale for our experimental design, our approach to EEG analysis, and our hypotheses regarding the recruitment of maintenance and updating processes in belief reasoning during early childhood.

2.1.1 Cluster-Mass Analyses

Most research looking at the neural correlates of ToM look at the ToM brain network, consisting of the dmPFC and bilateral TPJs. These regions are argued to be involved in representing others' mental states and attributing beliefs (Carrington & Bailey, 2009; Mahy et al., 2014; Saxe, 2006). While past research has linked slower frequency bands (e.g., alpha) to these regions (Bowman & Brandone, 2024; Sabbagh et al., 2009), the role of beta oscillations in belief-reasoning remains less well understood. Specifically, it is unclear whether beta activity is most prominent over canonical ToM regions or if its distribution differs in young children due to developmental factors.

Given the lack of prior studies examining the spatial, spectral, and temporal characteristics of beta oscillations during belief-reasoning, a key challenge is determining where beta EEG signals are most robust and whether they align with established ToM neural networks. While EEG provides time-sensitive measures of neural activity, it is not well

known for its spatial resolution for localizing activity. As such, the optimal scalp locations for measuring beta activity in preschoolers remain uncertain.

To address this challenge, the current study adopted a data-driven approach using cluster-mass analyses (Candia-Rivera & Valenza, 2022; Maris & Oostenveld, 2007) to systematically identify significant differences in beta activity across multiple dimensions: spatial (electrodes), spectral (frequency points), and temporal (time points). Statistical comparisons were performed at each time point, frequency point, and electrode between groups (passers vs. failers). Clusters were formed by grouping adjacent data points (neighbouring electrodes, contiguous time points, or adjacent frequencies) that showed significant effects. To determine statistical significance, cluster heights were computed by summing the test values within each cluster, and this was compared to a null distribution generated through a thousand permutations, in which group labels were randomly shuffled.

This cluster-based permutation approach to analysis offers several advantages. Firstly, it corrects for multiple comparisons by controlling the family-wise error rate at the cluster level rather than at each individual test. This enhances statistical rigour and reliability, reducing the likelihood of false positives. Secondly, this method allows us to identify significant effects in beta EEG across electrodes, frequencies, and time points without relying on predefined electrode clusters based on past ToM studies. This data-driven approach ensures that our findings reflect true spatiotemporal dynamics of belief-reasoning rather than being constrained by assumptions of previous research. By leveraging this technique, we aimed to identify whether beta oscillations are involved in belief-reasoning processes and, if so, to precisely map where and when these effects emerge in the developing brain.

2.1.2 Location-Change Event

Most studies on the neurocognitive processes underlying performance in belief reasoning tasks examine those processes as they are recruited when observers are asked

where the protagonist will search for the target object (Liu et al., 2009; Sabbagh & Taylor, 2000). While this is a reasonable event to examine, it takes place after the observer witnessed the events that would have led to either maintaining or updating the way they represent the protagonist's mental states. Thus, this approach is not ideal for addressing the theoretical questions about the cognitive processes underlying belief reasoning, per se. Instead, what is necessary is a method that can index relevant neurophysiological processes as they unfold during the critical moments of the belief-reasoning task.

We propose that the critical moment in a location-change task occurs when the object is moved. This event provides participants with real-time information about the protagonist's belief state. In a recent study, Bowman & Brandone (2024) demonstrated that belief-reasoning can be captured using EEG during this location-change event. In their study, 3- to 5-year-olds watched a video in which an actor placed a toy car in one of two locations before leaving. EEG was recorded as the car was moved to the other location during the actor's absence. Results revealed that alpha EEG (6–9 Hz) suppression over the right temporoparietal region was significantly associated with children's ToM scores, suggesting that neural activity during the location-change event reflects belief processing.

Alpha suppression is commonly interpreted as an index of attentional engagement (Klimesch et al., 1998; Rihs, Michel, & Thut, 2009). In this context, reduced alpha power may indicate that children are allocating cognitive resources to track belief-relevant information when the object is moved. Notably, the regional specificity of this suppression—over the right temporoparietal region—suggests that the underlying neural systems may be actively supporting belief reasoning. However, while these findings point to the engagement of ToM-related processes, alpha EEG alone does not specify the exact computations involved. Further research is needed to clarify the nature of the cognitive operations being carried out during this critical moment.

The present study builds upon previous EEG findings by investigating beta oscillations during the location-change event to further explore the neural mechanisms of belief reasoning. Modulations in beta EEG are linked to cognitive updating and maintenance that are essential for belief-reasoning. If beta suppression occurs during the location-change event, it may indicate that children are not only attending to the event, but also actively updating their mental representations based on new information (representational monitoring) or overriding a preexisting bias (shared-beliefs heuristic). In contrast, beta enhancement would suggest the opposite: maintenance of their belief representations (representational monitoring) or continued reliance on default assumptions (shared-beliefs heuristic).

2.1.3 Objectives and Hypotheses

The objective of Chapter 2 was to examine beta EEG in preschoolers, ages 3 to 6 years old, as they completed a ToM task. Our current theoretical accounts make different predictions regarding cognitive strategies and their corresponding beta EEG activity in the FB condition (see Table 1). For passers, we expected them to exhibit either A) beta enhancement to reflect cognitive maintenance under the representational monitoring account or B) beta suppression to index updating under the shared-beliefs heuristic account. Conversely, children who failed the FB task were instead expected to show signs of either A) beta suppression suggesting erroneous updating during representational monitoring or B) beta enhancement because of an inappropriate maintenance of shared-beliefs heuristic. By analyzing beta activity between these groups, this study aimed to evaluate whether children's ToM aligns more closely with the representational monitoring or the shared-beliefs heuristic accounts.

Table 1

Cognitive Processes of Belief-Reasoning of Passers and Failers in the False Belief Condition

Strategy	Passers	Failers
Representational Monitoring	MAINTAIN: When object moves from original location, observer maintains representation of protagonist's mental states, because their mental states are not changing.	UPDATE: When object moves from original location, observer updates representation of protagonist's mental states
Shared-beliefs Heuristic	UPDATE: Due to their different experiences, observer and protagonists have different mental states, so update (i.e., override) use of the bias and actively reason about mental states.	MAINTAIN: Throughout the story, observer assumes protagonist shares same belief and maintain reliance on the bias.

2.2 Methods

2.2.1 Study Participants

This study, approved by the General Research Ethics Board at Queen's University (Appendix A), recruited 64 participants (3-6 years old) from the local community via word of mouth, social media, and the Child & Adolescent Developmental Database. Participants were compensated with $15 cash or gift card, stuffed toy, or junior scientist t-shirt. The demographics of our participants reflected the predominantly white, middle-class university population in eastern Canada from which it was drawn (see Table 2). 25 participants were excluded from analyses due to reasons such as refusal to wear EEG net (8), outlying task performance, e.g., failure on TB task (5), poor EEG signal-to-noise ratio (4), and FB scores that precluded classification as passing or failing (8). The final EEG sample, therefore, consisted of 39 participants (18 female), of which there were 21 passers (*M* age= 57mo, *SD*= 7.00) and 18 failers (*M* age= 46mo, *SD*= 7.12).

Table 2

Participant Demographics

Demographic Characteristic	%	n
Ethnicity		
White	64.1	41
White and West Asian	4.7	3
East Asian	3.1	2
White and Southeast Asian	3.1	2
White and Hispanic/Latino/Latina	3.1	2
White and Indigenous/First Nations/Aboriginal/Inuit/Metis	3.1	2
White and East Asian	1.6	1
South Asian	1.6	1
West Asian	1.6	1
Missing	14.1	9
Parent 1 Education		
High School Graduate, diploma, or equivalent	1.6	1
Some college credit, no diploma	4.7	3
Trade/Technical/vocational training	10.9	7
Associate's	3.1	2
Bachelor's	23.4	15
Master's	18.8	12

Professional Degree	6.3	4
Doctorate Degree	15.6	10
Missing	15.6	10
Parent 2 Education		
High School Graduate, diploma, or equivalent	1.6	1
Some college credit, no diploma	6.3	4
Trade/Technical/vocational training	18.8	12
Associate's	1.6	1
Bachelor's	20.3	13
Master's	14.1	9
Professional Degree	10.9	7
Doctorate Degree	10.9	7
Missing	15.6	10
Yearly Household Income		
35,000 to 49,999	4.7	3
50,000 to 74,999	10.9	7
75,000 to 99,999	7.8	5
100,000 to 149,999	25	16
> 150,000	31.3	20
Prefer not to say	6.3	4
Missing	14.1	9

2.2.2 Materials and Stimuli

Theory of Mind Task. Participants' EEG was recorded during a multi-trial theory of mind task which was presented using E-Prime software (Psychology Tools Inc.). Figure 2 demonstrates a trial from the TB and FB conditions. The task consisted of 24 short, animated scenarios presented on a computer monitor with accompanying audio narration played through speakers. The task presented FB (12 trials) and TB (12 trials) trials in a randomized order. For each trial, it depicted a character acting on the basis of their true or false beliefs, resembling a story according to the "location-change" false belief task (Baron-Cohen et al., 1985). The first 3 images in both conditions were the same and illustrated the following series of events: Picture 1, a character introduces their pet animal (e.g., cat, dog, bird); Picture 2, the character places their pet animal in one of the two locations set in the scene (e.g., character places cat into the box); Picture 3, the character turns around and leaves their pet animal. The location in which the pet animal is placed is counterbalanced across trials so that they are

placed in either the left or right location for an equal number of times. After the character leaves, the subsequent series of events depended on the trial condition.

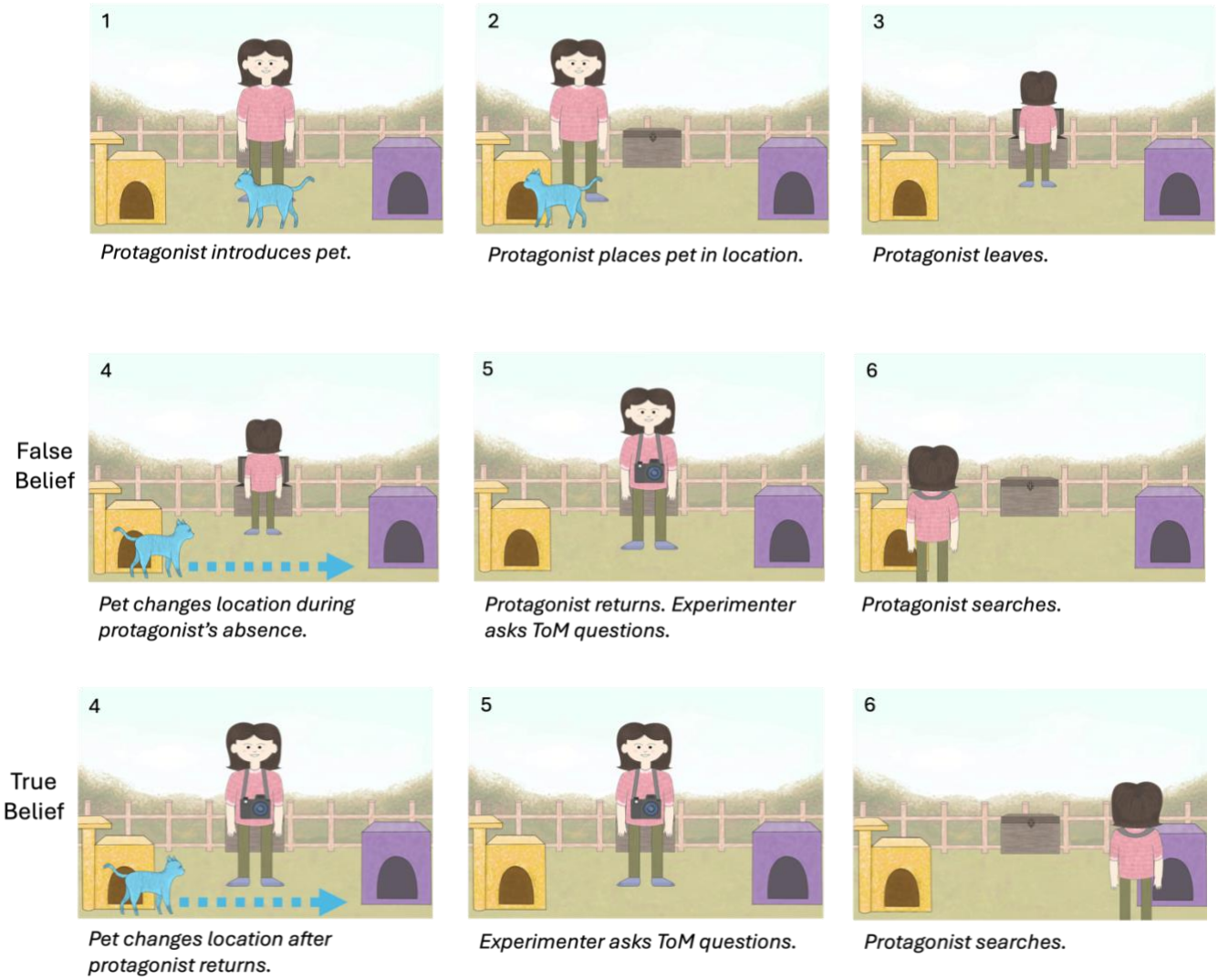
In the FB trials, the participant watched a video clip of the animal switching to the other location (e.g., cat moves from the box) before the character returns, consequently having a false belief about where their pet is. Following the logic of a traditional false belief task, the character should thus have a false belief about the location of their pet. In the TB condition, the animal switches to the other location after the character returns, and thus, having seen the pet move the story character has a correct belief about their pet's location.

The event of interest within each trial is the video clip showing the animal switch locations (location-change event) in both TB and FB trials. As the location-change event occurs prior to when participants make a belief judgment, it can be argued that is when belief-reasoning processes occur.

After the location-change clip, the experimenter asked the participant two questions: an attention question ("where did the animal go?") and the theory-of-mind reasoning question ("where will the character look for it?"). To answer the TB trials correctly, the participant had to reason that their own belief of where the animal is located matches the character's beliefs, thus the participant would have to predict that the character will look for the animal in the correct location. To answer the FB trials correctly, the participant had to reason that the character's knowledge of their animal's location does not match their own, thus the participant would predict that the character will look for their animal in the original, incorrect location. Participants were instructed to point to the location they think is correct on the computer screen and their behavioural responses were recorded. The final image in the trial illustrated the character searching for the animal based on either their true or false belief about its location.

Figure 2

Example Scenarios of False and True Belief Conditions



Note. Protagonist introduces pet (Picture 1), places it in one of two locations (2), and leaves (3). EEG event of interest is the location-change event (4; when the animal moves from Location A to B). Participants are instructed to respond to experimenter's ToM questions (5) and then presented with search event (6).

2.2.3 Procedure

Upon arrival at the testing building, a research assistant greeted families at the entrance. The research assistant then led families to the laboratory. Parents/legal guardians were instructed to review the letter of information, sign consent forms for child participation and video recordings, and complete a demographics questionnaire. After parents/legal guardians signed the consent forms and the child assents to participation, the child was invited into the EEG suite and seated in a comfortable seat. Participants completed one practice FB and TB trial. Participants indicated their response to the questions by pointing at the computer screen. After confirming the participant's task comprehension, the experimenter prepared for EEG placement.

Prior to placing it on the participant's head, the EEG net was soaked in a mild electrolyte solution (1.5 teaspoons of potassium chloride and a drop of baby shampoo in 1L of water). While the net was soaking for approximately 5 minutes, the experimenter measured and lightly marked (with a soft, washable crayon) the vertex of the participant's head; this mark was used to guide net placement. The experimenter ensured that excess water was off of the net. The net was stretched over the participant's head such that all the electrodes made contact with the scalp evenly. Once the net was in place, the experimenter worked to ensure that the electrodes were positioned properly. Throughout this procedure, the experimenter monitored the electrode impedances to ensure that all electrodes were making good contact with the scalp.

Thereafter, children completed resting-state and active-state EEG tasks. In the resting-state EEG condition, children's brain activity was recorded while they watched a 6-min video consisting of two alternating components: (a) a 30-second animation of a cartoon rabbit running and (b) a 30-second animation of the same cartoon rabbit sleeping. Children were instructed to remain as still as possible when the video of the rabbit sleeping was presented.

For the active-state EEG task, the theory-of-mind task was conducted, consisting of 4 blocks of 8 trials, with the opportunity for breaks in between blocks. During breaks, electrode impedances were checked, and additional electrolyte solution was applied to individual sensors if necessary.

