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Neural Correlates of Emotional Face Perception as a Foundation for Social Development in
Early Childhood

By

ZOE PESTANA
DISSERTATION

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Abstract

Faces are among the most important sources of social information in early childhood, providing cues about others' emotions, intentions, and mental states that support children's developing social understanding and behavior. The ability to perceive emotional facial expressions has been proposed to play a foundational role in the development of theory of mind (ToM) (Mitchell & Phillips, 2015; O'Brien et al., 2011), yet empirical evidence directly linking emotional face perception and ToM remains limited, particularly during early childhood when both abilities undergo rapid development. Moreover, although theoretical models of prosocial development posit that successful prosocial behavior depends on both children's capacity to reason about others' mental states and their ability to perceive socially relevant cues (Eisenberg & Mussen, 1989; Rahal & Fiedler, 2021), little research has examined how these processes work together to predict children's social behavior.

To address these gaps, the present dissertation examined the role of emotional face perception in social-cognitive development using event-related potentials (ERPs), which provide a temporally precise measure of neural responses to emotional facial expressions (Luck, 2014). Across two studies of preschool-aged children, neural indices of early, automatic attentional orienting (P1) (Batty & Taylor, 2006), structural face processing (N170) (Blau et al, 2007), and attentional allocation to faces (Nc) (de Haan et al., 2002) were used to characterize individual differences in emotional face perception and their relations with behavioral measures of ToM and prosocial tendencies.

The first study investigated whether individual differences in preschool children's neural responses to emotional facial expressions (as indexed by N170 and Nc) were associated with individual differences in behavioral ToM. Findings revealed a specific role for the Nc component, such that a greater Nc amplitude to negative (fear and anger) relative to neutral facial

expressions were associated with more advanced mental-state reasoning, suggesting that individual differences in the allocation of attention to emotional faces are meaningfully related to emerging ToM abilities.

The second study examined whether emotional face perception and ToM jointly predicted preschool children's prosocial tendencies. Results indicated that ToM was positively associated with prosocial behavior only among children who exhibited enhanced P1 amplitudes to emotional facial expressions, suggesting that early attention to emotional cues may facilitate the translation of social-cognitive inferencing into prosocial action.

Together, these findings provide novel evidence that individual differences in neural responses to emotional faces contribute to variability in preschoolers' social cognition and prosocial behavior. By integrating developmental neuroscience with existing empirical and behavioral theories, this dissertation advances understanding of the mechanisms linking emotional face perception, mental-state inferencing, and prosocial development during a critical period of early childhood.

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Chapter 1: Introduction

Successful social interactions depend on the ability to accurately perceive and interpret the emotional states of others. Facial expressions are among the most salient and informative social cues available to children, providing rapid access to information about others' feelings, intentions, and needs (Vicari et al., 2000). Children must integrate emotional cues from their environment to inform their assessment of the world around them and their actions within it (LoBue & Ogren, 2022). The ability to perceive emotional facial expressions is therefore fundamental to social communication and relationship formation. By recognizing and responding appropriately to emotional cues, children are able to navigate social interactions, coordinate behavior with others, and develop meaningful interpersonal relationships. Individual differences in emotion perception have been linked to a range of adaptive social outcomes, including empathy, prosocial behavior, and social-cognitive understanding (Besel & Yuille, 2010; Denham et al., 2003; O'Brien et al., 2011). Consequently, understanding how children perceive and process emotional information is critical for understanding their broader social development.

Existing theories posit that the processing of faces is prominent for social development, as it is vital to be able to interpret information from an emotional face to reason about others and to understand what they are thinking or feeling (Richler & Gauthier, 2014). Facial expressions give us important clues about how someone is feeling, which can help to predict someone's response and behavior (Pollak et al., 2000; Krawczyk, 2018). Face processing develops early, with infants showing preferences for faces and the ability to discriminate among emotional expressions within the first year of life (Belteki et al., 2025; Frank, Vul, & Johnson, 2009; Leppänen & Nelson, 2012). Throughout early childhood, children become increasingly proficient at identifying and interpreting emotional facial expressions, with substantial

improvements occurring during the preschool years (Herba & Phillips, 2004). At the same time, considerable individual differences emerge in children's ability to recognize and process emotional information. These differences may have important implications for children's developing social competence because emotional expressions provide a primary source of information about others' internal states.

One domain that may be particularly influenced by emotion perception is Theory of Mind (ToM), or the ability to understand and reason about others' thoughts, beliefs, desires, and intentions, particularly those that may differ from one's own (Wellman & Liu, 2004). The preschool period is marked by significant advances in ToM, particularly children's ability to understand false beliefs and reason about others' mental states (Rakoczy, 2022; Sabbagh et al., 2013). Although emotion perception and ToM are often studied as distinct domains, both involve understanding the internal experiences of other people. Emotional expressions provide observable evidence of internal states and may therefore serve as an important foundation for the development of more complex mental-state reasoning (Sabbagh & Flynn, 2007). For example, children who are more attuned to others' emotional reactions may have greater opportunities to infer the beliefs, desires, and situational interpretations that give rise to those emotions. Consistent with this perspective, theoretical accounts of ToM posit that successful interactions require the integration of both emotion perception and mental state inference, given that perceiving emotional faces provides input for understanding others' thoughts, intentions, and desires (Bird & Viding, 2014; Mitchell & Phillips, 2015). Thus, emotion perception may play an important role in supporting the development of ToM during early childhood.

Beyond contributing to children's understanding of others, emotion perception and ToM are also important for children's broader social behavior. Prosocial behaviors, such as helping,

sharing, and comforting, emerge during early childhood and contribute to positive peer relationships and social adjustment (Hay & Cook, 2007; Salerni & Caprin, 2022). Engaging in prosocial behavior often requires children to recognize when another person is experiencing distress and to respond appropriately. Emotion perception may facilitate prosocial behavior by helping children identify emotional cues that signal another person's needs (Eisenberg et al., 2006). Indeed, attention to and perception of emotional facial expression of others' distress cues can motivate empathic concern and promote helping and comforting behaviors (Eisenberg et al., 2006; Marsh, Kozak & Ambady, 2007). Whereas ToM may support prosocial responding by allowing children to understand another person's perspective, goals, or beliefs. Existing theoretical perspectives posit that children who have a better ability to understand their own and others' internal states are more equipped to interpret the cause of others' distress and therefore more motivated to engage in prosocial actions (Eggum et al., 2011). Together, these abilities provide important foundations for socially adaptive behavior. Rather than operating independently, emotion perception, ToM, and prosocial behavior might be interacting components of a unified system. Emotion perception provides the initial input by signaling others' emotional states, ToM transforms this input into inferences about underlying mental states, such as beliefs and intentions, and prosocial behavior reflects the behavioral output of this interpretive process. Within this framework, successful social functioning depends on the efficient coordination of these processes, such that children must not only detect emotional cues, but also interpret their meaning and translate that understanding into contextually appropriate action.

The present dissertation examines the role of emotional face perception and social cognitive development. The first study investigates relations between preschool children's neural

correlates of emotional face perception and their behavioral theory of mind. The second study investigates how ToM interacts with preschool children's neural correlates of emotional face perception to predict emerging prosocial tendencies. Each of these studies address important open questions in the field. First, although theoretical accounts posit a direct relation between emotional face perception and ToM, empirical evidence linking the two is limited, and the existing research has been conducted exclusively in adults. Existing research therefore cannot directly address whether variation in emotion perception is associated with variation in ToM as it emerges during childhood. The first study of the dissertation provides the first direct test of whether individual differences in preschoolers' emotional face processing is associated with individual differences in their behavioral ToM abilities during a period of substantial development over the preschool years (3-to-5). In doing so, I shed light on whether and how individual differences in emotional face perception are an important foundation for the emergence of social-cognitive abilities early in development. By testing this proposed relation during a period of rapid growth in both emotion processing and ToM, the findings help clarify the developmental mechanisms linking perception and social cognition in preschoolers.

The second open question addresses whether and how emotional face perception combines with children's ToM to predict prosocial tendencies. Models of prosocial development posit that successful prosocial behavior depends not only on one's ability to reason about others' mental states, but also on the capacity to perceive and attend to socially relevant information (Eisenberg & Mussen, 1989; Rahal & Fiedler, 2021; Vaish & Hepach, 2020). Despite these theoretical models emphasizing an integration of social-cognitive and perceptual processes, empirical research has not found evidence to support them, in large part because studies have focused on assessing individual predictors of prosocial development (e.g., ToM alone) rather

than investigating how ToM and perceptual processes together may predict prosociality. This focus on a singular predictor has yielded inconsistent results. Although some studies demonstrate that ToM positively predicts children's prosocial outcomes (Cassidy et al., 2003; Eggum et al., 2011; Gross et al., 2015; Wu and Su, 2014), others have found that better ToM does not predict increased prosociality (Imuta, et al., 2016), and sometimes predicts antisocial or aggressive behaviors (O'Toole et al., 2017). Comprehensive empirical evaluations are lacking, and thus whether and how social-cognitive and perceptual processes interact to predict prosocial development, remains empirically unknown. The second study in the dissertation directly addresses this gap by testing whether and how preschool children's emotional face perception interacts with their behavioral ToM to predict prosocial tendencies. In doing so, the study advances theoretical models of prosocial development by evaluating whether social-cognitive and perceptual processes jointly contribute to children's prosocial tendencies. This work helps clarify why ToM alone has shown inconsistent associations with prosocial behavior and provides a more integrated account of the mechanisms underlying early prosocial development.

Across both studies, to address current gaps, the dissertation incorporates neuroscience methods that capture individual differences in neural responses to emotional facial expressions, providing a novel window into the neural mechanisms that support emotion perception during early development. More broadly, neuroscience approaches offer several advantages for developmental research in preschool-aged children, including the ability to index cognitive and affective processes that may be difficult to capture through behavior alone. Neuroscience offers an objective measure of young children's information processing and does not need to rely on verbal responses, or behavioral task demands that can be difficult for young children to execute. Both studies in this dissertation use the neuroscience method of event-related potentials (ERPs),

which provide millisecond level temporal resolution of neural activity directly from populations of firing neurons in the brain (Luck, 2014). Importantly, ERPs allow researchers to examine distinct stages of emotional face processing as they unfold over time. Several ERP components have been implicated in face and emotion processing during childhood. The P1 (85 – 145 ms post stimulus onset) component is thought to reflect early and automatic stages of attentional processing (Batty & Taylor, 2006; Taylor et al., 2001, 2004) and has been linked to initial attentional orienting (Gupta et al., 2019; Luna et al., 2023). The N170 (150 – 240 ms post stimulus onset) is associated with expertise and familiarity with faces (de Haan et al., 2002; Halit et al., 2003). The Nc (300 – 500 ms post stimulus onset) component is thought to reflect increased allocation of attention to emotional faces (Carver et al., 2003; de Haan et al., 2004). Together, these components provide insight into multiple stages of emotional face processing and offer a means of examining individual differences in children’s neural responses to faces.

Together, the dissertation studies provide a multi-level perspective on social-cognitive development by integrating neural, cognitive, and behavioral processes. Overall, the dissertation advances the hypothesis that individual differences in preschool children’s neural activity supporting emotional face perception is associated not only with children’s understanding of others’ mental states, but also plays a key, moderating role by interacting with ToM to predict emerging prosocial tendencies. By examining the role of neural correlates of emotional face perception in ToM and prosocial tendencies, this dissertation advances our understanding of how these three foundational social-cognitive constructs interact and develop.