2.2.4 Data Exclusion and Scoring Procedure

For each trial, participants received a score of 1 for each correct response and a score of 0 if incorrect. Correct responses varied depending on the condition. For Standard TB trials, participants needed to answer with Location B (the new location) to receive a point. For Standard FB trials, the correct answer would be Location A (the original location). Trials in which the participant failed the attention question ("Where did the pet go?") were excluded from analyses. The total score was then determined by calculating the proportion of correct responses out of completed trials for each condition. Based on binomial probability analysis, 95% confidence interval for correct responses ($p = 1/2$, 12 trials) ranged from 3 to 9 correct responses. Therefore, participants needed to score 9 or higher (>75%) to perform above chance. To be considered as "passers", participants would have needed to score at least 75% in the FB task. In contrast, "failers" were those who scored 25% or lower in the FB task.

Of the 482 total usable trials collected in the False Belief (FB) condition, 90 trials were removed, resulting in 392 trials for EEG analysis. In the True Belief (TB) condition, 105 trials were excluded from a total of 489, resulting in 384 trials in the EEG analyses. Exclusion criteria included trials with poor signal-to-noise ratio, participants who failed the TB task, and participants who were unable to be categorized as either a passer or failer (i.e., scoring in the middle range).

2.2.5 EEG Recording and Data Analysis

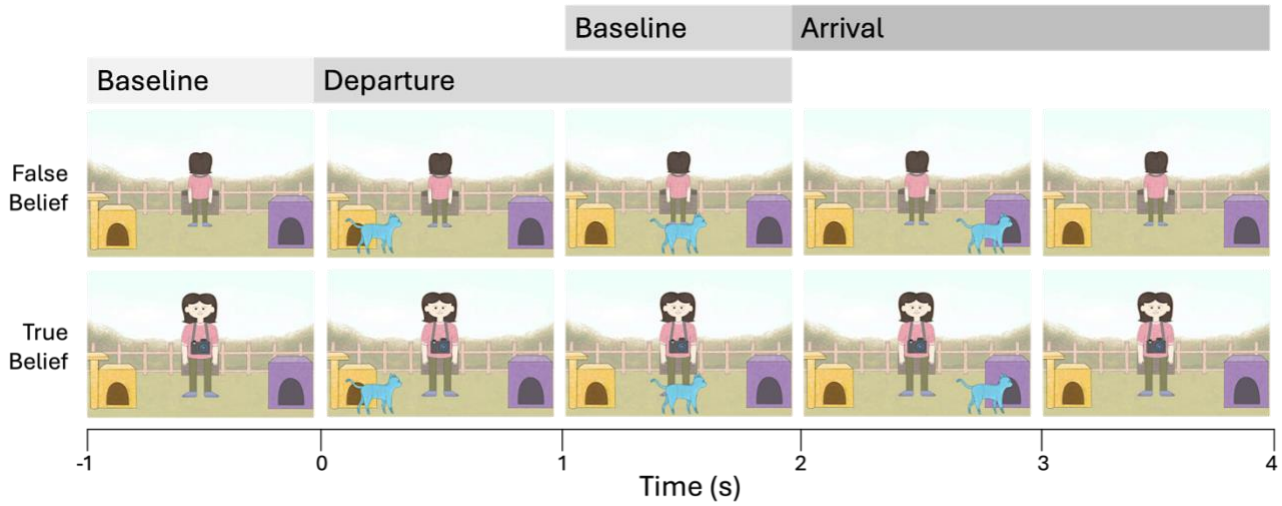
Recordings and Data Processing. The electroencephalogram (EEG) was recorded using a Hydrocel Geodesic Sensor Net that consists of 128 Ag/AgCl electrodes that are

connected in an elastic geodesic tension structure that distributes the electrodes evenly when the net is fitted onto a head. EEG activity in all channels was recorded in reference to the vertex electrode (Cz), sampled at 250 Hz, and bandpass-filtered between .1 and 100 Hz. EEG was recorded continuously throughout the presentation of all trials. Impedances were maintained below 40Ω.

Raw EEG signals were filtered using a 60 Hz notch filter to remove electrical noise. Bad channels (i.e., noisy, flat, or drifting channels) were detected by inspection and interpolated using a spherical spline in the NetStation software (EGI, Eugene, OR). Participants' continuous EEG data was segmented to epochs of 3200ms time-locked to the Departure (when the animal leaves) and Arrival (when the animal arrives to Location B) events within the location-change clip. This epoch included a 1100ms baseline period prior to the events, and 2100ms of the Departure/Arrival events (see Figure 3). We then re-referenced these single-subject averages to the average reference. After FB and TB trials of the location-change epochs were extracted separately, trials that contained large or paroxysmal artifacts were identified by visual inspection and removed from further analysis. For further data quality checks, signal-to-noise ratio distributions were obtained for each participant by dividing mean power over standard deviation across trials. Participants with signal-to-noise ratio distributions trending below 1 were excluded from further analysis.

Figure 3

Departure and Arrival EEG Events within the Location-Change Event



Note. Start of location-change event is at 0s. End of location-change event is at 3s. Departure and Arrival events each last 3s, consisting of 1s baseline period and 2s event of interest.

ERSP Decomposition. EEG recordings were analyzed with EEGLAB2025.0 (Delorme & Makeig, 2004), FieldTrip-20250114 (Oostenveld et al., 2011) as well as custom MATLAB R2024b (MathWorks Inc., MA, USA) scripts. For the time-frequency analyses, a Morlet wavelet convolution was computed to characterize power in the range of 13-30 Hz for beta in .35 Hz frequency steps at 100 timepoints over the 3200ms recording epochs relative to the 1100ms baseline period. Due to the cycling parameters chosen, the recording epoch was truncated by 500ms at the beginning and end of the epoch, reducing the observable data points to the length of 2200ms. Baseline correction was conducted for each subject by using a relative change method of dividing baseline-subtracted values of each frequency point by the average of the baseline values of that frequency (Hu et al., 2014).

2.2.6 Statistical Analyses

Performance Analysis. Preliminary analyses of performance were conducted in RStudio using custom scripts. To look at how age and belief condition influence the outcome variable of score, a Bayesian linear mixed effects model was implemented. The fixed effects included the belief condition (FB, TB) and age in months, and their interactions. Random effects included random intercepts for each subject (subid). The model was specified as:

$$score \sim age * belief + (1|subid)$$

Cluster-Mass Analyses of Failers vs. Passers. Statistical analyses of EEG were conducted in MATLAB and RStudio using custom scripts and plugins. To determine significant modulation (i.e., suppression or enhancement) in beta activity across the location-change event, we employed a cluster-based permutation approach (Candia-Rivera & Valenza, 2022). Non-parametric tests were conducted at each time point (100), for each frequency point (50), across all electrodes (129), generating statistical maps of beta differences. In assessing group differences between passers and failers, Mann-Whitney U tests were used.

These tests were conducted separately for the Departure and Arrival events. First, a preliminary mask was created by selecting time points where the statistical test p-values were below an initial significance threshold ($p < .05$). Candidate clusters were then identified by grouping contiguous significant time points (minimum: 300ms) in neighbouring electrodes (minimum: 3 channels) and adjacent frequency points. Cluster-level statistics were computed using the cluster-mass statistic, which sums the absolute test statistics within each identified cluster. Statistical significance was assessed via a Monte Carlo permutation test. Across 1000 iterations, group labels were randomly shuffled, and the same clustering procedure was applied to generate a null distribution of cluster statistics. Observed clusters with statistics that exceeded the critical threshold ($p < .05$) were deemed significant. Clusters of 3 or more neighbouring electrodes that showed significant differences in beta activity spanning more than 300ms (10 timepoints) were selected for further analysis.

ERSP Analyses of Changes from Baseline. To determine whether, in the identified electrode clusters, there were any significant modulation (i.e., suppression or enhancement) in beta activity relative to baseline, we again employed a cluster-mass statistical approach. Significant electrodes were first grouped based on shared region (e.g., posterior parietal). Wilcoxon signed-rank tests were conducted for average beta power across 100 time points to create a field of Z-values. This field was then thresholded to only include Z-values that surpassed an initial significance criterion ($p < .05$). The thresholded timeline was submitted to a clustering algorithm. Cluster-mass statistics were calculated as the sum of the negative log of the p-values of significant tests that were temporally contiguous. The height of each identified cluster was established by summing positive z-values (enhancement) and negative z-values (suppression) within the cluster. The significance criteria for these cluster heights were determined by a randomization procedure. Across 1000 iterations, the condition assignment of any given participant's baseline EEG data was randomly scrambled, and the

resulting randomized data was submitted to the same procedure described above. Cluster heights were computed for all identified clusters and pooled to create a null hypothesis distribution of cluster heights for evaluating our clusters. Clusters in our original, observed data that exceeded a $p < .05$ criterion compared within this null-hypothesis distribution were selected for reporting and interpretation.

Group Differences in Mean Beta. To examine mean differences, beta power within significant electrode clusters was averaged across significant timepoints. For any relevant electrode sites, an ANOVA was conducted with mean beta power as the dependent variable and group (passers, failers) as the independent variable. These analyses were done separately for Departure and Arrival events that were found to be significant in the cluster-mass analyses.

2.3 Results

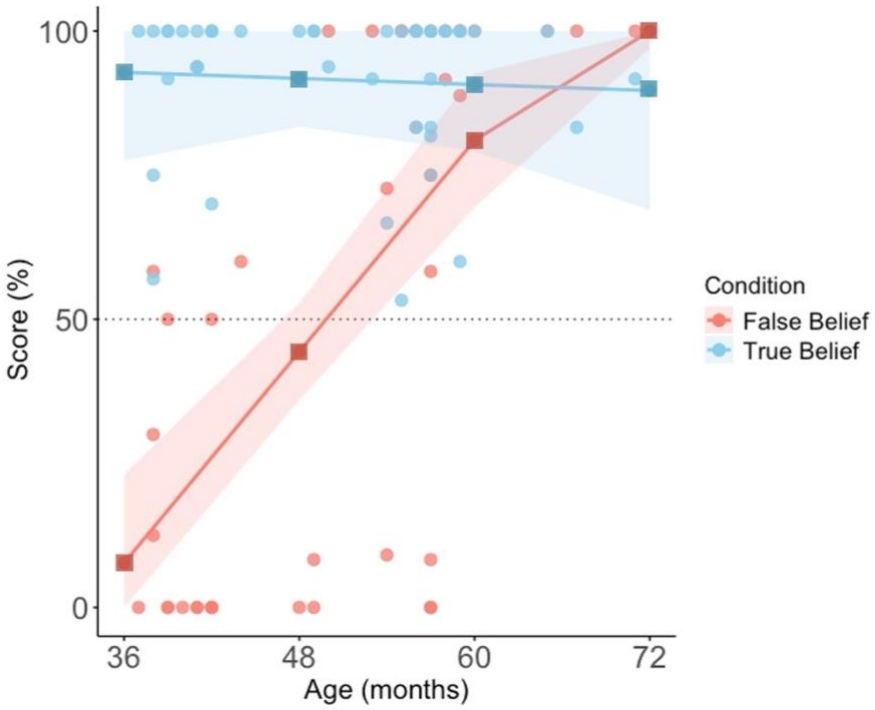
2.3.1 Preliminary Analyses

We examined the effects of condition (FB, TB), age (centred), and their interaction on children's ToM performance using a Bayesian linear mixed-effects model. The model included condition and age as fixed effects and subject as a random intercept. This approach was chosen after initial attempts with a standard linear mixed-effects model revealed signs of overfitting, likely due to sample size constraints relative to model complexity. The model revealed a significant main effect of condition, with the TB condition yielding higher scores than FB, $\beta = 39.23$, $SE = 5.46$, $t(85) = 7.18$, $p < .001$. Additionally, there was a significant main effect of age on score, $\beta = 27.76$, $SE = 4.07$, $t(85) = 6.83$, $p < .001$, indicating that with age, participants' scores tended to increase. The analysis showed a significant interaction between age and condition, $\beta = -28.56$, $SE = 5.50$, $t(85) = -5.20$, $p < .001$. This suggests that the positive effect of age on performance differed by condition.

Simple slopes analyses were conducted to examine the effect of age within each trial condition. In the FB condition, age was a significant predictor of scores, b= 27.80, SE= 4.07, t(81.4) =6.83, p < .001, 95% CI [19.67, 35.85]. However, in the TB condition, age was not a significant predictor, b= -0.80, SE= 4.07, t(81.4)= -0.20, p= .84, 95% CI [-8.89, 7.29]. This suggests that age significantly predicted performance in the FB condition but not in the TB condition. Figure 4 shows children's performance in FB and TB tasks across age. It is important to note that is includes data not just from sample used in EEG analyses, but the full sample that provided usable task results.

Figure 4

Model Fit of Children's Performance in False and True Belief Tasks Across Age



Note. Red and blue circles represent participants' observed scores, while red and blue squares along the line show the estimated means based on model predictions. Shaded ribbons around the lines indicate the 95% confidence intervals for the predicted values. Data derived from full sample of participants that provided usable task results.

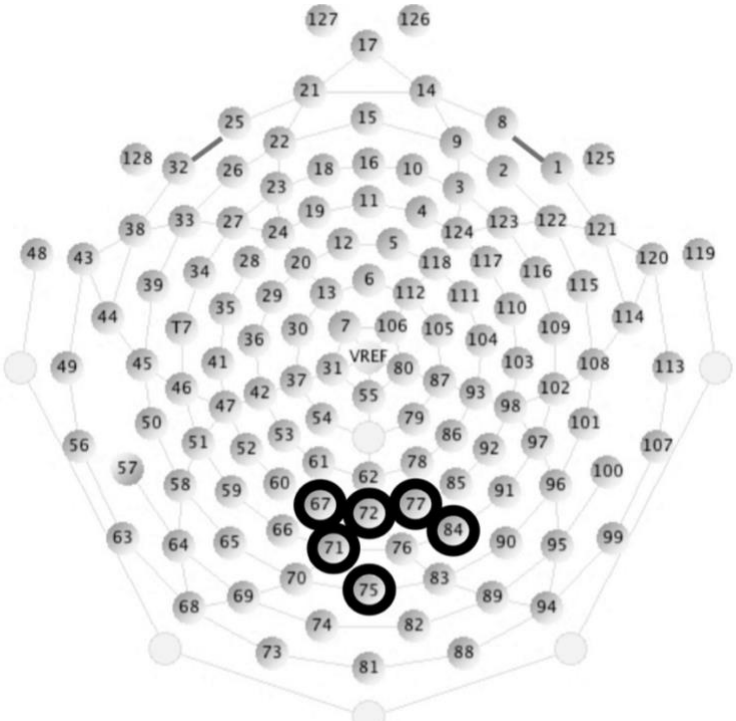
2.3.2 Beta EEG in False Belief Condition

Cluster-Mass Analyses of Failers vs. Passers. To determine when and where there were significant differences in beta between failers and passers in the FB condition, non-parametric cluster-mass analyses were conducted on time-frequency-channel data structures. This was done for separately for FB Departure and Arrival events. From the clusters that formed, electrodes with significant differences for more than 300ms were selected for interpretation. Interpretable clusters were found only in the FB Arrival event. Here, between-group comparisons revealed a significant negative cluster of beta differences (relative suppression in failers vs. passers) over posterior parietal electrode sites (E67, E71, E72, E75, E77, E84; $p < .001$, cluster mass= 4.21). Average duration of group differences in beta was 380ms (see Table 3). These results suggest that failers exhibited more sustained suppression than passers did during the FB Arrival event.