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Chapter 2: The neural correlates of emotional face perception is related to theory of mind development in preschoolers

Abstract

The perception of facial expressions is a vital element of social behavior, as facial cues offer critical information to inform inferences about other's internal mental states (Theory of Mind, ToM). Behavioral work shows that children's emotion understanding predicts ToM performance, and both processes engage overlapping social cognitive neural systems, pointing to a potential neural link between emotional face perception and ToM. Thus, we test whether and how individual differences in children's neural responses to emotional faces relate to individual differences in their ToM skills during the preschool years, when these skills undergo critical development. We examined typically developing 3- to 5-year-old children's (N = 145) neural responses during an emotional faces task with the N170 and Nc ERP components. Using linear mixed effect models, we related ERP amplitude for N170 and Nc to children's behavioral ToM both with a mental state reasoning scale (modified Wellman & Liu, 2004 composite) and mental state decoding scale (Simplified Eye Reading Test; SERT). Our results showed that increased attentional allocation (as reflected in increased Nc amplitude) to negative emotions, and more subtly expressed negative emotions, were each associated with better mental state reasoning (as reflected in ToM composite). However, no relations were found between either ERP component and mental state decoding (SERT scale). These findings suggest that individual differences in how the brain 'tunes' to emotional faces is important in mental state inferencing, giving vital information into how ToM develops during the preschool years.

Introduction

During the preschool years, children begin to develop Theory of Mind (ToM), or the ability to understand and attribute others' mental states (e.g., beliefs, intentions, and desires) (Wellman & Liu, 2004). This foundational social cognitive skill is essential for interpreting and predicting social behavior and supporting cooperative interactions and engagement (Carlson, Koenig, & Harms, 2013; Westby & Robinson, 2014). Despite decades of research charting the development of children's ToM, there are still open questions about the factors that contribute to its development and to individual differences in ToM.

Theory of Mind and Emotion Perception are Broadly Connected

One construct that is particularly relevant to ToM development is emotional face perception. Intuitively, emotional face perception is related to ToM given that emotional cues on a person's face offer critical information to inform inferences about that person's internal mental states (Richler & Gauthier, 2014). For instance, when you interpret a fearful face, you infer that the person feels afraid and potentially believes there is nearby danger. Likewise, a look of anger may prompt mental state inference to understand whether a person's desires or expectations were not met, and what/who the offending entity is. Indeed, scholars posit that successful interactions require the integration of both emotion perception and mental state inference, given that perceiving emotional faces provides input for understanding others' thoughts, intentions, and desires (Mitchell & Phillips, 2015). This integration is also highlighted in other theoretical models of socio-emotional understanding. For example, the self-to-other model of empathy proposes that understanding another person's emotional state involves integrating both affective cues (e.g., facial expressions) and contextual information about the social situation (Bird & Viding, 2014). Emotion perception relies increasingly on ToM processes when emotional cues

are ambiguous or incongruent, requiring individuals to infer another person's likely emotional state (Biró et al., 2025). Thus, these theories broadly show this link between emotion perception and ToM.

Empirical research supports the theorized connection between emotion perception and ToM. For example, the ability to label and interpret emotions has been shown to predict children's ToM performance both concurrently (Cutting & Dunn, 1999; Grazzani et al., 2018) and longitudinally (O'Brien et al., 2011). Additionally, researchers have found a significant positive correlation between affective perspective-taking and ToM performance in preschool children (ages 3-5), suggesting that children who are better able to understand and interpret others' emotions also demonstrate stronger mental state inferencing abilities (Harwood & Farrar, 2006). Similarly, in adults, face recognition ability has been shown to be a strong predictor of ToM performance, highlighting the importance of accurately processing facial cues for understanding others' mental states (Lee et al., 2013; Meinhardt-Injac et al., 2018). Together, these findings support the broader hypothesis that emotion perception is empirically linked to ToM abilities.

Emotion Perception is Connected to Specific Aspects of Theory of Mind: Mental-state Decoding and Mental-state Reasoning

Emotion perception may also play a critical role in the development of *different aspects* of ToM. Specifically, some theories of ToM emphasize two distinct components: mental-state *decoding* and mental-state *reasoning*. Mental-state *decoding* is thought to involve a rapid initial extraction of socially relevant cues from perceptual input, such as facial expression, gaze direction, and other observable indicators of internal states (Sabbagh & Flynn, 2007). Mental-state *reasoning* is a later-occurring process that involves integrating this decoded social

information to infer unobservable mental states, such as beliefs, intentions and desires (Thoma et al., 2013). Research has documented that decoding processes happen earlier in the processing stream compared to reasoning (Njomboro et al., 2008; Sabbagh et al., 2004; see also Bowman et al., 2012). Different aspects of emotional face processing may support each of these different aspects of ToM. For example, given that the initial *decoding* aspect of ToM involves interpreting others' mental states from perceptually available social information (e.g., tone of voice or facial expression) (Sabbagh et al., 2004), the perception of emotional faces may directly support this aspect of ToM. Specifically, rapid initial detection of face cues—such as those that change with different emotional expressions—may support the early mental-state decoding process which involves detection of these same face cues (Njomboro et al., 2008). Indeed, by definition, mental state decoding depends directly on perceptual sensitivity to affective signals and rapid social information processing. Thus, individual differences in the rapid, early detection of different emotional facial cues should predict individual differences in mental-state decoding. There is some empirical evidence to support this notion. Researchers have found that social perception (defined as perception of biological motion in noise) correlated significantly with mental state decoding from eye-region photographs in children (ages 7-12) (Rice et al., 2016). Additionally, mental-state decoding, as measured by the Reading the Mind in the Eyes Task, has been shown to relate to emotional intelligence in adults, particularly abilities involving the perception, understanding, and regulation of emotions (Megías-Robles et al. 2020).

Likewise, other attentional aspects of emotion-perception that occur later in the processing stream (Carver et al., 2003; de Haan et al., 2002; Dennis & Hajcak, 2009; Kennedy & Montreuil, 2021), may support the later, more complex mental-state *reasoning* aspect of ToM. Mental-state reasoning, likely following from mental-state decoding, is a more complex process

involving integrating contextual information and making inferences about a person to understand their behavior (Lee et al., 2005; Sabbagh et al., 2004). Emotional face perception may also support this mental-state reasoning by directing attention to relevant affective information that can then invite reasoning about the mental states (e.g., intentions, desires, beliefs) accompanying the emotional expression (Njomboro et al., 2008; Sabbagh et al., 2004). There is some empirical support for these notions. For example, processing of faces and gaze direction is related to mental state reasoning in children 6-to-8-years-old and 16-to-18-years-old as assessed with the mentalizing animation task, which requires mental-state inference from geometric animations (Cambell et al., 2006). Thus, emotion perception may serve as a foundational social-cognitive process that supports more complex mental-state reasoning by providing information that can be integrated into inferences about others' thoughts, intentions, and behavior.

Overall, evidence suggests that emotion perception may support different aspects of ToM, including both the decoding of others' mental states from social cues and the more complex process of reasoning about others' thoughts, intentions, and behavior. Examining how emotion perception may be related to these different aspects of ToM can shed light on the existence of these theoretical ToM aspects more generally and how they operate, including how they may be similarly or differently connected to emotion perception. Furthermore, a better understanding of the links between emotion perception and different aspects of ToM inform a more detailed account of the specific processes through which emotional information supports mental-state inferencing.

Foundations of ToM Development in Emotion Perception: The Value of the Neuroscience Approach

Although prior research has examined the neural correlates of ToM (e.g., using event-related potentials, ERPs: Bowman et al., 2012; Liu et al., 2004; Liu et al., 2009; see also Richardson & Saxe, 2020; Saxe, 2009 for reviews with other neuroscience methods), little is known about whether individual differences in the neural processing of faces and emotional expressions are associated with ToM abilities. Given the theory and empirical evidence highlighting a connection between emotion perception and ToM in adults and children, one possibility is that emotion perception is a foundational aspect supporting ToM development and contributing to its individual differences. Specifically, we hypothesize that how the brain ‘tunes’ to support emotional face perception early in development could support the development of ToM, as well as explain its early individual differences. That neural activity supporting emotion perception might also relate differently to different aspects of ToM (e.g. mental state decoding, mental state reasoning).

Existing neuroscience research provides important support for this perspective by demonstrating that how the brain supports the processing of emotional facial information is closely linked to broader social-cognitive functioning. From a developmental perspective, the neural circuitry supporting emotion perception develops over the first year of life (Pascalis et al., 2005; Scott & Monesson, 2010), with individual differences in this neural development predicting infant and child behavior in broader social domains (e.g., empathy, cooperation; Bray et al., 2022; Knyazev et al., 2024). These individual differences in infants’ neural system supporting emotion perception also have been linked to later socioemotional outcomes, including emotion regulation and attachment security (Peltola et al., 2015; Stern et al., 2024).

Given that faces provide some of the earliest and most socially relevant sources of emotional information, developmental changes in neural systems involved in detecting and

attending to facial expressions may shape how children attend to, interpret, and learn from social interactions. To elaborate, as the brain becomes increasingly tuned to facial cues during development, individual differences emerge in the neural circuitry underlying emotion perception; these early neural mechanisms supporting the detection and interpretation of emotional cues may then provide a foundation for subsequent social-cognitive development. Indeed, emotion perception is a key source of visible information relevant for making inferences about peoples' invisible internal states, and thus the early development of the neural system supporting emotion perception may help scaffold the emergence of more complex forms of social cognition, including ToM. From this perspective, variation in how brains have tuned to support detection of and attention to emotional information in early development may have cascading effects on later abilities to decode and reason about the mental states of others.

In the present study, we aim to provide empirical evidence that would be directly consistent with the hypothesis that the way the early brain has tuned to detect and interpret emotionally relevant facial cues supports emerging ToM as it develops. Existing theory and research already provide indirect support. For example, scholars have posited that emotional facial expressions and ToM processes operate through partially distinct but interactive neural systems. According to theoretical accounts, emotionally salient facial cues are detected rapidly by subcortical systems, particularly the amygdala, which play a role in the early detection of biologically and socially relevant information (Adolphs, 2008; Compton, 2003; Schmitgen et al., 2016). This emotional information facilitates the prioritization of emotional stimuli for further cognitive processing (including ToM) (Compton, 2003). Importantly, according to this account, emotional face perception and ToM reflect complementary but parallel processes, such that emotional facial cues facilitate higher order mental state inference. Overall, this neuroscience

perspective discusses connection in the neural activity supporting emotion perception and cognitive processing (e.g. ToM), highlighting that detection of and attention to emotional facial cues can support more complex mental-state inference activity. This perspective is thus consistent with the notion that the early development of the neural system supporting emotion perception may serve as a foundational support for the development of ToM and its individual differences first measurable in early childhood.

The notion that there is a neural connection between emotional face perception and ToM is also supported in existing empirical findings. For example, in adults, both emotion perception and ToM rely on similar social-cognitive neural systems (Mitchell & Phillips, 2015). Functional Magnetic Resonance Imaging (fMRI) studies link affective face processing and affective ToM to regions associated with emotion such as the amygdala, as well as regions associated with mental-state inferencing such as temporoparietal junction (TPJ), medial prefrontal cortex (MPFC), superior temporal sulcus (STS), and temporal pole (TP) (Mier et al., 2010; Mitchell & Phillips, 2015). Additionally, there is evidence that adding facial emotional expressions during affective ToM judgements increased activity in the right amygdala (Schmitgen et al., 2016) (a region connected to emotion processing). Further connections between the neural activity supporting emotion perception and ToM are illustrated in the finding that when inferring others' emotional states, an observer's own affect can modulate neural responses within core ToM neural networks (e.g., superior temporal gyrus, precuneus and sensorimotor cortices; Qiao-Tasserit et al., 2024). Overall, these findings indicate that not only does the brain activity supporting emotion perception interconnect with the brain activity supporting ToM, but that engaging in emotion processes may also actively influence the recruitment of ToM related networks during mental-state inferencing. Such findings are thus also consistent with the notion that how the brain has

developed to support emotion perception may foundationally support the development of children's ToM.