Table 3

Channel Group showing Sustained Differences Failers vs. Passers in FB

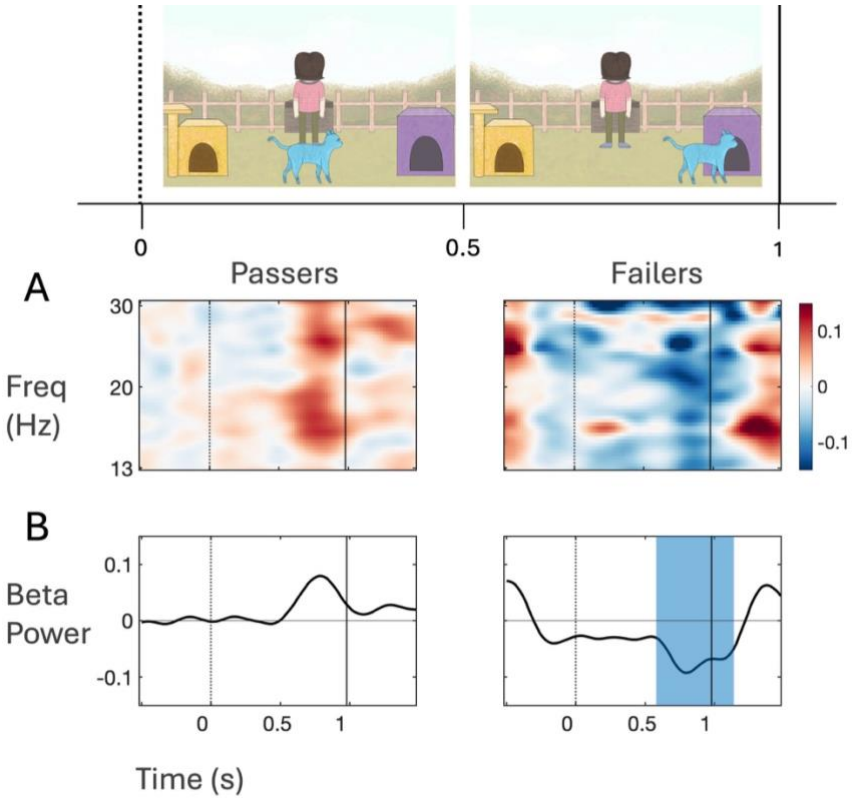
Channel Group	Min – Max Time (ms)	Average Duration (ms)	Min – Max Frequency	Average Frequency (Hz)
Posterior Parietal	640 – 1100	380 (SD = 62.60)	14.8 – 27.8	19 (SD = 1.10)



ERSP Analyses of FB. To further characterize the observed cluster differences in the FB Arrival event, we averaged baseline-corrected beta ERSPs across significant channels that were identified in the cluster-mass analyses (over posterior parietal; see Table 3 for individual channels). The data was then subjected to a within-group cluster-mass analyses, comparing beta ERSPs to the baseline period for each participant. In the FB Arrival event, failers showed sustained beta suppression over the left parietal. This suppression spanned 590ms (see Figure 5; time window: .59s to 1.18s). In contrast, passers exhibited visually apparent beta enhancement in the ERSP plots; however, this pattern did not reach statistical significance in the cluster-mass analysis relative to baseline. Figure 5 shows beta ERSP plots and mean beta power across time over posterior parietal during the Arrival event.

Figure 5

Beta ERSPs over Posterior Parietal during FB Arrival Event

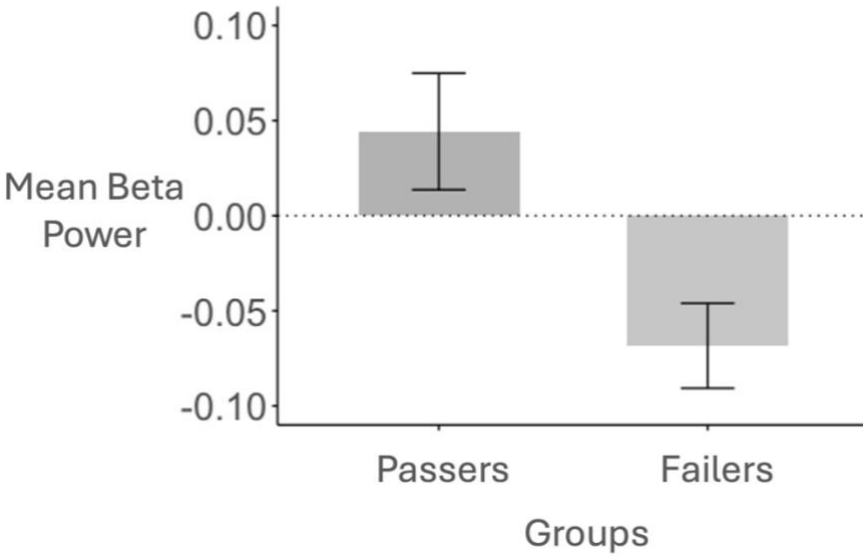


Note. Dotted vertical line at 0s marks end of baseline period. Solid vertical line at 1s marks end of Arrival event. Power is shown as a ratio relative to the baseline period. A) *Beta ERSP plots*. Warmer colours indicate enhancement and cooler colours indicate suppression. B) *Mean beta power line plots*. Blue highlights indicate significant ($p<.05$) suppression relative to baseline.

Mean Group Differences in FB. Beta power over the posterior parietal was averaged across the largest time window in the FB Arrival event. This consisted of a 590ms event as the animal reaches the second location in the FB task (time window: 0.59 to 1.18s). An ANOVA was conducted to examine the effects of group on relative change in beta. We found a significant difference between groups, $F(1, 37)= 8.32$, $p= .01$, with a moderate effect size ($\eta^2 = .18$). Figure 6 shows mean beta power over posterior parietal at FB arrival in passers and failers.

Figure 6

Mean Beta Power Over Posterior Parietal at FB Arrival



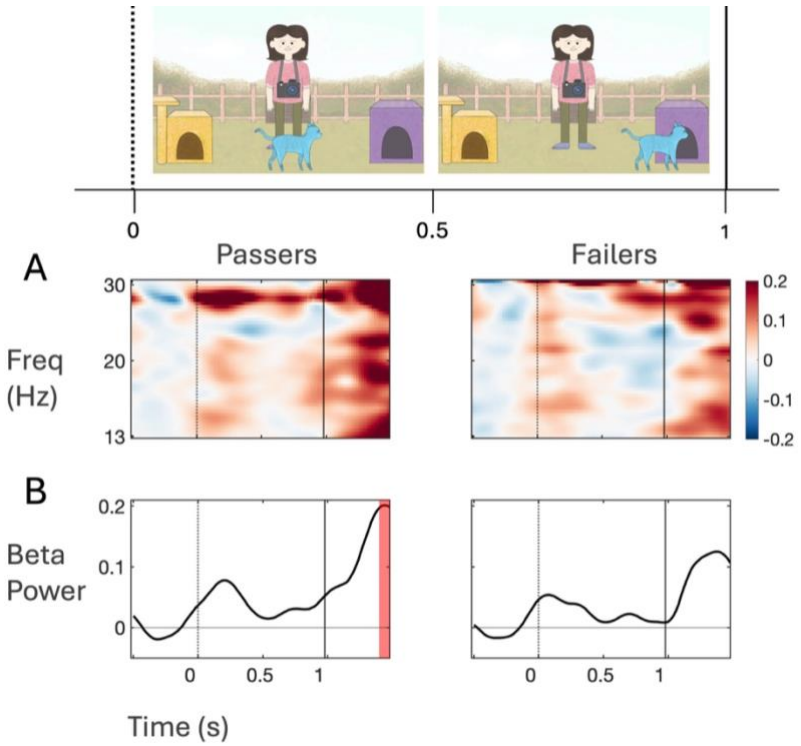
Note. Mean beta power is shown for passers and failers. Power is shown as a ratio relative to the baseline period. Error bars represent standard errors.

2.3.3 Beta EEG in True Belief Condition

ERSP Analyses of TB. Cluster-mass analyses on time-frequency-channel data from the TB condition revealed no significant clusters of beta differences between passers and failers. This suggests that passers and failers exhibit similar beta activity in response to TB events. To examine how beta changes from baseline, we averaged beta ERSPs across the same channels (see Table 3) used in the FB analyses. This was done for the Arrival event in which we found a significant main effect of group in the FB condition. Then, we conducted within-group cluster-mass analyses to examine differences between the Arrival event and the baseline period. Results show that passers exhibit some significant enhancement at the end of the epoch, post-Arrival (time window: 1.45s – 1.54s). Figure 7 shows beta ERSP plots and mean beta power across time over posterior parietal during the Arrival event.

Figure 7

Beta ERSPs over Posterior Parietal during TB Arrival Event

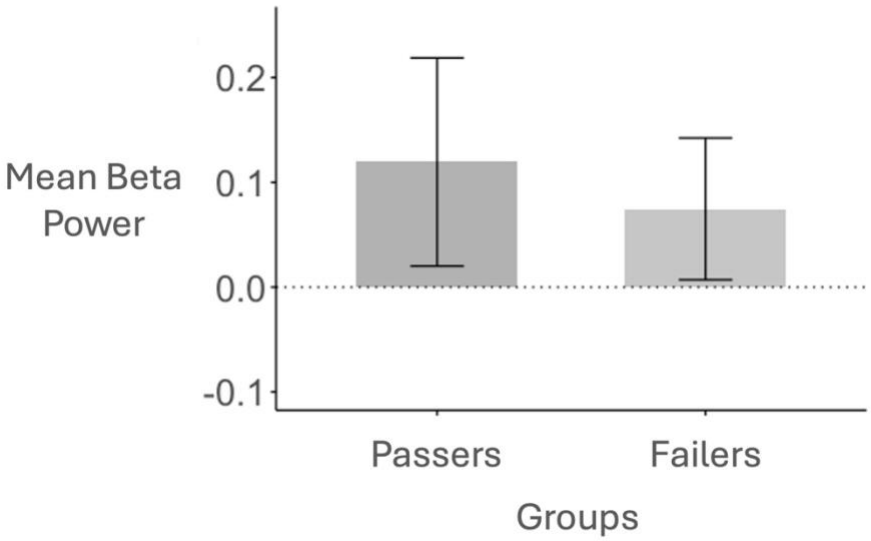


Note. Dotted vertical line at 0s marks end of baseline period. Solid vertical line at 1s marks end of Arrival event. Power is shown as a ratio relative to the baseline period. A) *ERSP plots of beta in passers and failers.* Warmer colours indicate enhancement and cooler colours indicate suppression. B) *Mean power line plots.* Red highlights indicate significant ($p<.05$) enhancement relative to baseline.

Mean Group Differences in TB. To further characterize how mean beta differs between groups, we conducted an ANOVA using the last 0.5s (1.01 to 1.54s) in which we found evidence of significant modulation. We found no significant differences between group, $F(1,37)= 0.13$, $p= .72$. While failers exhibited some evidence of enhancement in the ERSP plots (see Figure 7), they did not reach significance. However, analyses of mean differences at the end of the event shows that beta in failers does not differ from passers. Along with the non-significant 3D cluster-mass analyses, these results suggest that passers and failers process the TB Arrival event similarly. Figure 8 shows mean beta power over posterior parietal at TB Arrival event in passers and failers.

Figure 8

Mean Beta Power Over Posterior Parietal at TB Arrival



Note. Mean beta power is shown for passers and failers. Power is shown as a ratio relative to the baseline period. Error bars represent standard errors.

2.4 Discussion

This study examined beta EEG modulations in preschoolers aged 3 to 6 years old as they completed FB and TB tasks. By analyzing beta oscillatory activity, we aimed to distinguish between the representational monitoring and shared-beliefs heuristic accounts of ToM. Our findings offer novel insights into the neurocognitive processes underlying belief-reasoning and the development of ToM in early childhood.

Consistent with previous literature, we observed a significant main effect of condition on ToM score, with children performing better in the TB condition than in the FB condition. As the TB serves as our control, these results confirm that children understood basic task structure and were paying attention (e.g., memory of object's location). Age was a strong predictor of ToM performance, with older children demonstrating higher scores overall. Importantly, our interaction effect revealed that age-related improvements were more pronounced in the FB condition. This supports established findings that FB reasoning undergoes a gradual developmental process from age 3 to 5 years.

2.4.1 Beta EEG in Passers vs. Failers

Our EEG analyses looked at beta EEG in passers vs. failers. In the FB condition, we found significant group differences in beta activity at the moment the animal reaches its final destination in the FB condition (FB Arrival event). These differences were found in electrodes over the posterior parietal site. Failers exhibited beta suppression relative to passers, suggesting that failers engaged in cognitive updating when reasoning about others' false beliefs. Conversely, passers did not show significant beta suppression or enhancement, possibly reflecting a lack of updates to their belief representations. These differences emerged towards the end of the Arrival event (when the animal goes into Location B), pinpointing when belief representations are formed within the ToM task.

For the TB condition, initial cluster-mass analyses revealed no significant difference in beta power across channels, time, and frequencies between passers and failers. This suggests that passers and failers process TB scenarios in a similar manner, both exhibiting some evidence of beta enhancement that would be indicative of cognitive maintenance. However, it is important to note that the electrode site examined for the TB condition were selected based on the significant differences observed in the FB condition. Since our analyses concerns differences between groups, the current results do not fully reflect the mechanisms engaged for TB reasoning. Future research may look into beta differences between FB and TB conditions to determine how processes differ in the TB scenario.

2.4.2 Implications for Theories of ToM Development

The current findings contribute to our understanding of the cognitive and neural mechanisms that support ToM development, and in particular, they provide support for the representational monitoring account (Apperly & Butterfill, 2009; Leslie, Friedman, & German, 2004), as well as broader theoretical frameworks of conceptual change (Wellman & Cross, 2001; Gopnik & Wellman, 1994).

We found that children who failed the FB task exhibited beta suppression over posterior parietal during the belief formation window (i.e., the location-change event). Beta suppression can be interpreted as a correlate of representational updating (Hall et al., 2024; Lundqvist et al., 2024; Zavala et al., 2018), suggesting that children erroneously updated their representations of the protagonist's belief to match reality, despite the protagonist having missed the animal's relocation. This neural signature implies a failure of representational maintenance, the ability to hold onto one's representations of another's outdated beliefs when it conflicts with one's own current knowledge. These findings fall in line with the representational monitoring hypothesis, which posits that belief-reasoning involves dynamically updating or maintaining belief representations depending on the other person's

experiences. In the FB condition, accurate reasoning requires not updating belief representations, but instead maintaining an earlier, now-false belief representation.

Importantly, these results also speak to the conceptual change account of ToM development. According to this view, children experience a major conceptual change over preschool years, from a view that beliefs mirror reality, to an understanding that beliefs are independent representations of the world that may diverge from the truth (Gopnik & Wellman, 1992; Wellman, 2010). The current findings provide neural evidence for this developmental transition. The fact that failers showed evidence of representational updating during the location-change event suggests that their belief-reasoning was tied to their own experience of the truth. Because they updated the protagonist's belief as if it had been updated along with reality, this exemplifies how they do not yet understand beliefs as subjective, representational constructs.

In contrast, children who passed the FB task showed some evidence of beta enhancement (although not significantly different from baseline) during this same time window, indicating that they did not update their representations of the protagonist's belief. This suggests some engagement in representational maintenance, as passers were able to hold onto the protagonist's distinct belief of the animal's earlier location.

2.4.2 Conclusion

This study provides evidence that beta EEG activity reflects the cognitive processes engaged during belief-reasoning in preschool-aged children. Our results support the representational monitoring account, showing that children who fail FB tasks exhibit beta suppression during location-change event. This suggests an inappropriate updating of their representations of the protagonist's beliefs in line with reality. In contrast, children who succeed in FB reasoning show some evidence of beta enhancement, consistent with the active maintenance of their representations of the protagonist's outdated beliefs.

Crucially, these neural differences emerged during the moment when beliefs are formed, rather than when responses are selected, pointing to a developmental shift in children's understanding of beliefs as subjective representations that can potentially diverge from reality. This pattern aligns with conceptual change account (Gopnik & Wellman, 1992; Wellman, 2010), which posits that preschoolers gradually come to understand that beliefs are mental representations shaped by individual experience and not mirror images of the world.

By using beta oscillations as a neural index, our findings highlight how the ability to maintain versus update belief representations plays a central role in the development of ToM. These results help to advance our understanding of the neurocognitive mechanisms underlying belief reasoning.

Chapter 3 – Study 2

Beta EEG and Belief-Reasoning in Ignorant ToM Conditions

3.1 Introduction

A crucial factor in ToM tasks is how knowledge is distributed between the participants and story protagonists. In typical FB tasks, the protagonist remains unaware of the object's relocation, while participants always witness the event. This full knowledge may contribute to preschoolers' difficulty with FB reasoning. Prior research suggests that children perform better at judging another's false beliefs when they, too, are uncertain about the object's whereabouts (Birch & Bloom, 2003; Ghrear et al., 2021; Wellman & Bartsch, 1988). However, the neurocognitive mechanisms driving this effect remain unclear.

Beta-band EEG activity is shown to be a reliable neural correlate of belief reasoning (Study 1; Payumo, 2021). It has been shown to reflect cognitive processes such as cognitive maintenance and updating: beta power tends to increase during maintenance and decrease during updating (Engel & Fries, 2010; Kilavik et al., 2013; Schmidt et al., 2019). In Study 1, patterns of beta activity differentiated children who succeeded versus those who failed FB tasks, suggesting distinct cognitive strategies of representational monitoring. While failers erroneously updated their representations of the protagonist's beliefs, passers showed evidence of correctly maintaining representations of the protagonist's outdated beliefs.

The current study builds on these findings by examining beta EEG as children complete ToM conditions where they lack knowledge about the object's location. This will provide insight into why children perform better under these conditions and what factors contribute to children's ToM errors.