Limitations of Existing Neuroscience Research. Taken together, theoretical accounts and empirical findings provide indirect support for the idea that the neural systems supporting emotion perception contribute to ToM development. However, there are limitations to existing neuroscience research that leave open the question of whether and how the neural system for emotion perception supports development of children's ToM. Specifically, most existing neuroimaging evidence comes from studies of adults and therefore cannot directly address whether variation in the developing neural systems that support emotion perception is associated with variation in ToM as it emerges during childhood. If the developing brain's tuning to emotional information plays a foundational role in ToM development, then individual differences in neural responses to emotional facial expressions should be associated with individual differences in ToM abilities during the preschool years, when substantial changes and individual differences in ToM are measurable. To date, no study has directly tested this prediction. The present study addresses this gap by investigating whether individual differences in preschoolers' neural responses to emotional faces is associated with individual differences in their behavioral ToM abilities during a period of critical ToM development over ages 3 to 5 years. Evidence of such an association would provide more direct support for our hypothesis that the way the developing brain becomes tuned to emotional information contributes to the emergence of typically developing children's ToM.

Using Neuroscience to Investigate Links between Emotion Perception and Decoding and Reasoning aspects of ToM. Individual differences in the neural system supporting emotion perception may be foundational not only to the development of ToM more broadly, but also to

development of the different theoretically proposed aspects of ToM: mental-state decoding and mental-state reasoning. Indeed, early in development, the neural activity supporting emotion perception might differentially support development of these distinct decoding and reasoning aspects of ToM. Thus, a neuroscience approach that investigates how the neural correlates of emotion perception are related to the development of ToM decoding and reasoning can shed light on the existence of these theoretically proposed ToM aspects, how they operate, and how they may be similarly or differently connected to emotion perception.

Here too, existing theory and research indirectly support this notion. For example, neuroscience research in adults supports a distinction between mental state reasoning and mental state decoding. Adult fMRI research shows that the orbitofrontal and medial temporal areas have been connected to decoding mental states, while medial frontal areas have been related to reasoning about mental states (Frith & Frith, 2001; see also Sabbagh et al., 2004). Likewise, adult ERP research shows that when adults are asked to reason about the actor's expected action based on those internal states, a more positive deflection in the late positive component later in the processing stream at around 240–440 ms (Cao et al., 2012). Taken together, adult fMRI and ERP findings suggest that ToM decoding and reasoning reflect separable components at the neural level, and that 'decoding' processes occur first, followed by later 'reasoning' processes (Cao et al., 2012).

The identification of distinct neural correlates of mental-state decoding and mental-state reasoning raises questions about how these systems interact with other aspects of social cognition. One possibility is that neural systems supporting emotion perception contribute differently to development of each of these different decoding and reasoning aspects of ToM. First, neural correlates of emotion perception may support mental state *reasoning* by providing

affective information that can be incorporated into inferences about others' thoughts, intentions, and motivations. In line with this notion, neuroimaging research suggests a partial overlap between neural systems involved in emotional face processing and mental-state reasoning, including the MPFC and superior temporal regions (Frith & Frith, 2006). From this perspective, heightened neural sensitivity to emotional faces may facilitate children's ability to interpret and reason about others' internal states. Second, neural responses to emotional faces may also be associated with mental state *decoding* because emotional expressions provide highly salient perceptual cues about others' internal affective states (Sabbagh & Flynn, 2007). In line with this notion, Riadh et al. (2021) demonstrated that patients with prefrontal lesions showed impairments in both mental state *decoding* (e.g., participants completed the Reading the Mind in the Eyes task) and emotion understanding (e.g., participants were asked to recognize six basic emotions from facial expressions of the whole face) indicating a link between these two abilities.

Overall, the existing evidence suggests that emotion perception may relate to ToM through neural pathways that differentially support mental-state reasoning and mental-state decoding, underscoring the importance of distinguishing between these components of ToM. However, the hypothesis that early developing neural systems supporting emotion perception contribute to the development of these distinct aspects of ToM has not been directly tested. As described above, existing neuroscientific research is limited because it has primarily been conducted in adults, demonstrating overlapping neural activation and interactions between emotion processing and ToM systems, but providing little insight into how these relations emerge during development. To evaluate whether neural systems supporting emotion perception contribute to the development of mental-state reasoning, mental-state decoding, or both, these associations must be examined during early childhood, when ToM abilities are shown to be

rapidly developing, and robustly measurable individual differences first emerge (Wellman et al., 2001; Wellman & Liu, 2004). The present study addresses this gap by testing whether individual differences in preschoolers' neural responses to emotional facial expressions are associated with individual differences in mental-state reasoning and mental-state decoding. In doing so, this study provides a direct test of whether the developing brain's tuning to emotional information contributes to the emergence of ToM, including its possible distinct aspects.

The Present Study: Using ERPs to Index Neural Responses to Emotional Faces and Their Relation to Theory of Mind

As outlined above, although there is converging evidence from neuroscience, behavioral findings, and theoretical accounts, there has been no direct test of whether individual differences in children's neural correlates of emotional face perception predict individual differences in their ToM development in the preschool years. Such an investigation would provide empirical evidence consistent with the hypothesis that emotion perception plays a foundational role in ToM development. During a period marked by the emergence of critical ToM developmental milestones, individual differences in how the young brain becomes tuned to detect and attend to emotional facial cues should be empirically related to individual differences in emerging ToM ability, which may include both mental state decoding and mental state reasoning abilities. The present study addresses this question by using Event-Related Potentials (ERPs) to measure neural responses to emotional facial expressions and examining their relation to behavioral ToM performance in preschool children on tasks assessing both mental-state decoding and mental-state reasoning.

Event-related potentials (ERPs) are particularly well suited to measure links between children's emotion perception neural correlates and their mental-state decoding and reasoning

skills. For example, ERPs provide a non-invasive measure of neural activity with excellent temporal resolution and can be used reliably with young children. Importantly, ERPs can capture individual differences in neural responses to emotional facial expressions, offering a window into the neural mechanisms that support emotion perception during development. By relating these neural measures to behavioral assessments of ToM, ERPs provide a means of testing whether variability in the neural processing of emotional information is associated with individual differences in ToM as its behavioral advancements manifest in early childhood.

Several ERP components have been linked to the processing of faces and emotional expressions in childhood (N170 and Nc), and they have clear ties to face perception and attention. To constrain the scope of the study, we focused on the Nc and N170 components due to their well-established associations with face and emotion processing. In constraining our scope, we did not assess additional face- or emotion-related ERP components such as the P1, LPP, P400, or N290. We excluded the P1 and LPP from current analyses as these components are more broadly linked to attentional and affective arousal processes, as opposed to emotional face processing specifically (Batty & Taylor, 2006; Dennis & Hajcak, 2009; Kennedy & Montreuil, 2021). Likewise, the P400 and N290 components were additionally excluded because they are more robustly measurable during infancy and may be less reliably elicited in the present preschool age group (Halit et al., 2003; Jessen & Grossmann, 2015; Leppänen et al., 2007). These alternative components and their potential relevance are considered in the discussion as directions for future research. We discuss the specific utility and interpretation of relating children's behavioral ToM to our targeted components of N170 and Nc next.

The N170 reflects the structural encoding of the face (Blau et al, 2007; Eimer, 2000) and has been linked to familiarity and expertise with faces (Batty & Taylor, 2006; Dennis Malone, &

Chen, 2009; Naumann et al., 2022; Rossion & Jacques, 2011). A reduced N170 amplitude has also been interpreted to reflect more neurospecialization for face processing (Bentin et al., 1996; Sadeh & Yovel, 2010; Xia et al., 2024). Thus, variability in the N170 amplitude can be taken as an index of familiarity with and/or neurospecialization for face stimuli. The Nc reflects increased allocation of attention to emotional faces (Carver et al., 2003; de Haan et al., 2002). A larger Nc amplitude has been interpreted to reflect more attentional resources allocated to facial processing (Dennis, Malone, & Chen, 2009; Taylor-Colls & Fearon, 2015). The Nc is also enhanced in response to familiar relative to unfamiliar faces, such as mothers versus strangers' faces, suggesting that the component reflects broader social attentional processes as well (Barrett et al., 1988; Eimer, 2000; Swingler et al., 2010). Thus, variability in the Nc may index individual differences in the allocation of attention to socially meaningful facial information.

Importantly, to assess whether and how ToM behavior relates to *emotional* perceptual processes—beyond face or other social processes more generally—we examined ERP difference waves, computed by subtracting Nc and N170 ERP amplitudes to neutral faces from Nc and N170 ERP amplitudes to emotional faces (i.e., happy, angry, and fearful). Difference-wave analyses are commonly employed in ERP studies more generally (Luck, 2014), and more specifically in ERP studies of emotion processing to index sensitivity to emotional aspects of stimuli (Bruchmann et al., 2025; Dennis et al., 2009; Xia et al., 2024). Accordingly, individual differences in these difference waves can provide insight into whether variability in emotional face perception is associated with variability in ToM abilities. Should more advanced behavioral ToM performance be related to preschoolers' smaller N170 amplitude to emotional versus neutral faces, this would be consistent with the notion that advances in preschoolers' behavioral ToM performance are supported at least in part by early neurospecialization for emotional face

perception. Likewise, should more advanced behavioral ToM performance be related to preschoolers' larger Nc amplitude to emotional versus neutral faces, this would be consistent with the notion that advances in preschoolers' behavioral ToM performance are supported at least in part by more attentional neural resources given to emotional face perception. At the broadest level, any relations between children's behavioral ToM performance and their Nc or N170 ERP difference waves for emotional versus neutral faces would suggest links between early developments in children's ToM and how their brains have tuned to respond to emotional faces.

N170, Nc, Mental-state Decoding, and Mental-state Reasoning. An examination of whether and how children's behavioral ToM is related to N170 and Nc amplitude to emotional faces can also address open questions about the role of emotion perception in mental-state decoding and mental-state reasoning aspects of ToM. To elaborate, the N170 amplitude, occurring early in the processing stream (around 170 ms post stimulus), is thought to reflect the structural encoding of the face in terms of the perceptually available facial features (e.g., positions or structure of the eyes, mouth, etc. Pesciarelli, Leo, & Sarlo, 2016; Rossion & Jacques, 2011). This function reflected in the N170 amplitude could thus be especially useful for mental-state decoding, which is thought to occur earlier in the information processing stream (before mental-state reasoning), and draw upon perceptually available information (such as the features of the face). Relations between individual differences in N170 amplitude to emotional faces and behavioral ToM performance could therefore be interpreted as evidence for a role of emotional face perception in mental-state decoding. In contrast, the Nc occurs later in the processing stream (around 300-500 ms post stimulus), and so could be more closely related to the later-occurring mental-state reasoning. However, the posited attentional function of the Nc could be relevant for

both mental-state decoding and reasoning in that attention to emotional facial information can aid both the encoding of perceptually available cues to support mental-state decoding, and the integration of contextual information to support inferences in mental-state reasoning.

To better understand whether and how mental-state decoding versus reasoning processes are linked to the neural correlates of emotional face perception, the present study used different behavioral ToM tasks that are thought to differentially target mental-state decoding versus reasoning. Specifically, we assessed preschoolers' behavioral ToM performance using the Simplified Eye Reading Task (SERT) —a task developed for children in which participants identify a person's mental state from static, cropped photos of the person's eyes. This task is considered to draw more heavily upon mental-state decoding aspects of ToM given that participants must detect subtle differences in perceptually available information in pictures of eyes to select the correct corresponding mental-state from a list of given options. We also assessed preschoolers' behavioral ToM performance using verbal, story-based, ToM vignettes such as those in the commonly used Wellman & Liu (2004) ToM scale. These story-based ToM tasks are thought to draw more heavily upon mental-state reasoning aspects of ToM because they verbally describe scenarios in which relevant information—that is not perceptually available in task images or materials—is used to make inferences about protagonists' mental states based on described actions and story context. Importantly, these stories are void of any specific discussion of facial cues, or other perceptually salient information central to the decoding process.