3.1.1 Standard vs. Ignorant False Belief conditions

To investigate how children conceive of beliefs as mental states, Wellman & Bartsch (1988) designed a set of belief-reasoning tasks for 3- and 4-year-olds. These tasks were

structured as stories in which a character searched for a desired object (e.g., a puppy, candy, or toy). In some tasks, children were informed of the object's actual location, while in others, they remained ignorant. When asked where the character would look for the object, 3-year-olds performed above chance in conditions where they did not know its location compared to when they did. This suggests that ignorance may facilitate reasoning about another's mental states, and conversely, that privileged knowledge may hinder it. Wellman et al. (2001) argue that difficulty in FB tasks arise from the conflict between preschoolers' own beliefs and those of others. By inducing ignorance in FB tasks, children's own mental states become less *salient*, thereby minimizing this conflict and making it easier to reason about others' beliefs.

An alternative account, however, emphasizes a different mechanism. Rather than attributing children's errors to conflict between self and other perspectives, this view suggests that the challenge lies in overcoming a general cognitive bias. Birch & Bloom (2003) showed this in a task where 3- to 5-year-olds were either shown ("Standard") or not shown ("Ignorant") the inside of a toy. When asked whether a puppet, who did not know about its contents as well, would know what was inside, children were more likely to provide the correct answer (i.e., that the puppet does not know) in the Ignorant condition than in the Standard one. More recently, Ghrear et al. (2021) investigated how having privileged knowledge affects FB reasoning in children aged 3 to 6. Using a modified FB task, they found that children—especially 3-year-olds—struggled more to predict a character's belief when they themselves knew the true location of an object as opposed to when they were told the object was in an unknown location. Birch & Bloom (2003) argue that these ToM errors stem from a general cognitive bias toward assuming that others share the same knowledge as oneself—a "curse of knowledge" bias to which preschoolers are particularly susceptible. Ignorant FB tasks help mitigate this bias because, by withholding knowledge about the

object's location, children do not need to overcome their initial assumptions. Collectively, these studies show how inducing ignorance in children may improve their belief-reasoning.

The explanations for why preschoolers fail Standard FB tasks offered by Wellman et al. (2001) and Birch & Bloom (2003) focus on what happens at the decision stage– when children are asked to judge where the protagonist will look. At the decision event, children may struggle to negotiate conflicts in beliefs or inhibit their assumptions. However, findings from Chapter 2 suggest that the location-change event may be just as critical, especially for belief formation. To date, no study has specifically examined how beliefs are formed during the Ignorant FB scenario. Addressing this gap in our research could provide deeper insight into the factors shaping children's ToM performance.

3.1.2 Beta EEG in the Ignorant False Belief Condition

In Chapter 2, we found that beta EEG can differentiate passers and failers in Standard FB tasks. We found that preschoolers who failed exhibited significant beta suppression during the event, suggesting that they updated their representations of the protagonist's beliefs that they believe. In contrast, children who successfully reasoned about false beliefs showed evidence of beta enhancement, suggesting that they engaged in correct representational maintenance.

Applying these findings to our current investigation, we may expect children who fail Standard FB tasks to show greater beta enhancement in the Ignorant FB condition compared to the Standard FB condition. This pattern would suggest improved representational maintenance when children are entirely ignorant. In contrast, we may not expect significant differences in beta activity across knowledge conditions for passers, who already show appropriate representational maintenance in Standard FB tasks. These predictions are grounded in Wellman et al.'s (2001) "salience" argument that ignorance reduces the salience of one's own mental states, thereby facilitating belief-reasoning.

Alternatively, under Birch & Bloom's (2003) “curse of knowledge” hypothesis, improvements in Ignorant FB tasks may not stem from enhanced representational maintenance, but from the reduced need to overcome one’s own knowledge. In this case, successful performance may not necessarily be associated with maintenance processes but rather updating. Because failers lack privileged knowledge in Ignorant FB, they may find it easier to overcome initial assumptions. As such, we may expect failers to show greater beta suppression in Ignorant FB than Standard FB under this account.

3.1.3 Objectives and Hypotheses

The objective of Chapter 3 was to investigate the neurocognitive mechanisms underlying children’s improved performance in Ignorant ToM tasks. Preschoolers, ages 3 to 6 years old, completed a multi-trial ToM task in which they judged a story protagonist’s beliefs (false or true) about an animal’s location that they themselves either knew about (Standard) or did not know about (Ignorant). To examine representational monitoring, beta EEG (13-30 Hz) was analyzed during the location-change event.

Based on our previous findings, we expected children who failed the Standard FB task to exhibit beta suppression during the location-change event, indicating incorrect updates to their representations of the protagonist’s beliefs. This would replicate our Chapter 2 findings. If Wellman et al.’s (2001) theory is true that Ignorant FB facilitates representational maintenance in failers, then we would expect to see evidence of greater beta enhancement in failers that we would not see in the Standard FB condition. If Birch & Bloom's (2003)’s theory is true that Ignorant FB facilitates overcoming one’s knowledge, then we would expect to see evidence of greater beta suppression in failers than in Standard FB.

3.2 Methods

3.2.1 Study Participants

This study was approved by the General Research Ethics Board at Queen's University (Appendix A). We recruited 62 preschoolers ages 3 to 6 years old (35 female, *M* age = 57.5m, *SD*= 12.8) from the local community via word of mouth, social media, recruitment events, and the Child & Adolescent Developmental Database. Participants were compensated with $15 cash or gift card. The demographics of our participants reflected the predominantly white, middle-class university population in Eastern Canada from which it was drawn (see Table 4). A total of 27 participants were excluded from analyses due to reasons such as refusal to wear EEG net (1), not completing the task (8), outlying task performance, e.g., failure on TB task (4), and poor EEG signal-to-noise ratio (11), and intermediate FB scores the precluded classification as passing or failing (3). The final EEG sample, therefore, consisted of 35 participants (16 female). Of these remaining participants, 18 were passers *(M* age= 66.4mo, *SD*= 8) and 17 were failers (M age = 48mo, SD = 9).

Table 4

Participant Demographics

Demographic Characteristic	%	n
Ethnicity		
White	75.8	47
White and East Asian	6.5	4
Hispanic/Latino/Latina	4.8	3
South Asian	4.8	3
Black	1.6	1
East Asian and Southeast Asian	1.6	1
Southeast Asian	1.6	1
White and Black	1.6	1
White and West Asian	1.6	1
Parent 1 Education		
Some high school, no diploma	1.6	1
High School Graduate, diploma, or equivalent	1.6	1
Some college credit, no diploma	3.2	2
Trade/Technical/vocational training	8.1	5
Associate's	9.7	6
Bachelor's	35.5	22
Master's	17.7	11

Professional Degree	4.8	3
Doctorate Degree	17.7	11
Parent 2 Education		
Some high school, no diploma	1.6	1
High School Graduate, diploma, or equivalent	4.8	3
Some college credit, no diploma	11.3	7
Trade/Technical/vocational training	21	13
Associate's	9.7	6
Bachelor's	24.2	15
Master's	9.7	6
Professional Degree	6.5	4
Doctorate Degree	8.1	5
Missing	3.2	2
Yearly Household Income		
20,000 to 34,999	3.2	2
35,000 to 49,999	6.5	4
50,000 to 74,999	14.5	9
75,000 to 99,999	14.5	9
100,000 to 149,999	25.8	16
> 150,000	35.5	22

3.2.2 Materials and Stimuli

Theory of Mind Task. Participants' EEG was recorded as children completed a multi-trial ToM task. Task was presented using E-Prime software (Psychology Tools Inc.). Figure 9 demonstrates example trials from the 4 conditions: Standard FB, Standard TB, Ignorant FB, and Ignorant TB. The task consisted of 60 short, animated scenarios presented on a computer monitor. The task presented 15 trials from each condition in a randomized order. For each trial, it depicted a character acting on the basis of their true or false beliefs, resembling a story according to the "location-change" FB task (Baron-Cohen et al., 2013).

The first four images in all conditions were the same: the character introduces a bird on screen (picture 1), the character follows to watch the bird go into one of two birdhouses (picture 2), the character placing a bowl of berries in the middle "midpoint" platform (picture 3), and then turning around and leaving to get more berries from the bush behind (picture 4). The location in which the bird is placed is counterbalanced across trials so that they are

placed in either the left or right location an equal number of times. After the character leaves, the subsequent series of events depended on the trial condition.

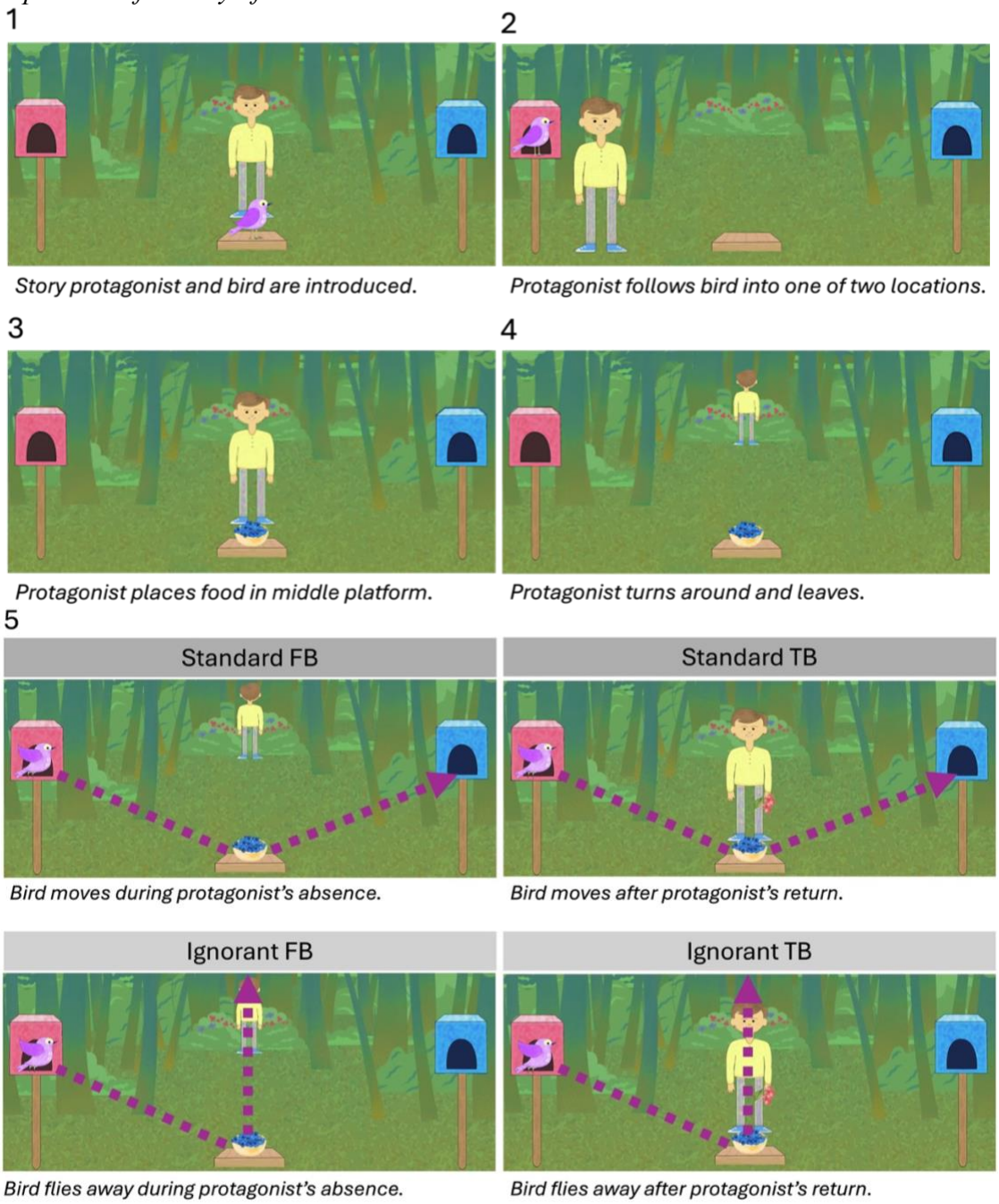
In the Standard TB condition, the character comes back in time so that they witness alongside the participant the bird fly to the midpoint, then to the other birdhouse. In the Standard FB condition, the participant sees the bird fly to the second location, while the protagonist is turned around and so misses the event. The conditions will serve as control comparisons against the ignorant conditions. In the Ignorant TB condition, both the participant and protagonist see the bird fly to the midpoint to get berries and then up into the trees out-of-scene, leaving both parties ignorant about its location. In contrast, in the Ignorant FB condition, while the participant sees the bird fly to the midpoint and then up into the trees, the protagonist does not return in time to see this happen. This leaves the participant ignorant about the object's location and the protagonist not knowing that the bird left its original location. In all conditions, the clip in which the animal transfers locations are referred to as the location-change event.

After these events, the experimenter asked the participant three questions: the attention question ("where is the bird?"), the knowledge question ("did [character] see where the bird went?"), and the ToM reasoning question ("where will [character] look for the bird?"). To get the Standard FB and Ignorant FB trials correct, participants would need to reason that the character did not see the bird leave the original location and thus look for it there ("[character] will look in [Location A]"). In the Standard TB condition, the character sees the bird go into the alternate birdhouse and so participants would need to judge that the character will look for it in its new location ("[character] will look in [Location B]"). As for the Ignorant TB condition, the character sees the bird fly up into the trees and so participants would need to guess that while the character knows the bird left its original location, they also do not know where the bird is ("[character] does not know where bird is").

After the participant responds, a picture is presented of the protagonist searching for the bird based on their belief. In both Standard and Ignorant FB conditions, the protagonist is seen searching for the bird in its original location. In the Standard TB condition, the protagonist looks for the bird in the new location they saw it go into. In Ignorant TB trials, a question mark appears above the protagonist's head to indicate that they do not know where to look for the bird.

Figure 9

Example trial of Theory of Mind Task in all Conditions



Note. Protagonist introduces bird (Picture 1), follows it in one of two locations (2), places berries in midpoint platform (3), and leaves (4). EEG event of interest is the location-change event (5), comprising of bird's Departure (Location A to midpoint), Arrival in Standard condition (midpoint to Location B), or Disappearance in Ignorant conditions (midpoint to trees). After location-change event, participants are instructed to respond to experimenter's ToM questions (not pictured) before presentation of protagonist's search (not pictured).

3.2.3 Procedure

Upon arrival at the testing building, families were greeted by the experimenters and were led to the laboratory. Parents/legal guardians were instructed to review the letter of information, sign consent forms for child participation and video recordings, and complete a demographics questionnaire. After parents/legal guardians signed the consent forms and the child assents to participation, the child was invited into the EEG suite and seated in a comfortable seat. Participants completed practice trials of all four task conditions and instructed to indicate their responses to the questions by pointing at the computer screen. After confirming the participant's task comprehension, the experimenter prepared for EEG placement.

Before placing the EEG net on the participant's head, it was soaked in a mild electrolyte solution (1.5 teaspoons of potassium chloride and a drop of baby shampoo in 1L of water). While the net was soaking for approximately 5 minutes, the experimenter measured and lightly marked (with a soft, washable crayon) the vertex of the participant's head; this mark was used to guide net placement. Prior to placement, the experimenter ensured that excess water was off the net. The experimenter stretched the net over the participant's head and worked to ensure that the electrodes were positioned properly and evenly across the scalp. Once the net was in place, the experimenter monitored the electrode impedances to ensure that all electrodes were making good contact with the scalp.

Thereafter, the procedure was conducted in the following order: 1) 20-minute ToM task with 30 trials; 2) five-minute snack break; 3) 20-minute ToM task with 30 trials. The whole ToM task was split into 8 blocks, with varying number of trials within each block. Upon completion of each block, the children would be rewarded with a sticker. During the snack break, electrode impedances were checked again, and additional electrolyte solution was applied to the sensors if necessary.

3.2.4 Data Exclusion and Scoring Procedure

For each trial, participants received a score of 1 for each correct response and a score of 0 if incorrect. For Standard TB trials, participants needed to answer with Location B (the new location) to receive 1 point. For Standard FB trials, the correct answer would be Location A (the original location). In the case of Ignorant TB trials, participants were correct if they responded with "it flew away," “up there,” or “they don’t know” or pointed up to the trees. Lastly, for Ignorant FB trials, participants needed to respond with Location A to earn a point. Trials in which the participant failed the attention question (“Where did the bird go”) were excluded from analyses. The total score was then determined by calculating the proportion of correct responses out of completed trials for each condition. Binomial probability analyses indicated that, under chance performance (p= 1/3) across 15 trials, the 95% confidence interval for correct responses ranged from 2 to 9. Therefore, participants needed to score 9 or higher (≥60%) to perform above chance. To be considered as “passers”, participants would have needed to score at least 60% in the Standard FB task. Participants who scored 2 or below (<13%) in Standard FB were classified as “failers”.