The present study then relates individual differences in children's N170 and Nc difference wave amplitudes to emotional faces to their behavioral performance on these two separate tasks designed to differentially capture mental-state decoding versus reasoning. Whether and how children's ERPs to emotional faces relate to each of these different tasks could thus

provide insight into the role of emotional face perception and each of these different aspects of ToM. Specifically, a role of emotional face perception in ToM decoding should manifest in individual differences in N170 and/or Nc amplitude predicting SERT performance; whereas a role of emotional face perception in ToM reasoning should manifest in individual differences N170 and/or Nc amplitude predicting performance on story-based ToM vignettes (e.g., Wellman & Liu, 2004; Wimmer & Perner, 1983).

Other Key Features of the Present Study: the role of Emotion Specificity and Emotion Intensity in Supporting Preschoolers' Theory of Mind. Other key features of our study design facilitate investigation of whether and how children's neural correlates supporting perception of specific emotions (e.g., angry faces versus happy faces) as well as perception of the intensity of emotions (e.g., full intensity versus reduced intensity) are related to their behavioral ToM performance.

Emotion Specificity. Children's ToM may be more strongly supported by the neural correlates of perceiving certain specific emotions over others. Neural correlates of negative emotion perception differ from those of positive emotion perception, recruiting different brain regions as evidenced by fMRI research (Dal Monte et al., 2012; Morris et al., 1996; Northoff et al., 2000). It is therefore possible that children's ToM development may be more strongly linked to how the brain has tuned to support either positive or negative emotion perception, specifically. For example, relations between neural correlates of emotion perception and children's behavioral ToM may be best captured in how the brain supports perception of negative emotions. Fear and anger are more salient emotions (Javela, Mercadillo, & Ramirez, 2008) and signify threat for the perceiver. This salience and threat indication may thus invite more ToM inference and a stronger motivation to infer the mental states that lead to or result from these negative emotional displays

(Marsh, Ambady, & Kleck, 2005). Given this strong tie between negative emotion perception and mental-state inference, individual differences in how the brain has tuned to respond to negative emotions may more strongly relate to individual differences in children's behavioral ToM performance. In contrast, neural circuitry supporting positive emotion perception may be less strongly related to ToM because there is less ambiguity in interpreting the mental states accompanying a positive emotional expression. Indeed, behavioral research shows that positive emotional expressions (i.e., smiles) were easier to make inferences about compared to negative emotional expressions (i.e., frowns) (Krull, & Dil, 1998). The present study will investigate whether and how children's behavioral ToM performance differentially relates to their N170 and Nc amplitudes to specific individual emotions including negative emotions (i.e., fearful and angry faces) and positive (i.e., happy faces). Given existing research, we predict that individual differences in the processing of highly salient negative emotional faces (e.g., fear and anger) will show strong associations with emerging ToM abilities than the processing of positive emotional expressions.

Emotion Intensity. Beyond investigating which specific emotional expressions (e.g., positive or negative) may be related to ToM, we can also examine whether perception of the *intensity* of emotional expressions may be related to ToM. Emotional facial expressions can be displayed with 'full-intensity' wherein the emotional expression represents the maximal version of the canonical display (e.g., angry face with extreme furrowed brow, grimace mouth showing clenched teeth) or 'reduced-intensity' wherein the expression of the emotion is more subtle (e.g., less furrowed brow, reduced grimace). Whether and how the brain is tuned to perceive *reduced-intensity* emotional expressions may more strongly relate to ToM. Unlike highly salient, full-intensity emotional expressions, reduced-intensity facial cues provide less explicit affective

information and therefore place greater demands on mental-state inferencing. Thus, we may expect N170 and/or Nc amplitude to reduced-intensity emotions (e.g., full-intensity anger versus reduced-intensity anger; reduced-intensity anger versus neutral) to be related to behavioral ToM, indicating that the extent to which the brain responds to these more subtle differences in emotional expression is linked to behavioral advancements in ToM performance. Alternatively, stronger associations with ToM may emerge for *full-intensity* emotional expressions. Full-intensity expressions provide more clear and salient information about others' emotional states, which may facilitate the detection and interpretation of social cues that support ToM processing. The present study can directly test each of these possibilities.

Exploring the role of General Social Attention Processes in children's ToM. Lastly, when evaluating links between neural correlates of emotion perception and ToM, it is possible that we could find that relations between the ERPs for emotional face perception and ToM are not due to emotion-specific processes but instead are related to general social attentional processes. Faces and mental states are inherently social (Richler & Gauthier, 2014). Prior work has found that in preschoolers, general social attention and observation was related to more advanced ToM (LaBounty et al., 2017). It is possible that as general social attention increases, both the neural correlates of attention to faces (indexed by the Nc) and ToM will increase. Given that the N170 is not an attentional component, if relations between emotion perception and ToM are driven by attentional processes alone, we may not expect relations between ToM and N170. Under this notion of a general attention mechanism, we might expect that any relations between the ERP components and ToM would not be emotion specific or related to the intensity of emotions. In contrast, if ToM and emotion perception are related due to general social attentional

mechanisms, we might expect that solely the neutral condition independently would be related to ToM.

Summary. The present study is designed to address key questions regarding whether and how emotion perception serves as a potential foundation for ToM development and the emergence of ToM individual differences in early childhood. Specifically, it examines whether neural responses to emotional facial expressions (assessed with ERPs) contribute to variability in children's behavioral ToM abilities. If, as hypothesized, the tuning of the brain to emotional faces plays a meaningful role in supporting ToM development, then individual differences in neural responses to emotional expressions should be systematically related to individual differences in behavioral ToM performance. To test this hypothesis, we collected ERP data during an emotional faces task, in which children viewed photos of emotional faces. We related individual differences in N170 and Nc ERP amplitude to these emotional faces to individual differences in children's behavioral ToM performance on both a mental-state decoding task (the SERT) and a mental-state reasoning task (the Wellman & Liu, 2004 scale). We also included covariates of children's language ability and executive functioning, given their empirical and theoretical implications in ToM (Henry et al., 2013; Hughes & Ensor, 2007; Miller, 2006).

Methods

Participants

A total of 162 typically developing 3-to-5-year-old children participated in this study (82 girls, 80 boys, $M_{age} = 4.5$ years, $SD = 0.86$). Children were recruited from a research database and were compensated for the one-time visit with small toys and a monetary gift card. All children were right-handed and had no history of neurodevelopmental disorders. Participants' demographics reflected those of the community from which they were drawn (Sacramento and

surrounding region). The largest percentage of children's parent-reported race/ethnicity was White Not-Hispanic/Latinx (51.83%), with the remainder being multi-racial, Asian/Pacific Islander, Black, and Hispanic/Latinx (see Supplemental Appendix 2.I for additional demographic details). Median household income was \$100K or greater (range: \$5K-\$100k). The median highest educational attainment for either parent was a master's degree (range: high school to Ph.D., J.D., or M.D). Seventeen children were excluded from ERP analyses for the following reasons: timing error in stimuli presentation (n = 4), technical error (n = 2), sibling participated prior (n=1), child was later diagnosed with Autism Spectrum Disability (n = 1), and refusal to wear EEG cap (n = 9). Thus, 145 participants were included in analyses.

The Institutional Review Board approved all methods used in this study. Parents gave informed consent and children provided assent.

Measures

All behavioral measures were standard and have been used in prior research with preschool children. We thus provide brief descriptions of each measure below and report additional details in supplement appendix 2.II.

Theory of Mind measures

Simplified Eye Reading Task (SERT) – Mental State Decoding

Simplified Eye Reading Test (SERT) was used to assess mental state decoding (Peterson & Slaughter, 2008). Participants viewed images of adults' eye expressions from the Reading the Mind in the Eyes task (Baron- Cohen et al., 2001), and chose between two simplified, forced choice adjectives that best described the image (2 practice, 9 test trials; higher scores = more mental state decoding). See Figure 2.1 for example trial stimulus.

Figure 2.1

SERT trial stimuli example



Note: This trial asks: “This is a lady. Is she sad or is she angry?” The adjectives in this task were simplified, so that they were understandable for children as young as 3 years.

Theory of Mind Composite (ToM composite) – Mental State Reasoning

A composite of ToM tasks tested children’s reasoning of others’ mental states and actions. Six of the vignettes were taken from the Wellman and Liu (2004) ToM scale (diverse desires, diverse beliefs, knowledge access, contents false belief, explicit false belief, belief emotion) and two additional false-belief tasks were added (Wimmer & Perner, 1983) (max score: 8; higher scores = more mental state reasoning).

Covariate measures

Kaufman Brief Intelligence Test (Kbit) – Verbal Intelligence

As a measure of verbal intelligence, we administered the verbal and matrices tasks from the Kaufman Brief Intelligence Test (KBIT) (Kaufman & Kaufman, 1990). This required children to select an image from a grid that they thought showed the meaning of a target word (verbal task) or completed a pattern (matrices task) (reported raw score consistent with prior work (Bowman et al., 2017); higher scores = greater verbal intelligence).

Executive Functioning Composite

Dimensional Change Card Sort (DCCS; Zelazo, 2006) and Forward Digit Span (Wechsler, 1974) constituted measures of children's executive functioning. For the DCCS, children play with cards that have two-dimensional features (color and shape) and must sort based on changing rules (e.g., sort by color, then by shape). Children are scored on the post-switch trials (5 trials total, max score = 5). In the Forward Digit Span task, children were presented with digit sequences ranging from two to eight digits in length (e.g., in a three-digit sequence the experimenter says aloud three digits e.g., "4, 6, 2" and the child must repeat those same digits in the same order e.g., "4, 6, 2"). Two trials were administered for each digit-sequence length (e.g., two trials of a two-digit sequence, two trials of a three-digit sequence, two trials of a four-digit sequence, etc.). If the child correctly recalled the digit sequence for at least one out of the two trials at a given digit-sequence length, then the experimenter would move to the next sequence length. However, if the child got both trials incorrect at a given digit sequence length, then the task ended (maximum score = 16). A single EF composite measure was created as an average of the standardized proportion scores of each individual task (DCCS and forward digit span performance was correlated at $r(121) = .37, p < .001$) (higher scores = more advanced EF skills).

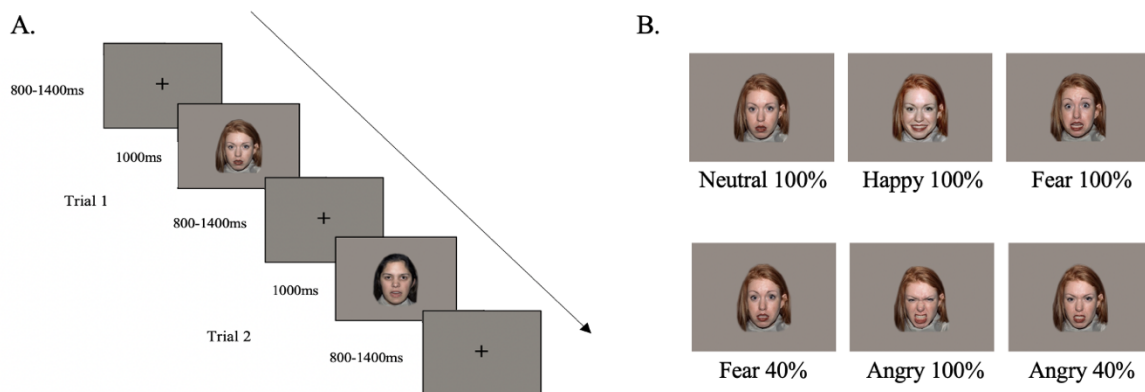
ERP Facial Emotion Perception Task

The ERP facial emotion task has been used previously to study Nc and N170 amplitude in infant and preschool children (Bowman et al., 2022; Xia et al., 2024; Xie et al., 2019). Full details are reported in supplemental appendix 2.III. In brief, preschoolers passively viewed faces in six emotion categories: full intensity happy, angry, and fearful faces; reduced intensity angry and fearful faces; and neutral faces (50 trials of each emotion category; 300 trials total, see figure 2.2). Faces were presented for 1000 ms and were preceded by a fixation cross for 800–1400 ms

and were presented in a randomized order via E-Prime Version 3.0 (Psychology Software Tools, Pittsburgh, PA). The ERP experiment lasted approximately 30 minutes including short breaks.