In the Standard FB condition, 111 out of 493 total trials were excluded, yielding 382 trials for EEG analyses. For the Ignorant FB condition, 122 out of 492 trials were excluded, resulting in 370 usable trials. Exclusion criteria were consistent with Study 1 as we excluded trials with poor signal-to-noise ratio and participants who were unable to be classified as passers or failers due to intermediate performance.

3.2.5 EEG Recording and Data Processing

Recordings and EEG Pre-processing. The electroencephalogram (EEG) was recorded using a Hydrocel Geodesic Sensor Net that consists of 128 Ag/AgCl electrodes that are connected in an elastic geodesic tension structure that distributes the electrodes evenly when the net is fitted onto a head. EEG activity in all channels was recorded in reference to

the vertex electrode (Cz), sampled at 250 Hz, and bandpass-filtered between .1 and 100 Hz. EEG was recorded continuously throughout the presentation of all trials. Impedances were maintained below 40Ω.

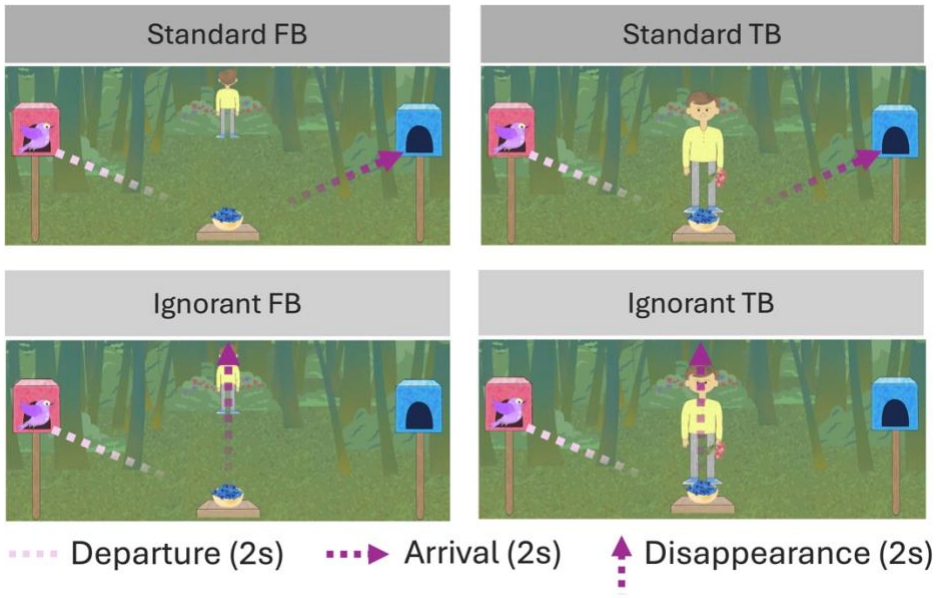
Raw EEG signals were digitally filtered using a 60 Hz notch filter to remove electrical noise. Bad channels (i.e., noisy, flat, or drifting channels) were detected by inspection and interpolated using a spherical spline in the NetStation software (EGI, Eugene, OR). Thereafter, preprocessing was continued on EEGLab (Makeig & Delorme, 2004). Data was re-referenced to the average reference. Continuous recordings were segmented to create 2500ms epochs of Departure and Arrival/Disappearance events within the location-change clip (see Figure 11). This included 500ms baseline, 1000ms as animal reaches the second location or disappears, and 500ms post-stimulus event. After trials of each of the four conditions were extracted separately, trials that contained large or paroxysmal artifacts were identified by visual inspection and removed from further analyses. For further data quality checks, signal-to-noise ratio distributions were obtained for each participant by dividing mean beta power over standard deviation across trials. Participants with signal-to-noise ratio distributions trending below 1, indicating too much noise, were excluded from further analysis.

ERSP Decomposition. EEG recordings were analyzed with EEGLAB2025.0 (Delorme & Makeig, 2004), FieldTrip-20250114 (Oostenveld et al., 2011) as well as custom MATLAB R2024b (MathWorks Inc., MA, USA) scripts. Recordings were segmented into distinct Departure and Arrival/Disappearance events (see Figure 10). These events included a pre-stimulus baseline period (1s), the event of interest (1s), and a post-stimulus period (1s). For the ERSP analyses, a Morlet wavelet convolution was computed to characterize power in the beta range of 13-30 Hz in .05 Hz frequency steps. This was done for 100 timepoints over the length of the Departure (2.5s) and Arrival/Disappearance (2.5s) events. Due to the cycling

parameters chosen, the recording epoch was truncated by 250ms at the beginning and end of the epoch, reducing the observable data points to the time range of -0.5 to 1.5s. Baseline correction was conducted for each subject by using a relative change method of dividing baseline-subtracted values of each frequency point by the average of the baseline values of that frequency (Hu et al., 2014).

Figure 10

Departure and Arrival / Disappearance EEG Events within Location-Change



Note. Departure and Arrival/Disappearance events each last 2s, consisting of 500ms baseline period, 1s event of interest, and 500ms post-stimulus period

3.3.6 Statistical Analyses

Performance Analysis. Preliminary analyses of performance were conducted in RStudio using custom scripts. To look at how age and the knowledge condition influence the outcome variable of score, a linear mixed effects model was implemented. The fixed effects included the knowledge condition (standard, ignorant) and age in months, as well as their interactions. Random effects included random intercepts for each subject (subid). This was done separately for FB and TB conditions. The model was specified as:

$$score \sim age * knowledge + (1|subid)$$

Cluster-Mass Analyses Between and Within Groups. EEG data were analyzed using the same cluster-based permutation approach as in Study 1 (Candia-Rivera & Valenza, 2022), implemented via FieldTrip and custom MATLAB scripts. The procedure for statistical testing (Mann-Whitney U tests for between-groups, Wilcoxon Signed Rank test for within-group), cluster identification (minimum length = 300ms, minimum neighbouring electrodes =

5), and significance assessment ($p < .05$) followed similar parameters as the previous study. Cluster-mass analyses were conducted separately between groups (passers vs. failers) and within-group (Standard FB vs. Ignorant FB).

ERSP Analyses of Changes from Baseline. To determine whether, in the identified electrode clusters from the cluster-mass analyses, there were any significant modulation (i.e., suppression or enhancement) in beta activity relative to baseline, we employed a cluster-mass statistical approach (Maris & Oostenveld, 2007), using the same method as in Study 1.

Mean Group Differences in Beta. To investigate group differences in beta activity, an ANOVA was conducted with mean beta power as the dependent variable and group (passers vs. failers) as the independent variable. Mean beta power was averaged across significant time points at the electrode sites identified in the cluster-mass analyses. Separate analyses were conducted for each of the four conditions, focusing on Departure, Arrival, and Disappearance events that showed significant modulation. In addition, within-groups ANOVAs were performed to compare Ignorant versus Standard conditions.

3.3 Results

3.3.1 Preliminary Analyses

A linear mixed effects model was fit to examine the effects of age (centred) and knowledge condition (Standard, Ignorant) and their interactions on task performance, with subject included as a random intercept. Separate models were run for each belief condition (FB, TB).

Standard and Ignorant FB Conditions. For the FB conditions, the fixed effects revealed a significant main effect of age (centred), $B = 21.93$, $SE = 4.44$, $t(70) = 4.94$, $p < .001$, suggesting that older children had higher scores overall. The main effect of knowledge condition was not significant, $B = -1.08$, $SE = 3.57$, $t(51) = -0.30$, $p = .76$. Additionally, a significant interaction between knowledge condition and age was found, $B = 10.51$, $SE = 3.58$.,

$t(51) = 2.94$, $p = .005$, suggesting that the effect of knowledge condition on scores varied depending on the child's age.

A simple slopes analysis was conducted to examine whether the effect of age on scores varied across knowledge conditions within the FB task. In the Ignorant FB condition, age was a significant predictor of scores, $b = 21.90$, $SE = 4.44$, $df = 70$, 95% CI [13.10, 30.80]. In the Standard FB condition, the slope was even steeper, $b = 32.40$, $SE = 4.44$, $df = 70$, 95% CI [23.60, 41.30]. These results indicate that age positively predicted performance in both knowledge conditions during the FB task, with a stronger effect in the Standard condition. Figure 11 (False Belief plot) shows children's scores in percentage on Standard and Ignorant FB tasks across age, along with model estimates.

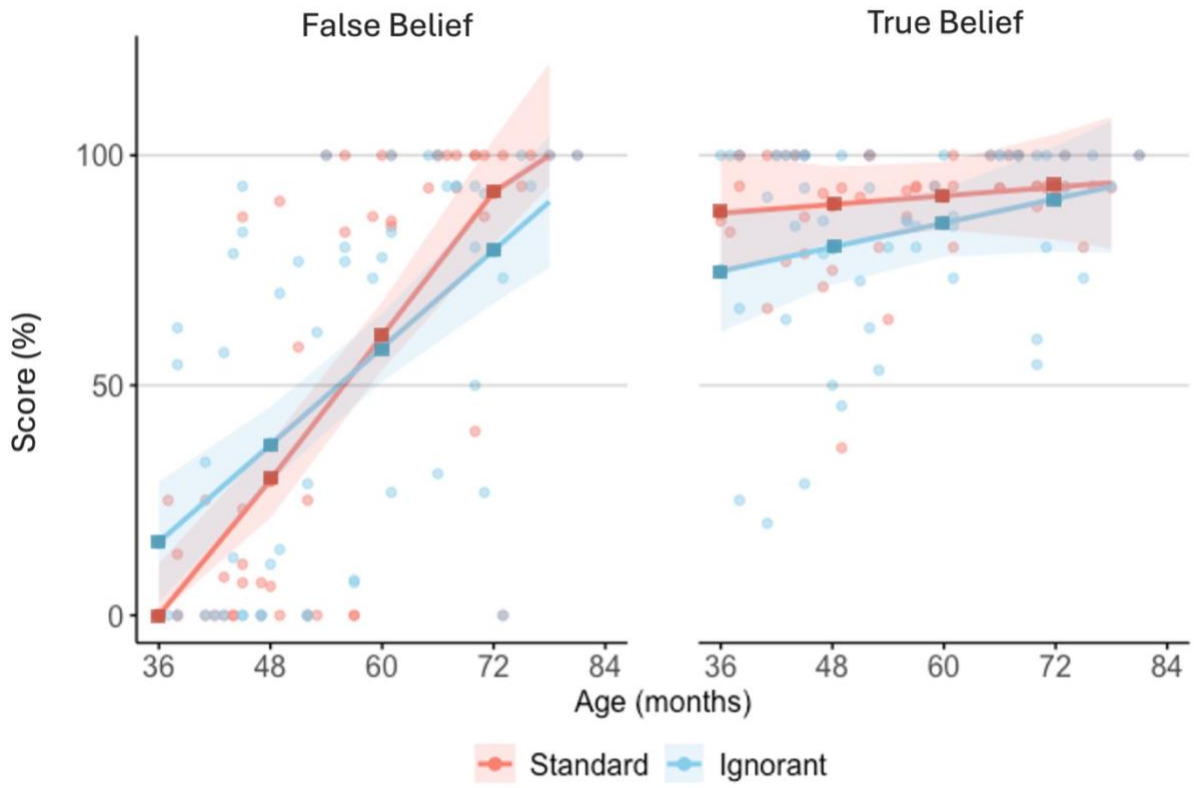
A Phi correlation (φ) was computed to examine the association between children's performance on the Standard FB and Ignorant FB tasks. Results revealed a strong positive association, $\varphi = 0.77$, suggesting that children who passed one task were likely to pass the other, and those who failed one task were likely to fail the other. A chi-square test was conducted to determine whether this association was statistically significant. The test indicated a significant relationship, $\chi^2 (1, 53) = 28.63$, $p < .001$, suggesting that performance in the Standard FB condition was highly related to performance in the Ignorant FB condition.

Standard and Ignorant TB Conditions. For the TB condition, the model revealed significant main effects of both knowledge and age (centred). Older children had significantly higher scores overall, $B = 5.45$, $SE = 2.32$, $t(91.52) = 2.35$, $p = .02$. Additionally, children in the Standard TB condition scored significantly higher than those in the Ignorant TB condition, $B = 7.10$, $SE = 2.66$, $t(51.00) = 2.67$, $p = .010$. The interaction between knowledge condition and age was not significant, $B = -3.49$, $SE = 2.67$, $t(51) = -1.31$, $p = .20$, indicating that the effect of knowledge condition did not vary meaningfully by age in TB conditions.

To further examine age effects in the TB conditions, a simple slopes analysis was conducted to see how age differed by knowledge conditions. In the Ignorant condition, age significantly predicted higher scores, b= 5.45, SE= 2.32, df= 91.5, 95% CI [0.84, 10.06]. However, in the Standard condition, the relationship between age and score was non-significant, b= 1.96, SE= 2.32, df= 91.5, 95% CI [–2.65, 6.57]. These results suggest that task performance in TB may be modulated by the knowledge context, with stronger age effects in the Ignorant condition. Figure 11 (True Belief plot) shows children's scores in percentage on Standard and Ignorant TB tasks across age, along with model estimates. It is important to note that figure includes data not just from sample used in EEG analyses, but the full sample that provided usable task results.

Figure 11

Model Fit of Children's Performance in Standard and Ignorant ToM Conditions Across Age



Note. Red and blue circles represent participants' observed scores, while red and blue squares along the line show the estimated means based on model predictions. Shaded ribbons around the lines indicate the 95% confidence intervals for the predicted values. Data derived from full sample that provided usable task results.

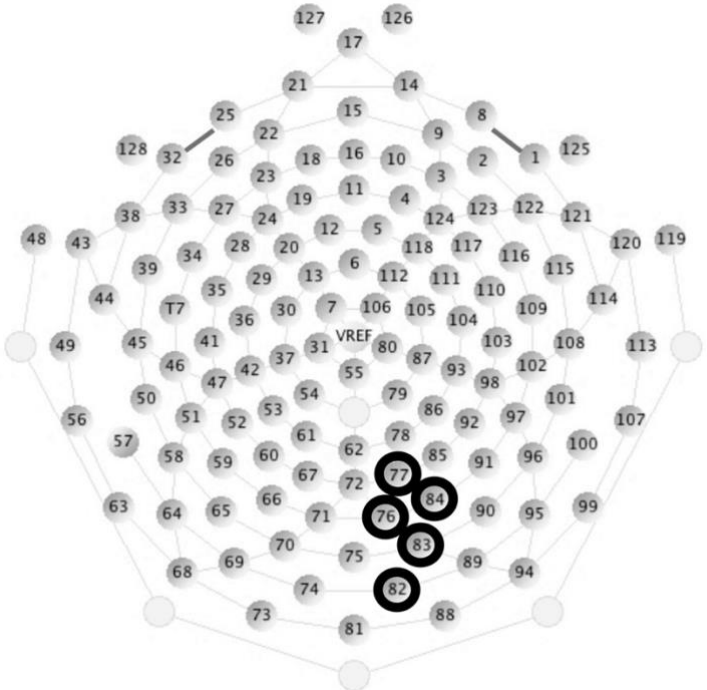
3.3.2 Beta EEG in Failers vs. Passers

Cluster-Mass Analyses in Standard FB. To characterize beta differences between failers and passers in the Standard FB condition, non-parametric cluster-mass analyses were conducted on 3D data (time-frequency-channel) structures. This was done for Departure and Arrival events separately. From the clusters that formed, electrodes with significant relative modulation for more than 300ms were selected for interpretation. Interpretable results were found only in the Arrival event, revealing a negative cluster of beta differences (suppression in failers compared to passers) over posterior parietal electrodes (E76, E77, E82, E83, E84; $p < .001$, cluster mass= 4.31). Average duration of sustained differential activity was 402ms with minimum-maximum time window of 0 to 516ms (see Table 5). These results suggest that failers exhibited more sustained suppression over posterior parietal than passers, towards the end of the Standard FB Arrival event.

Table 5

Characteristics of Channel Group exhibiting Group Differences in Standard FB

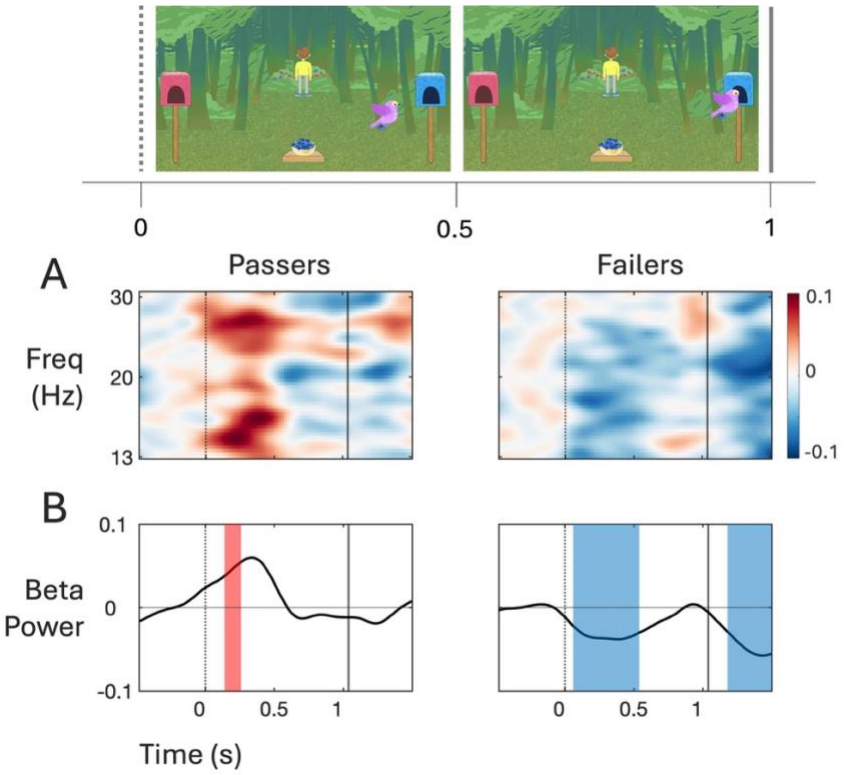
Channel Group	Min – Max Time (ms)	Average Duration of Differences (ms)	Frequency Range (Hz)	Average Frequency (Hz)
Posterior Parietal	0 – 516	402	14.33 – 17	15.98



ERSP Analyses of Standard FB. To look at changes from baseline, we examined the time window in the Arrival event in which we found significant beta differences. Beta ERSPs were baseline-corrected and averaged across significant channels (E76, E77, E82, E83, E84) over posterior parietal. The data was then subjected to within-group cluster-mass analyses to compare average beta power during the Arrival event to the baseline period. In the FB Arrival event, failers showed significant beta suppression. The largest suppression event occurred from time 0.07s to 0.53s (duration: 436ms), as the bird reaches the second location. In contrast, passers showed significant enhancement from 0.15s to 0.26s (duration: 112ms). Figure 12 shows beta ERSP plots and mean beta power across time over posterior parietal during the Arrival event.

Figure 12

Beta ERSPs over Posterior Parietal in Standard FB Arrival Event

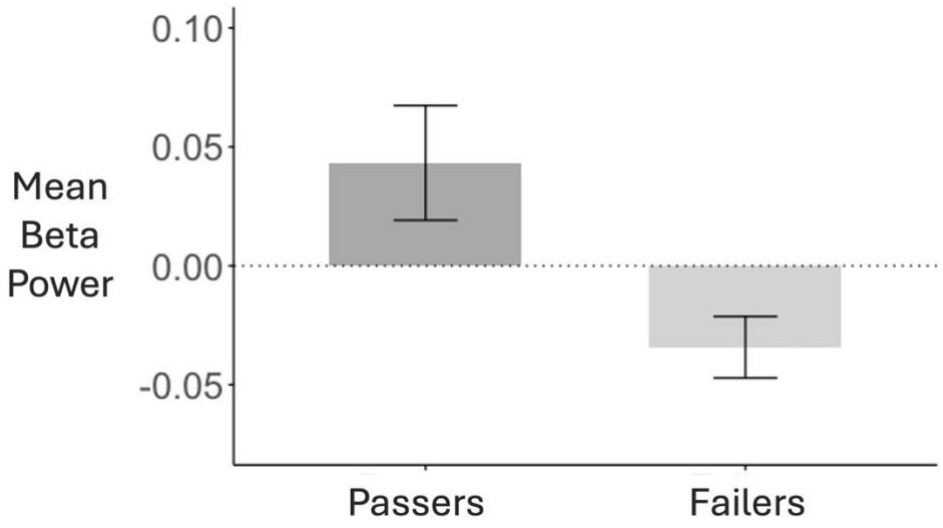


Note. Dotted vertical line at 0s marks end of baseline period. Solid vertical line at 3s marks end of Arrival event. Power is shown as a ratio relative to the baseline period. A) *Beta ERSP plots.* Warmer colours indicate enhancement and cooler colours indicate suppression. B) *Mean beta power line plots*. Highlights indicate significant ($p<.05$) suppression (blue) or enhancement (red) relative to baseline.

Mean Group Differences in Standard FB. In further characterizing group differences, beta power over the posterior parietal was averaged across the largest time window showing significant suppression as observed from the ERSP cluster-mass analyses (time window: 0.07s to 0.53s). Figure 13 shows mean beta power over posterior parietal at the Arrival event. An ANOVA was conducted to examine the effects of group on beta change. We found a significant main effect of group on beta change, $F(1,33)= 7.76$, $p= .009$**,** with a medium-to-large effect size, $\eta^2= 0.19$, 95% CI [.03, 1.00]. This confirms a significant difference in beta power between the failers and passers in the Standard FB condition.

Figure 13

Mean Beta Power Over Posterior Parietal at Standard FB Arrival

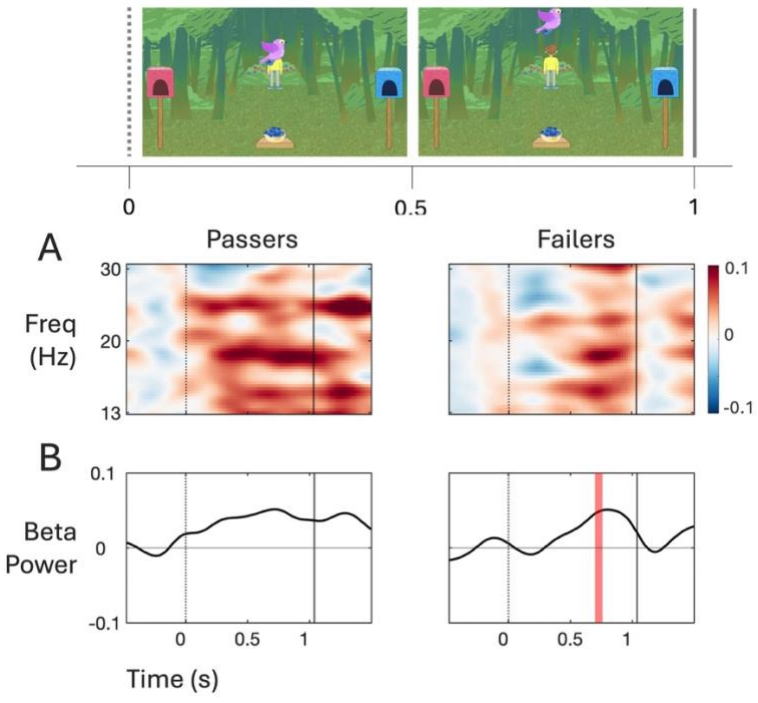


Note. Mean beta power is shown for passers and failers. Power is shown as a ratio relative to the baseline period. Error bars represent standard errors.

ERSP Analyses of Ignorant FB. 3D cluster-mass analyses did not reveal significant group differences in beta power across channel, time, and frequency in the Ignorant FB condition. To investigate changes from baseline, we examined ERSPs in the Disappearance event using the same electrode site as the Standard FB analyses. Beta ERSPs were baseline-corrected and averaged across significant channels (E76, E77, E82, E83, E84) over posterior parietal. Group data was subjected to separate within-group cluster-mass analyses to compare beta ERSPs in the Disappearance event to the baseline period. While both groups exhibit evidence of an enhancement pattern, failers showed significant beta enhancement, occurring briefly from time 0.68s to 0.74s (duration: 56ms), as the bird reaches the second location. Figure 14 shows beta ERSP plots and mean beta power across time over posterior parietal during the FB Disappearance event.

Figure 14

Beta ERSPs over Posterior Parietal in Ignorant FB Disappearance Event

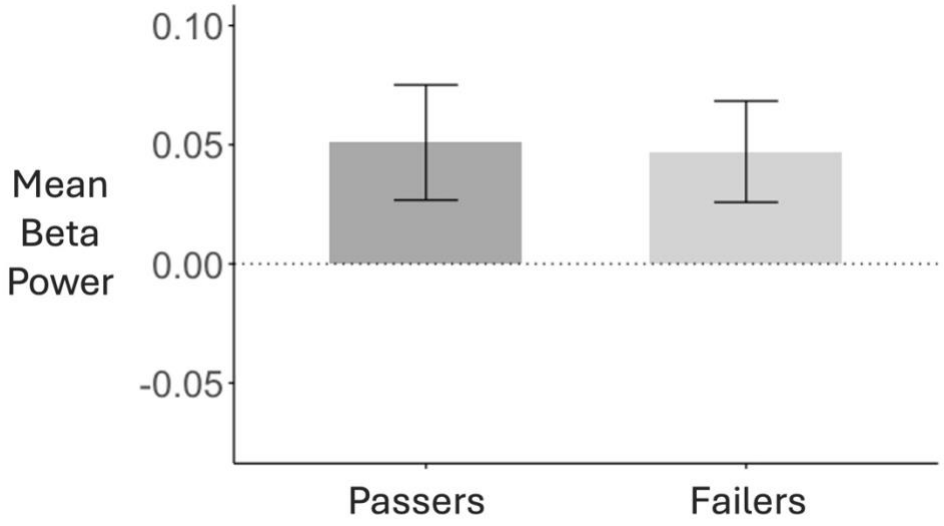


Note. Dotted vertical line at 0s marks end of baseline period. Solid vertical line at 3s marks end of Disappearance event. Power is shown as a ratio relative to the baseline period. A) *Beta ERSP plots.* Warmer colours indicate enhancement and cooler colours indicate suppression. B) *Mean beta power line plots*. Red highlights indicate significant ($p<.05$) enhancement relative to baseline.

Mean Group Differences in Ignorant FB. To further characterize beta activity over the posterior parietal, beta power was averaged for both groups across the time window showing significant enhancement (time window: 0.68s to 0.74s). An ANOVA was conducted to examine the effects of group on beta change. We found no significant main effect of group on beta change, $F(1,33) = 0.014$, $p = .91$. Along with the non-significant 3D cluster-mass analyses, these results suggest that beta power was similar between the failers and passers in the Ignorant FB condition. Figure 15 shows mean beta power over posterior parietal at the Disappearance event for both groups.

Figure 15

Mean Beta Power Over Posterior Parietal at Ignorant FB Disappearance



Note. Mean beta power is shown for passers and failers. Power is shown as a ratio relative to the baseline period. Error bars represent standard errors.

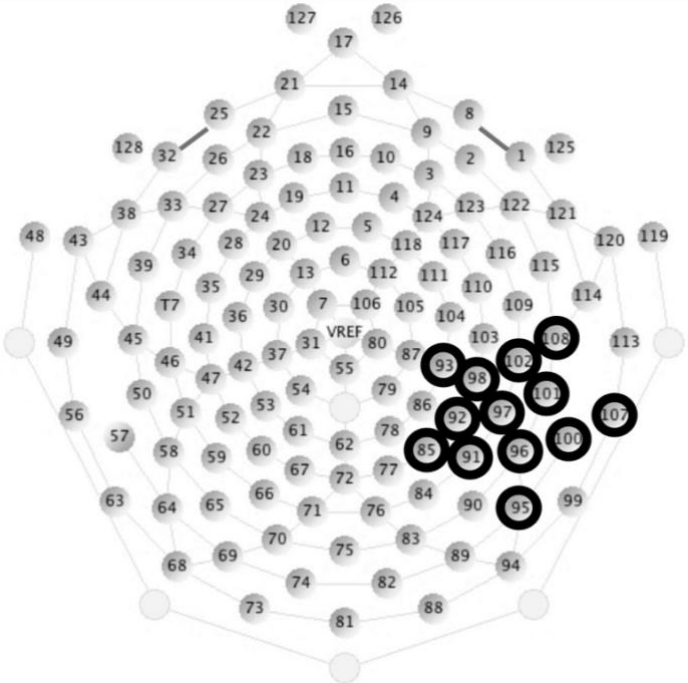
3.3.3 Beta EEG in Ignorant vs. Standard FB

Cluster-Mass Analyses in Failers. 3D cluster-mass analyses were conducted to characterize differences in time-frequency-channel datapoints between Ignorant and Standard FB conditions in failers. Electrodes were considered interpretable if they showed significant relative modulation for more than 300ms. In the Arrival/Disappearance event, within-group comparisons revealed a significant positive cluster of beta differences, indicating enhancement in the Ignorant FB compared to Standard FB in failers ($p < .001$, cluster mass= 3.62). This enhancement was localized over the right temporo-parietal electrode site (E85, E91-E93, E95-E98, E100-E102, E107, E108), showing differential activity for an average duration of 551ms (see Table 6). These results suggest that failers exhibited more enhancement during the Ignorant FB Disappearance event than in the Standard FB Arrival event, particularly over the right temporo-parietal region.

Table 6

Characteristics of Channel Group exhibiting Condition Differences in Failers

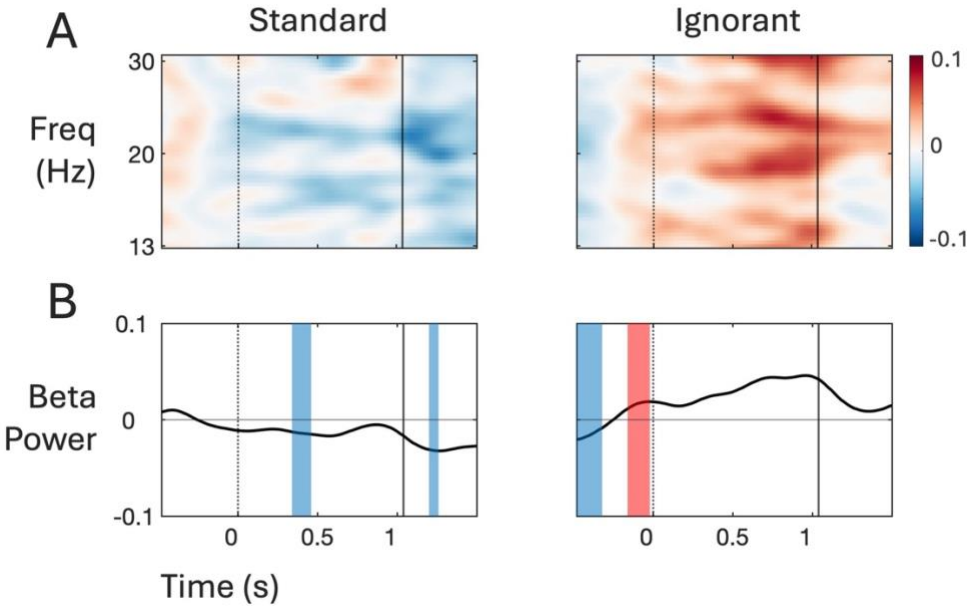
Channel Group	Min - Max Time (ms)	Avg Duration (ms)	Frequency Range (Hz)	Average Frequency (Hz)
Right Temporo-Parietal	576 – 1304	551	22 – 30	24.5



ERSP Analyses of Failers. To examine changes from baseline over right temporo-parietal in failers, beta ERSPs were baseline-corrected and averaged across significant channels (see Table 6). Data from each condition were separately subjected to within-group cluster-mass analyses, comparing beta at the Arrival/Disappearance event to beta during the baseline period. Results showed that in the Standard FB, failers exhibit beta suppression over during the Arrival event. The longest significant suppression event had a duration of 96ms (time window: 0.34s to 0.45s). In the Ignorant FB, failers showed evidence of beta enhancement, with the longest significant enhancement event occurring during the baseline period from -0.14 to -0.04s (duration: 136ms). Figure 16 shows beta ERSP plots and mean beta power across time over right temporo-parietal during the Disappearance event in failers.