Figure 2.2

ERP Emotional Faces Stimuli



Note. ERP experimental design illustrating inter-trial interval stimulus duration (A) and examples of emotion conditions (B). Face stimuli consisted of emotional faces, including full intensity angry, fearful, and happy faces, reduced intensity angry and fearful faces, and neutral faces, taken from the Nim Stim data set (Tottenham et al., 2009). Faces were grouped into sets—White, Black, and East Asian (see supplemental appendix 2.III)—and children were shown the face set that best matched their own race or that best matched the faces children most frequently saw, as reported by parents at the time of testing. Stimulus presentation was random for each participant with the stipulation that no stimuli from the same emotion condition repeated consecutively. The reduced intensity images were created by morphing together the neutral and emotional expressions until the final images represented 40% of the actor’s emotional expression (i.e., fear or anger).

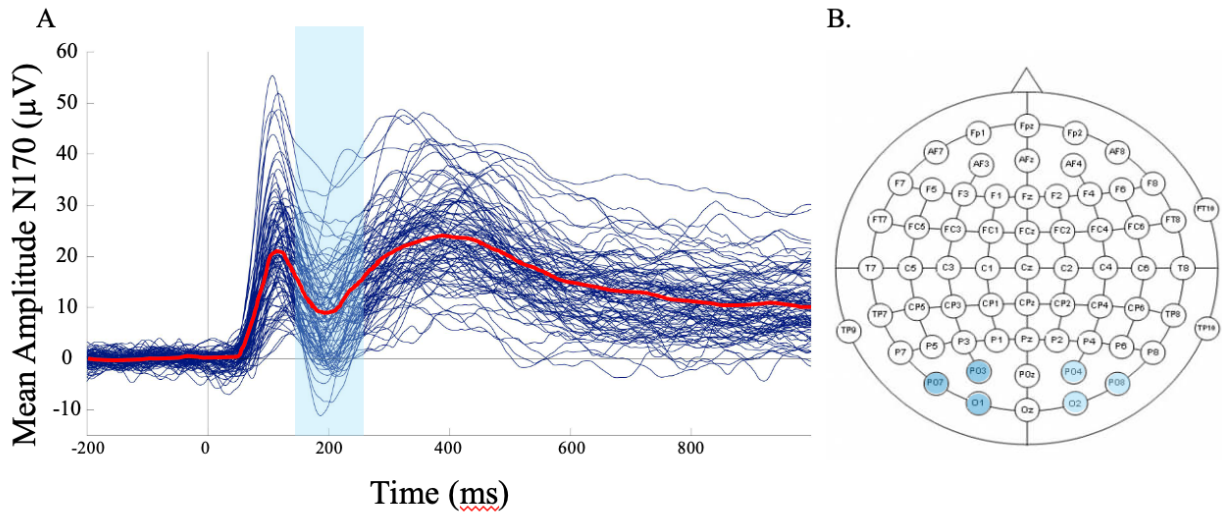
EEG Recording, Processing, and Analysis

Continuous EEG data were recorded throughout the experiment using BrainVision Recorder (Version 1.21.0393, Brain Products GmbH, Gilching, Germany), and a 64-channel montage in line with the international 10-20 system (see supplemental IV for additional EEG recording and processing details). Data were analyzed offline in MATLAB version 2019a (MATLAB, 2019) using EEGLAB version 2019_0 (Delorme & Makeig, 2004) and ERPLAB version 8.01 (Lopez- Calderon & Luck, 2014), processed in line with previous ERP research (e.g., Batty & Taylor, 2006, Xia et al., 2024). Continuous EEG was bandpass filtered using a Butterworth filter (0.1-30 Hz) and visually inspected for any egregious artifacts, which were then rejected (see supplemental V for continuous rejection protocol; validated in prior research with preschoolers, Xia et al., 2024). Consistently noisy channels were flagged for interpolation to improve the accuracy of Independent Components Analysis (ICA), which identifies blink components that are subsequently removed (Ullsperger & Debener, 2010) (see supplemental VI for ICA protocol, validated in prior research with preschoolers, Xia et al., 2024). Data were rereferenced to the average of all 64 channels. In line with previous research, trials were epoched from -200 ms to 1000 ms, baseline corrected, and epochs containing any channel that exceeded -120 to 120 μ V or for which sample-to-sample μ V exceeded 100 μ V were automatically rejected in ERPLAB (de Haan et al., 2004; Batty & Taylor, 2006). After epoching and artifact rejection, subjects contributed an average of 143.94 trials ($SD = 66.93$ trials, range = 13 – 272; average of 23.99 trials per condition; number of trials per condition did not differ, $F(3, 111) = 1.62, p = .189$). Number of contributed trials was unrelated to participant sex ($F(1, 132) = 1.11, p = .29$) and race/ethnicity ($F(4, 132) = 0.26, p = .9$) but was related to age ($F(1, 132) = 14.72, p < .001$). We included age in the final models to account for this relation.

Selection of electrodes and time windows for ERP components were informed by previous studies on emotional face processing (Hoyniak et al., 2019) and match those of prior uses of this exact task with preschool children (Xia et al., 2024). For N170, a time window of 150-240 ms was used based on this prior research and confirmed by visual inspection (see figure 2.3; Hoyniak et al., 2019).

Figure 2.3

Individual differences in N170 mean amplitude and channels



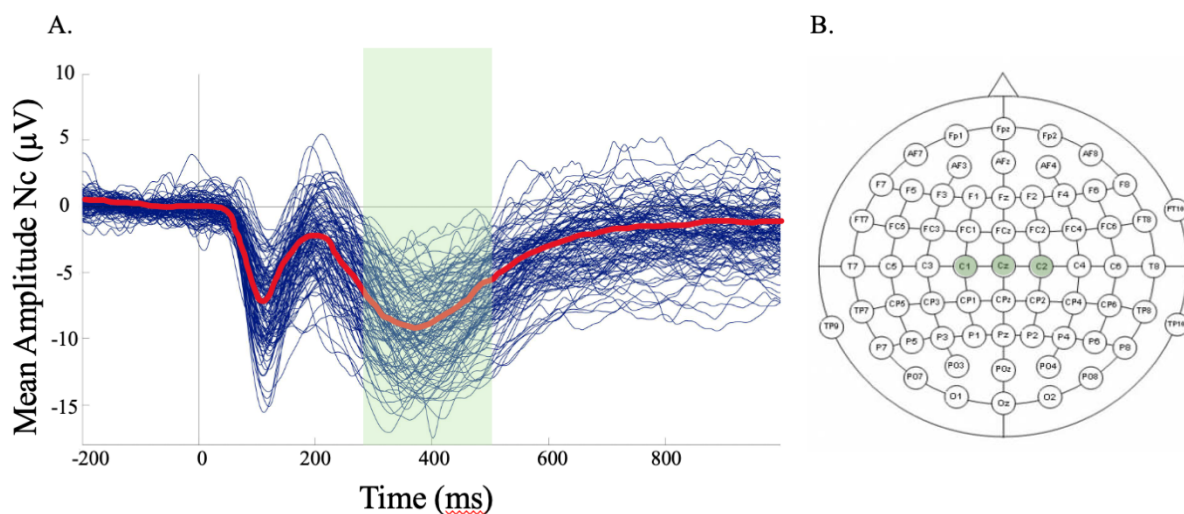
Note: Figure above shows the individual variability in children’s N170 mean amplitude. Each thin line represents an individual participant’s ERP component with thick red line indicating the grand mean average. Waveforms are shown for an average of all emotions. The line plot displays all participant’s N170 mean amplitude extracted from the averaged posterior-occipital electrode clusters (average of amplitudes in PO8, PO4, O2, PO7, PO3, and O1). The blue shaded box in A depicts the time window in which mean N170 amplitude was extracted. Figure B shows the

channels that were extracted for N170, which included sites: PO8, PO4, O2, PO7, PO3, and O1. Labels indicate the international 10-20 electrode positions with respect to our electrode montage.

For Nc, a time window of 300 - 500 ms was defined, similarly constrained by previous research and finalized by visual inspection, in line with previous research (see figure 2.4; Peltola et al., 2009; Pestana et al., 2025). A figure showing the scalp topography of grand-average waveforms averaged across all face conditions demonstrate maximal N170 activity over bilateral posterior-occipital electrodes and maximal Nc activity over central electrodes, supporting the electrode clusters selected for analysis (see Supplemental Appendix 2.IV for N170 and Nc topoplots).

Figure 2.4

Individual differences in Nc mean amplitude and channels



Note: Figure above shows the individual variability in children's Nc mean amplitude. Each thin line represents an individual participant's ERP component with thick red line indicating the grand mean average. Waveforms are shown for an average of all emotions. The line plot displays all participant's Nc mean amplitude extracted from the averaged central electrode cluster

(average of amplitudes in C3, Cz, and C4). The green shaded box in A depicts the time window in which mean Nc amplitude was extracted. Figure B shows the channels that were extracted for Nc including: C3, Cz, C4. Labels indicate the international 10-20 electrode positions with respect to our electrode montage.

ERP difference waves

We had an a priori plan to analyze each of the emotion difference waves from neutral as predicted by each ToM variable (SERT and ToM scale) (Lopez-Calderon & Luck, 2014).

Therefore, we calculated the differences in ERP mean amplitude by subtracting the neutral faces from full intensity (100%) emotions and reduced intensity emotions (40%) (see supplement 2.VII for details on LME data preparation). We additionally calculated differences in ERP mean amplitude by subtracting the reduced intensity (40%) from the full intensity (100%) emotions.

Data Analysis Plan

All analyses were conducted in R (version 4.1.3; R Core Team, 2019). LME models were fit using the lme4 package (version 1.1–25; Bates et al., 2009), and p -values were obtained using lmerTest (Kuznetsova et al., 2017). For all analyses, we use an alpha criterion of $p < .05$. For all focal analyses, we corrected for multiple comparisons using False Discovery Rate by using the Stats p.adjust function (R Core Team, 2014) and we report the corrected p -values.

Preliminary analyses were conducted using bivariate correlations to determine the placement of covariates (child age, sex, EF and language) in the LME models. Given analyses returned significant results, we included all four covariates as fixed effects in all LME analyses. Additional preliminary analyses were conducted to examine whether common patterns of emotion effects in the Nc and N170 were found in our data, giving confidence in our ERP task and replicating prior findings.