Figure 16

Beta ERSPs over Right Temporo-Parietal in Failers during FB Arrival (Standard) and Disappearance (Ignorant) Event

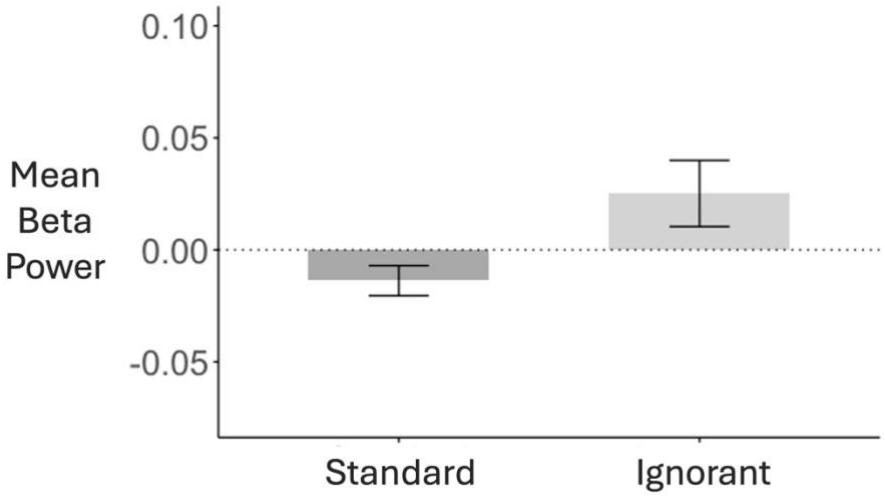


Note. Dotted vertical line at 0s marks end of baseline period. Solid vertical line at 3s marks end of Arrival/Disappearance event. Power is shown as a ratio relative to the baseline period. A) *Beta ERSP plots.* warm colours indicate enhancement and cool colours indicate suppression. B) *Mean beta power line plots.* Highlights indicate significant ($p<.05$) suppression (blue) or enhancement (red) relative to baseline.

Mean Condition Differences of Failers. Based on the ERSP cluster-mass analyses of the Standard FB, we specified the relevant time window as 0.34s to 0.45s. We averaged beta power across this time range for each condition and conducted an ANOVA to examine the effects of condition on beta change. We found no significant main effect of condition on beta change, $F(1,34)= 1.26$, $p= .27$, suggesting that failers exhibited similar beta activity between conditions at that particular moment. However, this null result should be interpreted carefully. The initial cluster-mass analysis did reveal condition differences in failers, and we take those findings as more informative, given the method's greater sensitivity to distributed effects across data dimensions compared to analyses of mean differences at specific timepoints. Figure 17 shows mean beta over right temporo-parietal, averaged across the relevant time window at the Arrival/Disappearance event.

Figure 17

Mean Beta Power Over Right Temporo-Parietal in Failers at FB Arrival (Standard) and Disappearance (Ignorant) Event

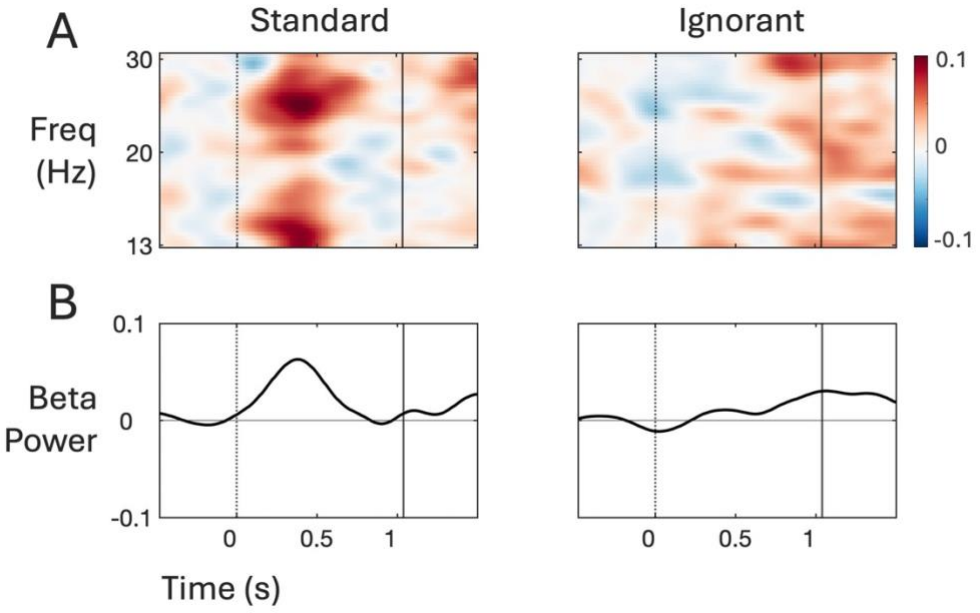


Note. Mean beta power is shown for passers and failers. Power is shown as a ratio relative to the baseline period. Error bars represent standard errors.

ERSP Analyses of Standard and Ignorant FB in Passers. Initial cluster-mass analyses of passers did not reveal significant differences in beta power across channel, time, and frequency between Standard and Ignorant FB. To investigate changes from baseline, we examined ERSPs in the Arrival/Disappearance event using the same electrode site found in our analyses of the failers. Beta ERSPs were baseline-corrected and averaged across significant channels over right temporo-parietal. Data from each condition was subjected to separate within-group cluster-mass analyses to compare beta ERSPs in the Arrival/Disappearance event to the baseline period. While passers show evidence of an enhancement pattern in both conditions, neither analysis resulted in significant enhancement from baseline. Figure 18 shows beta ERSP plots and mean beta power across time over right temporo-parietal during Standard and Ignorant FB events. Since there were no significant time windows, mean condition differences were not analyzed further.

Figure 18

Beta ERSPs over Right Temporo-Parietal in Passers during FB Arrival (Standard) and Disappearance (Ignorant) Event



Note. Dotted vertical line at 0s marks end of baseline period. Solid vertical line at 3s marks end of Arrival/Disappearance event. Power is shown as a ratio relative to the baseline period. A) *Beta ERSP plots.* warm colours indicate enhancement and cool colours indicate suppression. B) *Mean beta power line plots.*

3.3.4 Beta EEG in True Belief Conditions

Cluster Mass Analyses of Failers vs. Passers. 3D cluster-mass analyses were conducted across channel, time, and frequencies to examine group-level differences in beta activity of failers vs. passers. This was done separately for Standard TB and Ignorant TB conditions. Results indicated no significant group differences in either condition. As such, no further post-hoc or exploratory analyses were pursued for these comparisons.

Cluster Mass Analyses of Ignorant vs. Standard. To assess potential differences in beta activity between Ignorant TB and Standard TB condition, 3D cluster-mass analyses were conducted across channels, time, and frequencies. This was done separately for failers and passers. The analyses revealed no significant condition differences in either group. As a result, no further analyses were conducted.

3.4 Discussion

Chapter 3 examined beta EEG modulations in preschool-aged children (3 to 6 years old) as they completed ToM tasks under Standard and Ignorant knowledge conditions of FB and TB scenarios. We analyzed beta oscillatory activity as an index of representational monitoring during belief-reasoning. Here, we expand on our prior findings by examining how knowledge, whether the participant themselves have knowledge or ignorance about the situation, influences ToM.

While prior research has shown that children typically perform better when they are ignorant of the true state of affairs (Birch & Bloom, 2003; Ghrear et al., 2021; Wellman et al., 2001), our results did not replicate this pattern. Instead, children performed similarly between Standard FB and Ignorant FB conditions. Furthermore, the tight association we observed between performance in Standard and Ignorant FB tasks ($\varphi = .77$) suggest that FB reasoning was not really influenced by knowledge condition. Rather, children's performance seemed to reflect a stable underlying ability– children who had strong FB reasoning tended to perform well on the task regardless of whether they were presented with Ignorant or Standard versions. Similarly, children with weaker ToM skills tended to struggle in both versions of the task.

This divergence from prior work may be due to differences in task design. Unlike previous Ignorant FB tasks, which typically present narrated vignettes explicitly stating that the object's location is unknown (Birch & Bloom, 2007; Ghrear et al., 2021), our version had children observe the object disappear into an unknown location in real time. This design choice allowed us to capture neural activity during the location-change event itself, a moment central to belief formation. This methodological difference may have resulted in lower-than-expected performance in our Ignorant FB tasks. However, it is important to note that although performance improved with age in both knowledge conditions, simple slopes analyses

revealed a stronger age slope in the *Standard* FB condition. This suggests that younger children may be especially hindered by possessing privileged knowledge of the situation. Perhaps with more trials or a different task design, past findings would have been replicated.

3.4.1 Beta EEG in Standard FB

The current study incorporated a replication of our previous study in Chapter 2, which offered several key findings: 1) differences in beta between passers and failers were observed over posterior parietal during the end of the location-change event, 2) failers exhibited significant beta suppression relative to baseline in the FB task, whereas passers exhibited some evidence of enhancement relative to baseline, and 3) beta did not differ between groups in the TB condition.

Chapter 3 replicated all three of these findings. We found that children who failed Standard FB tasks displayed significant suppression in beta power relative to baseline. Conversely, passers exhibited enhancement in beta EEG from baseline during the location-change event. These differences were found over similar posterior parietal electrodes (E67, E71, E72, E75, E77, E84 in Chapter 2; E76, E77, E82, E83, E84 in Chapter 3) at the same time period (when the animal reaches its destination). In the Standard TB condition, passers and failers did not differ in their beta activity during the location-change event, both exhibiting no significant modulation from baseline.

These results replicate and extend previous findings, showing consistent differences in beta activity over the posterior parietal cortex between children who pass and fail FB tasks. Across two studies, over the same brain region, at the same time, group differences were found in beta EEG that tell us how preschoolers reason about false beliefs. The broader implications of these findings, including their relevance to the representational monitoring account, are further discussed in the general discussion (Chapter 4).

3.4.2 The Role of Knowledge in ToM

In the Ignorant FB condition, our cluster-mass analyses found no significant group differences in beta activity. This suggests that both passers and failers exhibited similar patterns of beta activity in response to ignorance in the FB task. As shown by ERSP analyses of beta over posterior parietal (Figure 15), both passers and failers display beta enhancement during the Ignorant FB Disappearance event (when the bird flies into the trees).

According to Wellman et al. (2001), children's updated knowledge of the target object's location in a FB task may interfere with their processing of others' beliefs. Ignorance may facilitate accurate representational monitoring as it reduces the salience of one's own beliefs. From a neural standpoint, we would expect to see beta enhancement in Ignorant FB conditions to reflect correct representational maintenance.

Although our EEG results align with this idea—both groups showed beta enhancement under ignorance—the behavioural results did not map onto the brain activity. Failers continued to perform poorly, even in the Ignorant FB condition. This raises an important question: If failers showed neural evidence of representational maintenance (as indexed by beta enhancement), why did this not translate into successful task performance?

These incongruent results are reinforced as our cluster-mass analyses showed that failers actually process Standard and Ignorant FB conditions differently, showing evidence of stronger beta enhancement over right temporo-parietal in the Ignorant condition. This indicates that failers were not simply inattentive or non-responsive—they demonstrated condition-sensitive neural responses. Yet, this distinction in processing did not correspond to any behavioural improvement between conditions.

One possibility is that beta enhancement in failers reflects a weak or inconsistent engagement of representational maintenance that is sufficient to register the protagonist's false beliefs, but not robust enough to support a correct belief judgment. That is, children may

have showed brief attempts at representational maintenance and registered that the character did not know the bird's location but ultimately reverted to default strategies of representational updating when they must make ToM judgments. Ignorant FB scenarios may allow children to engage the right processes (i.e., beta enhancement), but this engagement is transient or partial and is not sustained through to the behavioural decision. To study this possibility, beta EEG modulations may be examined through to the decision event.

Alternatively, this pattern might suggest that neural networks relevant for ToM are becoming active in failers, but their brains are not mature enough to produce correct responses. Behavioural performance may lag because broader cognitive systems (e.g., executive functions) are still developing. This suggests that beta enhancement in Ignorant FB may reflect a meaningful developmental milestone in failers. It may not be until relevant neural systems are sufficiently integrated that behavioural outcomes improved. To investigate this, beta EEG measures (e.g., coherence, functional connectivity) can be compared across age. This will help to determine a critical threshold of neural activation for successful behavioural outcomes.

3.4.3 Conclusion

This study replicates our findings from Chapter 2 and expands upon them by investigating Ignorant ToM conditions. We showed that children who fail Standard FB tasks engage different cognitive processes in Ignorant FB tasks. In contrast to the beta suppression that failers exhibited over posterior partial in Standard FB, failers exhibited beta enhancement over right temporo-parietal in Ignorant FB. This suggests that failers processed Ignorant FB differently from Standard FB, despite not translating into better performance in Ignorant FB. This has implications on our understanding of the role of knowledge in ToM and speaks to the dissociation between brain activity and behavioural responses.

Chapter 4

General Discussion

This dissertation investigated preschoolers' neurocognitive processing in various ToM tasks. These tasks took the form of animated stories in which children had to judge protagonists' beliefs about an animal's location. We examined beta EEG at critical moments during the location-change event, when the animal leaves its original location and moves to a different one during the protagonist's absence. Enhancement in beta power has been associated with cognitive maintenance, whereas suppression in beta power has been linked to cognitive updating (Engel & Fries, 2010; Kilavik et al., 2013; Schmidt et al., 2019). We were interested to see how modulations in beta power index cognitive maintenance and updating during belief-reasoning and how these processes differ between children who pass the FB task versus those who fail.

Chapter 1 provided an overview of current theoretical models of ToM, the functional role of beta EEG, and how beta may be used to index cognitive processes associated with belief-reasoning. To investigate beta's role in ToM, Chapter 2 examined beta EEG as children completed FB and TB tasks. By comparing children who passed versus failed the FB task, we observed that beta activity over the posterior parietal differentiated the two groups: passers showed some evidence of beta enhancement, while failers exhibited beta suppression. This pattern suggests that failers engaged in cognitive updating—incorrectly revising the protagonist's belief with their own current knowledge—whereas passers resisted such updating and maintained the character's belief representation.

As outlined in Chapter 1, this result aligns with the representational monitoring account of ToM (Apperly & Butterfill, 2009; Leslie et al, 2004), which posits that preschoolers' FB errors stem from failures to maintain protagonist's outdated beliefs. Had failers instead shown evidence of cognitive maintenance (i.e., beta enhancement), this would

have lent support to the shared-beliefs heuristic account (Epley et al., 2004; Nickerson, 1999), which assumes children use their own beliefs as a shortcut to infer others' beliefs. However, the beta suppression we observed in failers supports the view that they were actively, but incorrectly, updating their belief representations, consistent with the representational monitoring framework.

In Chapter 3, we replicated the core finding from Chapter 2: beta EEG patterns over posterior parietal differentiated passers and failers in a standard FB task. However, when children completed an alternative version of the FB task in which they were made ignorant about the animal's location, this group difference was no longer observed, suggesting engagement of similar mechanisms. Instead, a notable pattern emerged within the failers. Specifically, failers exhibited greater beta enhancement over right temporo-parietal in the Ignorant FB than in the Standard FB. This differentiation in beta EEG suggests that failers engaged with the two knowledge conditions differently. Although failers' performance remained low across conditions, the EEG results indicate some neural sensitivity to the level of conflict between their own and another's knowledge state.

Together, the findings from Chapter 2 and 3 provide converging evidence that beta activity in posterior parietal tracks children's engagement in representational monitoring and can distinguish between successful and unsuccessful FB reasoning. Across both studies, failers consistently exhibited beta suppression in FB tasks suggestive of representational updating, while passers showed evidence of representational maintenance. Chapter 3 extended these findings by showing that beta differed across knowledge conditions: failers exhibited greater beta enhancement in the Ignorant FB than in the Standard FB condition, specifically over right temporo-parietal regions. This neural sensitivity, along with poor behavioural performance, highlights a dissociation between brain responses and behaviour and suggests that the level of conflict between knowledge states can modulate belief-

reasoning processes at the neural level, despite not translating into correct answers. Ultimately, this work refines our understanding of ToM development by identifying specific neurocognitive mechanisms, as indexed by beta EEG, that contribute to success or failure in belief-reasoning.

4.1 Beta EEG as a Correlate of Belief-Reasoning

The following sections will provide an examination of the neural dynamics underlying preschoolers' belief-reasoning, focusing specifically on how beta EEG patterns vary between performance groups. Drawing on findings from both Chapter 2 and 3, we highlight group differences in beta activity over posterior parietal and right temporo-parietal areas, and discuss how these patterns inform our understanding of ToM development.

4.1.1 Beta EEG over Posterior Parietal in Standard False Belief

Our findings from Chapter 2, which were replicated in Chapter 3, highlight a robust association between beta activity over the posterior parietal site and children's success at FB tasks. Specifically, passers and failers showed distinct beta patterns during FB reasoning: passers exhibited evidence of beta enhancement, consistent with representational maintenance, while failers showed beta suppression, indicating representational updating.