Focal analyses examined whether the difference waves of N170 and Nc mean amplitude were modulated by emotion condition and child's ToM (SERT or ToM composite scale). For trial-level ERP amplitude LME analyses, our model progression followed best practices as recommended by Barr and colleagues (2013) and Heise, Mon, and Bowman (2022, 2025). Details of the LME model building can be found in Supplemental Appendix 2.VII. We began by creating four larger LME models (N170–ToM composite, Nc–ToM composite, N170–SERT, and Nc–SERT). Then, we created separate models estimated for each emotion condition (e.g., angry40-neutral, fear40-neutral, fear100-neutral, angry100-neutral, happy100-neutral, angry100-angry40, fear100-fear40) and each ERP–behavior pairing, resulting in a total of seven models per pairing (pairings: N170–ToM composite, Nc–ToM composite, N170–SERT, and Nc–SERT). For all models, there were two-level random slope and intercept models in which the outcome was trial level ERP mean amplitude difference waves relating N170/Nc to the ToM composite scale/SERT. In all models, fixed effects were child's ToM, age, sex, EF, language, and trial presentation number; a random intercept for subject. Finally, we fit four two-level LME models with random intercepts and slopes to examine N170 and Nc responses to neutral faces in relation to ToM (composite) and SERT.

Results

Preliminary Analyses

Preliminary analyses were conducted to determine the placement of covariates of age, sex, EF, and language in the LME models. Bivariate correlations confirmed that ToM composite was related to age, sex, EF, and language ($r_s > 0.38, p_s < .001$) and age, EF, and language were also related to SERT ($r_s > 0.34, p_s < .001$). Given theoretical and empirical relations between ToM and age, sex, EF, and language in existing literature (Henry et al., 2013; Hughs & Ensor,

2007; Miller, 2006), we included them as covariates. See supplemental 2.VIII for results of preliminary analyses.

We then tested if reasoning was related to decoding by examining bivariate correlations between the SERT and ToM composite. The two measures were significant in standard bivariate correlation analysis ($r(67) = .31, p = .01$). However, when we included the additional covariates (age, sex, EF, language) in a linear regression model, SERT and ToM composite performance did not significantly relate ($R^2 = 0.37, F(6,62) = 0.08, p = .67$). In addition to the associations described above, SERT was positively correlated with ToM, $r(99) = .29, p = .004$.

Additional analyses investigated effects of emotion condition on Nc and N170 amplitude. Results returned expected patterns of significant differences in amplitude across pairwise emotion comparisons for both components (see Supplement IX for detailed statistics and waveform figures). Most notably, children's Nc amplitude was more negative for emotion conditions (e.g., angry) compared to neutral (e.g., $\beta = 12.79, SE = 0.21, p < .0001$, see also Supplement IX), replicating prior findings (Dennis, Malone, & Chen, 2009; Hoehl & Striano, 2010). Also, in line with prior findings (Blau et al., 2007; Hermann et al., 2002), children's N170 amplitude was less negative (thought to reflect greater neural specialization; Bentin et al., 1996; Sadeh & Yovel, 2010; Xia et al., 2024) for emotion conditions (e.g., angry) compared to neutral (e.g., $\beta = 33.07, SE = 0.40, p < .001$, see also Supplement IX). These patterns confirm that our ERP task elicited expected patterns of neural responses to passively viewing emotional and neutral faces.

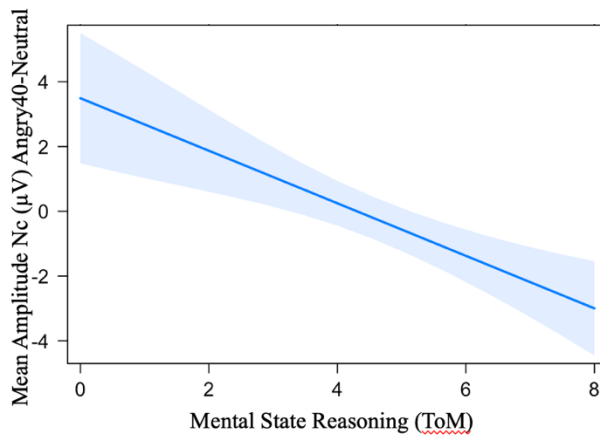
Focal Analyses

In the larger LME model with all emotion conditions, there was a negative relation between the ToM composite scale and Nc amplitude for reduced intensity angry faces relative to

neutral (Angry40-Neutral difference) ($\beta = -0.47$, $SE = 0.2$, *adjusted* $p = .02$). Similarly in the separate LME models, there was a negative relation between ToM composite scale and Nc mean amplitude for reduced intensity angry faces (Angry40-Neutral difference) ($\beta = -0.81$, $SE = 0.21$, *uncorrected* $p < .001$, *FDR-corrected* $p = .001$). This result indicates that children with a higher reasoning score in the ToM composite scale had a larger Nc amplitude to low intensity angry faces (compared to neutral) (Figure 2.5).

Figure 2.5

Nc Reduced Intensity Difference Waves to Angry Faces and Mental State Reasoning (ToM composite)



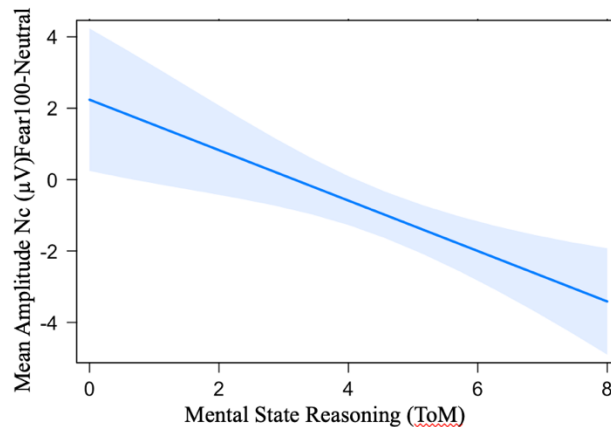
Note. Figure illustrates negative relation between ToM composite scale and mean amplitude Nc, such that a larger Nc to reduced intensity angry faces (compared to neutral) was related to a higher score on the ToM composite (reasoning) scale.

We additionally found that there was a negative relation between the ToM composite scale and Nc mean amplitude for full intensity fearful faces relative to neutral (Fear100-Neutral difference) in the separate LME model of emotion ($\beta = -0.71$, $SE = 0.21$, *uncorrected* $p = .001$,

FDR-corrected $p = .002$). This result indicates that children with higher scores on the ToM composite scale had a larger Nc amplitude to fearful faces (compared to neutral) (Figure 2.6).

Figure 2.6

Nc Full Intensity Difference Waves to Fearful Faces and Mental State Reasoning (ToM composite)



Note. Figure illustrates negative relation between the ToM composite scale and mean amplitude Nc, such that a larger Nc to full intensity fearful faces (compared to neutral) was related to a higher score on the ToM composite (reasoning) scale.

Relations between ToM composite performance and Nc amplitude to all other emotion conditions returned non-significant results, reported in Supplemental Appendix 2.X.

Additionally, analyses revealed that there were no relations between SERT and any ERP component (N170 and Nc) ($\beta s < 0.28$, $ps > .11$), nor were there any significant relations between the N170 or Nc relating to the ToM composite scale or SERT for the neutral condition ($\beta s < -1.4$, $ps > .05$, see Supplemental Appendix 2.X).

Discussion

This study investigated links between the neural correlates of emotional face perception and children's behavioral ToM. Specifically, we examined individual differences in the amplitudes of two ERP components (N170 and Nc) in multiple emotion conditions of different intensities and related these ERP amplitudes to children's behavioral performance on two different ToM tasks (the SERT and ToM composite scale). With these study parameters, we were able to investigate whether individual differences in how the brain has tuned to respond to emotional faces are related to children's behavioral ToM performance, including both mental-state decoding and mental-state reasoning processes, as well as examine the nature of those relations.

Results revealed that a greater Nc amplitude to reduced intensity angry faces (versus neutral) was related to higher scores on the ToM composite scale. Similarly, a greater Nc amplitude to full intensity fearful faces (versus neutral) was related to higher scores on the ToM composite scale. There were no significant relations between Nc amplitude and the SERT, nor were there any significant relations between N170 amplitude and either the SERT or the ToM composite.

Children's ERPs to Emotional Faces are related to their ToM Performance

At the broadest level, our findings provide evidence that individual differences in the neural correlates of emotional face perception are indeed related to children's behavioral ToM. This positive result is in line with findings from behavioral research showing that children's ability to understand emotions predicts their ToM performance, both concurrently (Cutting & Dunn, 1999; Grazzani et al., 2018) and longitudinally (O'Brien et al., 2011). Here we expand on these behavioral findings and demonstrate that how children's brains have tuned to respond to

emotional faces explains important variability in early ToM development. These findings provide evidence to support existing theories suggesting that early emotion perception supports the development of mental-state reasoning, potentially through partially shared and interacting neural systems (Compton, 2003; Mitchell & Phillips, 2015; Schmitgen et al., 2016).

Although not directly tested in the present study, these findings also are consistent with the possibility that *early* specialization of the neural circuitry supporting emotion perception is foundational for the development of ToM. Early in the first year of life, infants begin to exhibit strong preferences for faces, reliably attending more to faces relative to non-social visual stimuli (e.g., distractor items, etc.) (Belteki et al., 2025; Frank, Vul, & Johnson, 2009). Importantly, infants can discriminate emotional expressions and categorize them within the first 7-months of life by exhibiting differential attention patterns to certain faces over others (Kestenbaum & Nelson, 1990; Leppänen & Nelson, 2012). This early sensitivity to emotional expressions points to the rapid development of underlying systems that prioritize emotional facial cues. In particular, the neural system for face processing begins developing early in infancy, wherein infants read emotions on caregiver's faces, with this ability continuing to develop as children age (Conte et al., 2020; Xie et al., 2019). Importantly, this neural system for facial emotion perception undergoes specialization in the first two years of life (Leppänen & Nelson, 2009; Scott & Monesson, 2010). The protracted development and specialization supporting emotional face perception reveals individual differences that could set the stage for how other complex social-cognitive skills that use information from emotional face cues—such as ToM—develop. Behavioral research already shows longitudinal links between these constructs, in which early emotion understanding at age 3 predicts later development of ToM at age 4 (O'Brien et al., 2011).

Expanding on these behavioral results, the current study shows that there are concurrent relations between how the brain supports emotion perception and ToM in preschool. Importantly, these results set up a clear next step to investigate the possibility that infant neural responses to emotional faces may longitudinally predict their preschool ToM performance. Such infant studies can continue to examine the role of Nc amplitude to emotional faces, as well as include additional ERP components that reliably index infant face and emotion perception such as the N290 and P400 (e.g., Halit et al., 2003; Jessen & Grossmann, 2015; Leppänen et al., 2007). The methods of the present study can be easily adapted for such longitudinal investigation with infants; our emotional faces ERP task has been used in young infants (e.g., modified by having less emotion conditions; decreasing experiment length) (Bowman et al., 2022; Safyer et al., 2020). Alternatively, future work could use structural equation modeling with the ERP emotional faces task in infancy and preschool to better isolate how early neural differences in face perception relate to later ToM. Together, these approaches would allow researchers to directly test whether early neural specialization for emotional face perception is foundational for the emergence of ToM longitudinally, expanding on our concurrent findings.

Relations Between Children's ToM and Nc Amplitude to Angry and Fearful Faces Helps Reveal Nuances of Relations between Emotional Face Perception and ToM

Beyond the general relation found between children's neural responses to emotional faces and their ToM performance, the precise ways in which those relations occurred reveal important details about the specific nature of the link between emotional face perception and children's ToM, as we discuss in the next sections.

Attention to emotional faces is important for ToM

First, the significant relation wherein greater Nc amplitude to emotional faces was associated with better behavioral ToM highlights the role of attentional processes in the link between emotional face perception and ToM. The Nc component is visible 300 - 500 ms post the onset of an emotional face. Thus, our finding suggests that this later Nc could reflect sustained attention to emotional faces, compared to earlier, initial automatic attentional processes (occurring within the first 200 ms post-stimulus onset) (Richards, 2003; Richards, Reynolds, & Courage, 2010). A greater (more negative) Nc is thought to index increased allocation of attention to faces (Carver et al., 2003; de Haan et al., 2004). Thus, children who allocate more attentional resources to emotional faces versus neutral faces may be able to make more accurate inferences about people's mental states.

A general role of attention in ToM has been previously documented. Prior work has shown overlapping neural networks between ToM and attention orienting, localized to the right temporoparietal junction (Young, Dodell-Feder, & Saxe, 2010). Similarly, behavioral research shows that increased selective attention is related to better ToM abilities in preschoolers concurrently (Welch-Ross & Miller, 2000) and longitudinally wherein infants' increased attention to intentional action displays predicted their increased preschool ToM ability (Wellman et al., 2008). Our findings extend this previous work by highlighting that attention to emotional information on the face, beyond more general attention, is associated with better ToM. Emotional facial expressions provide visible cues to others' internal mental states, offering observable information that can be used to infer otherwise invisible thoughts, intentions, and desires (Frith, 2009). Attending more closely to this emotional information thus may facilitate more accurate inferences about others' mental states. At the same time, the association may operate in the opposite direction: emerging ToM may shape children's attention to emotionally

informative aspects of faces. Consistent with this possibility, prior work has shown that toddlers' visual scanning of sad faces is associated with their ToM skills (Poulin-Dubois et al., 2018). Thus, the development of attention to emotional facial information and ToM may be mutually reinforcing, a possibility that longitudinal research is needed to test.

To better ascertain how the role of attentional processes to emotional face perception relates to ToM, an important future direction could include measures of general attention (e.g., Attention Network Test, visual search task, etc.) along with ERP emotional face task and behavioral ToM. This approach would allow researchers to test the relative contributions of attention to emotional faces versus attention more generally in predicting ToM performance. Additionally, future work could incorporate tasks such as the dot-probe paradigm to test whether there are selective attentional biases toward emotional faces relating to ToM ability. Taken together, these approaches could help to further unpack the role of attention in the relation between emotional face perception and ToM performance.

Attention to Negative Emotions may be especially helpful in making accurate Mental State inferences.

Our results showed that this relation between Nc to emotional faces and ToM was revealed in the negative emotion conditions (fear and anger). Therefore, relations between ToM and attention to emotional faces (as indexed by the Nc) may be more strongly revealed in the attention to negative emotions. Negative emotional faces (e.g., anger and fear) are more salient (Whalen et al., 2013), and may more readily invite inferencing about underlying mental states given the importance of fearful and angry faces in signaling threat (“What does this fearful person know that I don’t know that is making them so scared?” “Does this angry person think I am a threat?”). In line with this notion, previous work has found that observing fearful faces can

enhance visuo-spatial perspective-taking abilities, relevant for ToM (Zwicker & Muller, 2010). Given the strong link between perception of salient, threatening, negative emotions and mental-state inferences, individual differences in children's ToM abilities may be more strongly predicted by individual differences in how the brain has tuned to attend to these negative emotional expressions.

We note that mental-state inferencing is posited to be linked to all emotional face perception, including positive emotions (Cutting & Dunn, 1999; O'Brien et al., 2011; Grazzani et al., 2018). While we did not find any relations between Nc amplitude to happy faces and children's ToM behavioral performance, these null results do not preclude the possibility of their existence. Replications are needed to establish the robustness of these null findings, and future research should also assess children's neural correlates of perceiving additional positive emotional expressions (e.g., positive surprise) as well as reduced intensity positive emotional expressions. The inclusion of these additional positive stimuli may reveal links between how the brain has tuned to attend to positive emotional faces and preschoolers' emerging ToM that were not detected in the present study.

Attention to Reduced-Intensity Emotional Expressions may be especially helpful in making accurate Mental State inferences.

Our finding of a relation between ToM and Nc amplitude to reduced-intensity expressions of emotions (i.e., reduced intensity angry) further suggests that attentional allocation to these such reduced-intensity emotional expressions may be especially relevant for children's ToM. Existing research suggests that reduced-intensity emotional expressions (compared to more intense) can be more ambiguous to interpret and are more difficult to detect (Barros et al., 2023). Thus, children who allocate additional attentional resources when viewing reduced-

intensity expressed emotions may be better equipped to accurately reason about the mental states. There is limited research on reduced-intensity emotional faces specifically relating to ToM; however, one study found that patients with Epilepsy had poor recognition of reduced-intensity fearful faces, and this was correlated with deficits in their ToM ability (Lin et al., 2022). Although this finding is in a clinical population, it is plausible that the relation between reduced-intensity faces and ToM in typical populations may manifest as a positive association, such that greater sensitivity to reduced-intensity emotional faces corresponds to better ToM performance. Our current findings are in line with this reasoning given the increased neural response for attention to reduced-intensity angry faces related to higher mental state reasoning. We note that this relation may not be driven by the reduced-intensity angry face specifically, but rather that anger may be a more salient emotion that is better capable of capturing individual differences that relate to behavioral ToM (as per our discussion above). As previously noted, future directions should include reduced intensity positive emotional faces to investigate whether our finding is specific to negative emotions per se, or whether ToM may also be related to perception of reduced-intensity positive emotional expressions as well. Additionally, the inclusion of other negative emotions (e.g., sadness) of varied intensity to the present study design would shed further light on the extent to which perception of reduced-intensity emotional expressions more generally (versus specific to anger) is related to preschoolers' ToM performance.

Attention to emotions specifically, beyond general social attention, may be especially helpful for mental state inferencing

It is possible that the observed associations between the neural correlates of emotional face perception and ToM reflect individual differences in general social attentional processes rather than emotion specific mechanisms. In our findings, children who were better able to

allocate attention to reduced-intensity emotional cues showed stronger mental state reasoning and that attention to the more salient emotions that may best engage attention (fear and anger) predict greater ToM. Thus, these observed effects could suggest that the relation between greater Nc amplitude to emotional faces and better ToM performance reflects a broader role of greater attention to social stimuli more generally, rather than a role of attention to emotions more specifically as related to ToM. Although we cannot rule out this possibility, additional results from the present study suggest that attention to emotional cues per se, beyond general social attention, accounts for individual differences in children's behavioral ToM. For example, if emotional face perception and ToM were related due to a common underlying role of general social attention, then we would predict that greater attentional allocation to social (but not necessarily emotional) stimuli, such as a neutral face, should also predict better behavioral ToM. In contrast, our results showed that Nc amplitude to the neutral face was not related to behavioral ToM. Rather, Nc amplitude to emotional faces (as assessed in our ERP difference waves) was associated with better ToM, pointing to a role of attention to emotional (beyond general facial) cues in ToM performance. As previously suggested, future work should incorporate measures of general social attention (e.g., Point-Light Displays, social scene attention without faces) to examine this link between attention to faces and ToM more clearly. Additionally, these measures of general social attention could also be used in replication attempts as a covariate to control for the effects of attention in the models. Such future research can shed light on the extent to which the link between Nc amplitude to emotional faces and ToM reflects either a general social attentional mechanism or an emotion specific process driving the effect. Future research could also examine the role of additional ERP components that have been shown to index other

orienting and attentional processes such as the P1 (Batty & Taylor, 2006) to further examine the role of general attention to social stimuli in ToM development.

Attention to emotional faces is related to ToM reasoning, but perhaps not related to ToM decoding

Lastly, a central aim of the study was to shed light on how emotion perception may be related to specific aspects of ToM: mental-state reasoning versus mental-state decoding. Recall that mental-state *decoding* involves a rapid initial extraction of socially relevant cues from perceptual input (e.g., faces, gaze direction), to interpret a person's mental state (Sabbagh et al., 2004). In contrast, mental-state *reasoning* describes a later-occurring process that involves using decoded social information to make inferences about unobservable mental states (e.g., beliefs, intentions, desires) (Thoma et al., 2013).

Our results could suggest that emotion perception is most strongly related to ToM *reasoning*. In support of this possibility, we only found significant results between children's neural responses to emotion perception and performance on a task that more strongly elicits ToM reasoning—namely, a modified Wellman and Liu (2004) scale that is void of relevant perceptual cues from facial expressions. In contrast, no relations were found between neural responses to emotional faces and performance on the ToM decoding task (SERT), which requires mental state inferences based solely on perceptual features of people's eyes. Moreover, we did not find any relations between ToM performance and the N170 ERP component that is thought to reflect decoding processes (Blau et al., 2007; Eimer, 200). Rather, we found positive associations between ToM and the Nc component, which is associated with attentional allocation, and reflects later, less automatic processes perhaps more related to reasoning. Indeed, the 300-500 ms timing of the Nc component overlaps with a late slow wave component identified in previous research

as children actively engaged in a ToM reasoning task (Bowman et al., 2012). These results are in line with prior work suggesting that mental-state reasoning occurs later in the processing stream and relies on neural systems that are partially distinct from those supporting earlier mental-state decoding (Lee et al., 2005; Sabbagh et al., 2004). Consistent with this distinction, fMRI research has shown dissociable neural networks for mental-state decoding versus mental-state reasoning, suggesting that these processes are supported by related but functionally distinct systems (Frith & Frith, 2001; see also Sabbagh et al., 2004). Taken together, the present study findings that the Nc amplitude for emotional (versus neutral faces) is related to mental-state reasoning, may indicate that how the brain has tuned to support attention to emotional facial expressions provides a critical input for mental-state reasoning, which depends on integrating emotionally relevant cues from faces to infer others' beliefs, intentions, and desire.

Future research could further explore associations between ToM and other ERP components that occur later and are also associated with conscious appraisal and reasoning processes, such as the late positive potential (LPP) (Dennis & Hajcak, 2009; Kennedy & Montreuil, 2021). Future research could also include ToM tasks that more directly probe children's reasoning versus decoding processes by using measures that examine children's ability to not only predict others' mental states but also explain how mental states are relevant in the depicted scenarios (such as the Comprehensive Assessment of ToM; Heise & Bowman, 2025). Each of these future directions would build off the present study findings and add further insight into the role of emotional face perception in ToM reasoning more specifically.

We note that the null relations between N170 and ToM, and the general lack of relations between ERPs to emotional faces and our ToM decoding task of the SERT, do not rule out the possibility that significant associations among these variables may emerge in different samples

or under different methodological or contextual conditions. We argue that, in the present study, the absence of relations between ERPs and SERT is unlikely to be driven by deficits in the SERT measure, as SERT scores showed variability and no evidence of ceiling or floor effects.

However, the requirement of the SERT that individuals decode mental states from stripped-down pictures of solely individuals' eyes may have provided too constrained a stimulus to engage in a more multifaceted decoding process that may connect with ToM. Future replication attempts should include other tasks that may better measure ToM decoding processes, such as using full faces and/or tones of voice to measure and examine whether significant relations between ERPs to emotional faces and these potentially richer ToM decoding processes emerge. Additionally, it is plausible that when measuring earlier in development (e.g., toddlerhood), we might see stronger relations between neural responses to emotional faces and ToM decoding, given that ToM decoding abilities are thought to develop before ToM reasoning (Cao et al., 2012). Each of these future directions would build on the present study findings and help more directly assess associations between neural responses to emotional faces and ToM decoding.

Limitations and Future Directions

The present study results suggest that increased neural resources supporting attention to emotional faces is related to better mental state reasoning. Here we discuss additional limitations beyond those already presented above that further qualify interpretation of results and motivate future work.