Importantly, the posterior parietal region identified in our EEG data aligns with brain areas implicated in previous ToM neuroimaging studies. For instance, Bardi et al. (2016) used fMRI and found greater activation in right posterior parietal cortex in FB vs TB trials in adults during a "belief formation" phase (corresponding to the location-change event we analyzed in our EEG studies). The authors attributed the posterior parietal activity to the right temporo-parietal junction (rTPJ), a region involved in mental state attribution. While our current analyses did not look at FB vs. TB differences, the temporal and functional similarities between the two studies are notable.

Generally, beta EEG in the posterior parietal has been shown to play a key role during online motor corrections. In motor control, online corrections refer to real-time adjustments of planned movements in response to unexpected changes in the environment (Archambault et al., 2015; Battaglia-Mayer et al., 2014). This suggests that the posterior parietal is not just executing movement but rather updating internal representations of spatial information and plans in response to new input.

In the context of the FB task, the location-change event (e.g., the animal moving locations) introduces new information that must be processed to reason about what someone else believes. When failers show beta suppression over posterior parietal cortex during this event, it implies that they are engaging in internal representational updating—just like in online motor corrections. But instead of updating a motor plan, failers may be inappropriately updating the protagonist's belief to match reality, which is precisely the kind of error predicted by the representational monitoring account of ToM development.

Our results suggest that the posterior parietal plays a critical role in FB reasoning as a neural substrate supporting representational monitoring. Failures in FB tasks may arise from inappropriate updates to one's representations of others' beliefs in line with their own, while successful reasoning depends on the ability to accurately monitor others' beliefs in line with their distinct experiences. These findings refine current theoretical models of ToM by underscoring what failers do differently and how cognitive strategies change across development.

4.1.2 Beta EEG over Right Temporo-Parietal in Ignorant False Belief

Chapter 3 presented children with Ignorant FB tasks to examine how knowledge affects belief-reasoning. Although behavioural performance did not differ between Standard FB and Ignorant FB, failers exhibited distinct beta patterns across knowledge conditions. Over the right temporo-parietal, failers displayed greater beta enhancement in the Ignorant

FB than in the Standard FB condition. This suggests that, even though they performed similarly between conditions, they differentiated between them at the neural level.

As discussed, the rTPJ is a key region in the ToM brain network. It is thought to support the attribution of mental states to others by enabling the decoupling of self-knowledge from others' perspectives (Saxe & Kanwisher, 2003). Applying this ideas to the Ignorant FB task, beta enhancement in this region may reflect an attempt by failers to separate their own ignorance from the protagonist's perspective. This self-other decoupling is an important step in belief-reasoning that is much harder to do in Standard FB tasks where observers hold privileged knowledge.

If the beta activity we observed over right temporo-parietal in Ignorant FB is instead driven by the same neural system that underlie posterior parietal beta activity in Standard FB, then enhancement over right temporo-parietal may reflect a common mechanism supporting representational monitoring. It could be that Ignorant FB allow failers to more easily maintain their representations of the protagonist's beliefs. Yet, despite showing the correct neural engagement, failers continued to perform poorly. This brings up discussion about the dissociation between brain responses and behavioural outcomes.

One possibility is that failers are in a transitional phase, where relevant neural networks are becoming active but are not yet sufficiently integrated to produce correct behavioural responses. In this view, beta enhancement in the right temporo-parietal region in the Ignorant FB reflects emerging engagement in representational maintenance, but the children are not yet able to translate this engagement into correct ToM judgments until relevant neural systems (e.g., prefrontal executive functions) have matured. Larger-scale studies examining other brain measures (e.g., cross-band coherence, functional connectivity) across development would help clarify whether a critical threshold of neural activation or cross-brain coherence is required for successful behavioural performance.

Another possibility is that beta enhancement in failers in Ignorant FB reflects momentary or task-specific engagement in cognitive maintenance, but that this engagement is not sustained or effectively applied throughout the task. That is, children may show brief or partial attempts at representational maintenance, but ultimately revert to default strategies like representational updating when making their final responses. Future work should analyze EEG during the decision event to investigate whether updating occurs immediately prior to the response, which would shed light on the timing and consistency of cognitive strategies during ToM reasoning.

4.2 Implications on Theoretical Accounts of ToM

Our EEG results shed light on the neural mechanisms of belief-reasoning, refining our theoretical models of ToM. Findings from both studies suggest that children who failed the FB task engaged in cognitive updating. As children received information of the animal's location during the location-change event, failers wrongly updated their representations of the protagonist's outdated beliefs of the event. In contrast, passers succeeded by maintaining their representations of the protagonist's initial beliefs.

These results provide support for the representational monitoring hypothesis, which posits that failure at the FB task may be due to inappropriate updates to representations of others' beliefs. Importantly, these processes were observed during the location-change event, the moment at which participants form their representations of the protagonist's beliefs based on their absence during the animal's move. Since these differences in beta emerged precisely during this belief-formation phase, this has implications on the development of preschoolers' understanding of beliefs.

4.2.1 Conceptual Change in ToM

Our findings comport with Gopnik & Wellman's (1994) conceptual change hypothesis, which argues that children's understanding of beliefs undergoes a conceptual

shift from a more objective, reality-bound perspective to one that recognizes beliefs as subjective mental representations. In the context of our study, failers appear to treat beliefs as direct reflections of reality. This aligns with the idea that younger children initially operate with a "copy theory" of belief, in which others' beliefs are misunderstood as truthful records of the world rather than mental states that can diverge from reality. This leads to inaccurate representational monitoring (i.e., updates when there should not be) in FB tasks.

In contrast, passers demonstrate an emerging ability to recognize the representational nature of beliefs, understanding that beliefs can persist independently of reality and may not be automatically updated with new information. This suggests that they have transitioned to a more sophisticated "representational" ToM (Gopnik & Wellman, 1992; Wellman, 2010). This conceptual change occurs as children gather evidence from their daily experiences that beliefs do not always match reality. This accumulation eventually leads to a reorganization of their conceptual framework of ToM. Once this is achieved, children are able to view others' beliefs as distinct from their own. In our research, this conceptual change may be expressed in passers' ability to withhold updates to their representations of the FB event, reflecting their understanding of the other's' differing beliefs.

4.2.2 Development of ToM into Adulthood

In contrast to children who passed, adults who were administered the same FB task as Study 1 were shown to exhibit beta suppression over frontal and parietal regions throughout the duration of location-change event (Payumo, 2021). We interpreted this as evidence for the use of the shared-beliefs heuristic—a cognitive shortcut in which adults begin with the assumption that others share their own beliefs and only revise that assumption when they realize that others no longer share them (Epley et al., 2004; Keysar et al., 2003). This strategy reflects a developmental shift: while children reason about ToM by tracking others' beliefs, adults adopt a more systematic heuristic approach.

This distinction reveals important developmental differences in the cognitive strategies employed during FB tasks. Children tend to rely on representational monitoring, which involves actively maintaining and updating the belief states of others while keeping their own beliefs distinct (Apperly & Butterfill, 2009; Leslie et al., 2004). This strategy is arguably more laborious and slower as belief representations must be monitored constantly. In contrast, adults' reliance on the shared-beliefs heuristic allows for quicker and less effortful social inference, enabling them to predict others' actions efficiently in most everyday scenarios without always engaging in full-fledged belief tracking. Only when the shared-belief assumption fails, such as when others are revealed to hold different beliefs, do adults recruit more effortful, deliberate representational monitoring processes.

This shift from low-level representational monitoring to high-level heuristic-based inferences is consistent with two-system models of ToM, which posit that adults possess both fast, automatic strategies and slower, deliberate reasoning mechanisms (Apperly & Butterfill, 2009; Frith & Frith, 2008). Our findings contribute to this framework by offering neural evidence that beta suppression in adults during FB tasks may index the use of heuristics rather than continuous belief tracking. Ultimately, this cognitive shift highlights how ToM reasoning becomes more efficient with age, though potentially at the cost of accuracy in more complex or ambiguous social situations.

4.3 Real-word Implications

Understanding how preschoolers reason about false beliefs has meaningful implications that extend beyond basic developmental science. One important avenue lies in the clinical domain, where insights from developmental and neural measures of ToM can inform assessment and intervention. Children with autism spectrum disorder (ASD), ADHD, or other neurodevelopmental conditions often struggle with ToM, though the underlying causes may differ. Beta EEG, as a neural correlate of belief-reasoning, could capture early

signs of atypical ToM development. As such, beta may eventually contribute not only to diagnostic tools, but also to frameworks for tracking developmental progress over time, helping clinicians differentiate between typical delays and more persistent difficulties.

Building on this, beta EEG may also help inform personalized interventions. By using beta EEG to clarify whether children's difficulties with belief reasoning are primarily conceptual (a lack of understanding that beliefs are representations) or executive (a difficulty in maintaining and inhibiting representations), we can design interventions tailored to their cognitive profile. For example, if difficulties are conceptual, interventions may focus on providing children with rich social experiences (e.g., storytelling, role-play, guided discussions) that expose them to conflicting perspectives and encourage reflection on others' mental states. Language-based interventions that introduce and scaffold the use of mental state terms (e.g., "think," "believe," "know") could also help children conceptualize abstract mental representations. Conversely, if difficulties are primarily executive, interventions might emphasize strengthening working memory, inhibitory control, and cognitive flexibility through structured games and activities (e.g., match-to-sample, card-sorting tasks). These approaches can also be translated into educational practices, where teachers incorporate perspective-taking activities and executive function training into everyday classroom routines to support both ToM and broader socio-emotional development.

Ultimately, beta EEG research offers a promising way to connect basic science with clinical practice and education, helping to ensure that interventions are developmentally informed and evidence-based. By distinguishing whether children's belief-reasoning difficulties are conceptual or executive in nature, beta EEG can guide tailored supports by informing more precise diagnostic tools in clinical contexts and helping educators integrate perspective-taking and executive function training into everyday practice. Taken together, integrating neural and behavioural measures moves us toward precision approaches that not

only advance developmental science but also yield practical benefits for children's learning, social relationships, and long-term well-being.

4.4 Limitations

Several limitations of the present study should be acknowledged. First, due to the constraints of working with young children and the complexity of EEG data collection, the number of usable trials per condition was limited. This may have reduced statistical power and increased susceptibility to noise in individual ERSP measures. Future studies with larger trial counts or repeated testing may help improve the reliability of the condition effects. Since there is also potential for fatigue, habituation, or learning effects given the repetition of EEG tasks, future designs may also incorporate shorter task blocks or adaptive formats to better sustain attention and data quality.

Second, the spatial resolution of EEG is inherently limited. While our findings suggest that beta activity over posterior parietal and right temporo-parietal may reflect activity in the right temporo-parietal junction, these interpretations should be made with caution. To address this limitation, source localization techniques may be used to infer distribution of beta EEG sources. Alternatively, using more spatially precise neuroimaging methods (e.g., fMRI or MEG) can also validate these claims.

Lastly, our participant demographics mostly consisted of white, middle-class, university-educated families. Results may not be generalized to broader population. Future studies should examine belief-reasoning across a broader range of cultural, socioeconomic, and developmental backgrounds to better understand when and how EEG signatures of belief reasoning begin to resemble adult-like patterns.

4.5 Future Directions

While beta oscillations have provided a valuable neural correlate for cognitive maintenance and updating processes during ToM reasoning, it is unlikely that they represent

the entire neural picture. Future studies should explore how other frequency bands contribute to ToM reasoning. Theta (4–8 Hz) oscillations, for instance, have been associated with cognitive control and working memory, all of which are highly relevant to navigating conflicting belief representations (Cavanagh & Frank, 2014; Hsieh & Ranganath, 2014). By further investigating other neural rhythms, future research could offer a more comprehensive view of the dynamic neural mechanisms that support belief-reasoning across development.

Regarding our analyses, we focused on beta activity during the location-change event, which we have argued is a critical moment for forming belief representations. However, this provides only a partial view of the belief-reasoning process. Future work should extend beta EEG analyses to the *decision event*, where children are prompted to predict the character's actions, and the *search event*, where children observe whether their prediction is correct or not. Investigating neural dynamics across these events would offer a more temporally nuanced understanding of belief-reasoning, encompassing not only how beliefs are constructed but also how they are applied in real-time decision-making and error detection.

Additionally, since our focus on the current studies were group differences between passers and failers, we did not include direct comparisons between FB and TB conditions. Such comparisons could provide valuable insight into the neural mechanisms specifically engaged during TB reasoning and how they differ from those underlying FB processing. Future research should address this gap to more fully characterize the cognitive and neural distinctions between these belief conditions.

Lastly, future research may wish to extend beta EEG investigations to other ToM paradigms. While the FB location-change task is well-established in ToM research, it captures a relatively narrow aspect of belief-reasoning. Future studies should incorporate a broader array of ToM tasks (e.g., contents change, deception, second-order belief) to examine whether observed neural patterns are consistent across contexts and belief conditions. Doing

so would help determine whether these effects are just responses to the specific task used, or if they reflect general features of belief-reasoning.

Together, these avenues of research could contribute to a more comprehensive model of the neural and cognitive architecture supporting ToM across development—highlighting how different brain rhythms, task events, and contexts shape the emergence of sophisticated social reasoning.

4.6 Conclusion

This dissertation offers new insights into the neurocognitive mechanisms that support belief-reasoning in early childhood, identifying beta-band EEG activity as a novel neural correlate of cognitive maintenance and updating during ToM tasks. Across two studies, we examined how preschool-aged children process belief information, revealing distinct beta oscillatory patterns in those who passed versus failed FB tasks. Beta suppression over posterior parietal regions was consistently observed in failers, suggesting inappropriate updating of the protagonist's belief. In contrast, passers exhibited evidence of beta enhancement, consistent with successful maintenance of a distinct belief representation.

We further examined how one's own knowledge state impacts belief-reasoning. Contrary to findings that Ignorant FB tasks should improve performance, we found no across-the-board benefit. However, beta activity in failers varied by condition, indicating that their neural systems were sensitive to the knowledge condition, even if this was not reflected in their ToM performance.

Taken together, these findings provide strong support for the representational monitoring account and contribute to a growing body of evidence suggesting that preschoolers gradually transition from a reality-bound conception of belief to a more sophisticated, representational understanding. They also underscore the complex role of one's

own knowledge in shaping belief-reasoning and highlight the value of neural measures, particularly beta EEG, in uncovering cognitive processes of ToM.

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Appendix A

Ethics Approval

October 08, 2019

Mr. Mark Payumo
Master's Student
Department of Psychology
Queen's University
Kingston, ON, K7L 3N6

GREB Ref #: GPSYC-947-19; TRAQ # 6027591
Title: "GPSYC-947-19 Theory of Mind Development and Beta EEG Activity"

Dear Mr. Payumo:

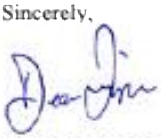
The General Research Ethics Board (GREB), by means of a delegated board review, has cleared your proposal entitled **"GPSYC-947-19 Theory of Mind Development and Beta EEG Activity"** for ethical compliance with the Tri-Council Guidelines (TCPS 2 (2014)) and Queen's ethics policies. In accordance with the Tri-Council Guidelines (Article 6.14) and Standard Operating Procedures (405.001), your project has been cleared for one year. You are reminded of your obligation to submit an annual renewal form prior to the annual renewal due date (access this form at http://www.queensu.ca/traq/signon.html/; click on "Events;" under "Create New Event" click on "General Research Ethics Board Annual Renewal/Closure Form for Cleared Studies"). Please note that when your research project is completed, you need to submit an Annual Renewal/Closure Form in Romeo/traq indicating that the project is 'completed' so that the file can be closed. This should be submitted at the time of completion; there is no need to wait until the annual renewal due date.

You are reminded of your obligation to advise the GREB of any adverse event(s) that occur during this one-year period (access this form at http://www.queensu.ca/traq/signon.html/; click on "Events;" under "Create New Event" click on "General Research Ethics Board Adverse Event Form"). An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example, you must report changes to the level of risk, applicant characteristics, and implementation of new procedures. To submit an amendment form, access the application by at http://www.queensu.ca/traq/signon.html; click on "Events;" under "Create New Event" click on "General Research Ethics Board Request for the Amendment of Approved Studies." Once submitted, these changes will automatically be sent to the Ethics Coordinator, Ms. Gail Irving, at University Research Services for further review and clearance by the GREB or Chair, GREB.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Sincerely,



Chair, General Research Ethics Board (GREB)
Professor Dean A. Tripp, PhD
Departments of Psychology, Anesthesiology & Urology Queen's University

c: Dr. Mark Sabbagh, Supervisor
Dr. Luis Flores, Chair, Unit REB