One additional limitation is that our face stimuli consisted of solely adult faces; it is plausible that there may be a difference between the way a child interprets an adult versus another child's emotional face (Marusak et al., 2013). Thus, we encourage future investigations

of children's ToM and their neural responses to incorporate stimuli of children's emotional faces. Moreover, in addition to incorporating richer/more nuanced assessments of ToM reasoning and decoding, we also recommend future work to include behavioral measures of emotion perception. Such behavioral tasks could include measures requiring children to label an emotional face, or to explain how a character might feel given different presented circumstances (Conte et al., 2019; Cutting & Dunn, 1999; O'Brien et al., 2011; Weimer et al., 2012). The addition of these behavioral emotion labelling and comprehension tasks can help reveal how such processes may relate to individual differences in children's ERPs to emotional faces and further illuminate which aspects of emotion cognition are related to ToM. Finally, future research would benefit from adopting more naturalistic measures in which children view emotional stimuli more like those they encounter in everyday life. Such naturalistic stimuli (e.g., videos of dynamic faces that move, live interaction of an experimenter's face expressing emotions) may provide a more ecologically valid context for examining neural responses to emotional face perception related to ToM (see Xia et al., submitted, for an example of a measure of children's neural responses to live, naturalistic emotional expressions). Indeed, prior work has shown that videos of dynamic expressions are recognized quicker and more accurately than static images, which makes this an effective future direction (Calvo et al., 2016).

The present study sample included participants that were racially and ethnically diverse, with almost half the sample identifying as Hispanic/Latinx, multi-racial, Asian/Pacific Islander, or Black, with the other half of participants identifying as White, Non-Hispanic/Non-Latinx. However, the sample was characterized by high levels of parental income and education, which may limit generalizability to more socioeconomically diverse populations. Future work should therefore aim to replicate these findings in samples with greater socioeconomic diversity to

better understand the robustness of these relations between the neural correlates of emotional face perception and mental-state inferencing in a larger, more representative population.

Conclusion

A vital aspect of social behavior is the ability to perceive other's facial expressions, which convey critical information about others' internal mental states. Results of the present study revealed both whether and how the neural correlates of emotional face perception are related to mental state inferencing. In particular, our results showed that increased attentional allocation (as reflected in increased Nc amplitude) to negative emotions, and reduced-intensity negative emotions, were each associated with better behavioral ToM reasoning. These findings suggest that individual differences in how the brain 'tunes' to attend to emotional facial cues are related to individual differences in how children reason about the invisible internal mental states that govern behavior, offering insight into the factors that may contribute to the development of ToM. Our findings point to potentially especially important roles of attention to negative emotions and reduced-intensity emotions as related to specifically ToM reasoning (versus decoding) processes. At the broadest level, the present study opens avenues for future research to further explore the potentially foundational role that neural correlates of emotional face perception may play in supporting ToM development.

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Supplemental Materials: Chapter 2

Index

Appendix 2.I: Participant Demographics

Appendix 2.II: Behavioral Measures

Appendix 2.III: Details on Faces Task Administration

Appendix 2.IV: Continuous EEG Egregious Artifact Rejection Protocol

Appendix 2.V: Independent Component Analysis (ICA) Blink Component Identification Protocol

Appendix 2.VI: Linear Mixed Effect Data Preparation and Model Selection

Appendix 2.VII: Preliminary Analyses

Appendix 2.VIII: Preliminary Analyses: N170 and Nc responses to emotional and neutral faces

Appendix 2.IX: Relation between ToM or SERT and N170/Nc

Appendix 2.I

Participant Demographics

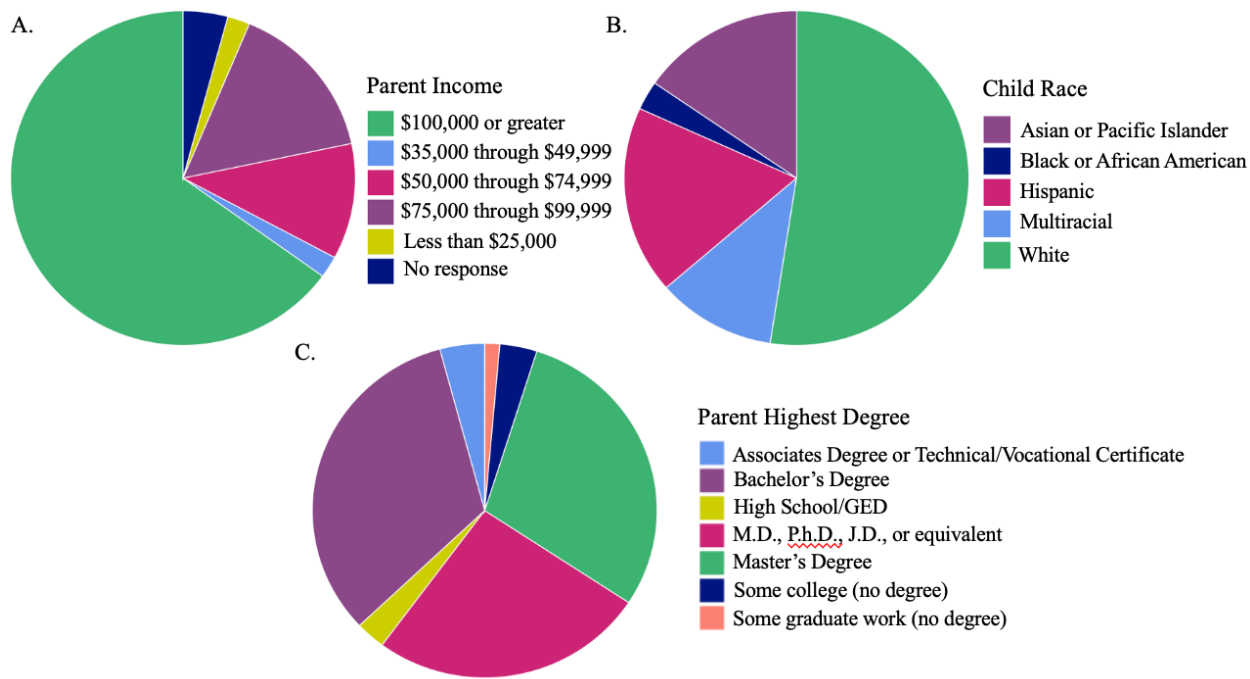


Figure S2.I.1. Demographic Information by parent's income (A), child's race (B), and parent's highest degree level (C). Demographic information was gathered by parent report for final sample (N = 145)

Children's race was reported as follows: 70.63% were White (18.18% are Mexican or other Hispanic/Latinx heritage), 15.38% were Asian or Asian American, 11.19% were multiracial (50% were Hispanic or Latinx as well as another race other than White), and 2.8% were Black. Across all children, 24.48% were reported as of Mexican or other Hispanic/Latinx heritage. Parental education was also reported: 2.8% of children had parents with a high-school equivalent of education, 4.2% had at least 1 parent with an Associate's degree, 3.5% had some college education but no degree, 32.87% had at least 1 parent with a Bachelor's degree, 29.37% has at least one parent with a Master's Degree and 25.87% had at least 1 parent with a doctorate

degree (M.D., Ph.D., J.D.). Family income was also reported; 67.88% of families earned greater than \$100k, 16.06% families earned \$75- \$99k, 11.68% earned \$50-74k, 2.19% earned \$35-49k, 2.19% earned less than \$25k, and 8 families did not report income.

Appendix 2.II

Behavioral Measures

Theory of Mind measures

Simplified Eye Reading Task (SERT) – Mental State Decoding (Peterson & Slaughter, 2009)

Five of the scored trials had an emotional mental state (e.g. sad) as the correct answer and four had a cognitive mental state (e.g. thinking) as the correct answer. The test trials were presented in one of three predetermined orders, in which both expression order and order of response options were counterbalanced. Coefficient alpha indicated that the SERT measure had moderate internal consistency ($\alpha=0.71$).

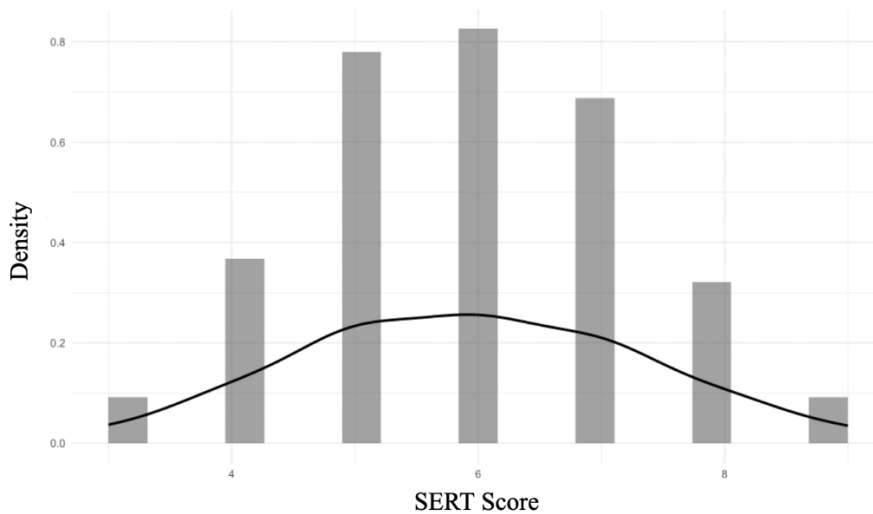


Figure S2.II.1. Distribution plot for SERT scores. This shows there is an even distribution of scores, with no ceiling or floor effects.

Theory of Mind Composite (ToM composite) – Mental State Reasoning (Wellman & Liu, 2004)

Each vignette tested the following aspects of mental-state reasoning, administered in the order listed: diverse desires (that others will have and act on different desires), diverse beliefs (that others will have and act on different beliefs), knowledge access (that others may not have the same knowledge), contents false-belief (that others may have false beliefs about the contents of an object), explicit false-belief (that others will act on false beliefs they hold about the location of an object), belief emotion (that others' emotions are based on their beliefs, even if those beliefs are false), and real vs. apparent emotions (that expressed emotions can be different than real emotions). However, we excluded the real vs. apparent emotion task when creating a ToM composite score because our scale reliability analysis showed that the overall reliability was strongest when this task was omitted (reliability with real apparent emotion: $\alpha = 0.6$, without real apparent emotion: $\alpha = 0.76$), a finding that aligns with previous research (Calero et al., 2013; McElwain et al., 2018). All tasks had warm-up and control questions, which children had to answer correctly to pass the task. Coefficient alpha indicated that the ToM composite had moderate internal consistency ($\alpha=0.76$), in line with prior research (Bowman et al., 2017; Sabbagh et al., 2009).

Kaufman Brief Intelligence Test (Kbit) – Verbal Intelligence (Kaufman & Kaufman, 1990)

Children received a score of 1 for a correct response and 0 for an incorrect one. There were 60 possible trials for a max score of 60, where higher scores indicate better verbal ability. The task was concluded once children received a score of 0 for 4 consecutive trials or if they reached the end of the 60 prompts.

Executive Functioning Composite (Wechsler, 1974; Zelazo, 2006)

For the DCCS task, children must first sort a set of cards that contain red boats, blue boats, red rabbits, and blue rabbits and sort them by shape for five trials. On each trial, the experimenter repeated the relevant rules, labeled the test card by the color, and gave the card to the child to sort. If the child correctly sorts five consecutive cards according to shape (e.g., rabbits go in the rabbit tray, boats go in the boat tray), then the experimenter will proceed to the post-switch trials. In the post-switch trials, the child must then sort the cards by color (e.g., red cards go in the red rabbit tray, blue cards go in the blue boat tray).

In the forward digit span task, the child must repeat a digit span that the experimenter says aloud, and the child's repetition must be in the same order in which the experimenter reads for that given trial to be marked as correct. The task began with a practice trial of two-digits per sequence (e.g., experimenter says "4, 6" and the child must repeat "4, 6"). If the child gets this trial correct, then the test-trials begins with two trials of two-digit sequences and increases by one digit per level for a maximum of eight-digits per sequence (e.g., if a participant continues to get all sequences correct, the most difficult trial possible constitutes the experimenter saying a sequence of eight digits e.g., "4, 6, 1, 3, 5, 7, 8, 2" and the child must repeat "4, 6, 1, 3, 5, 7, 8, 2"). Two trials are presented at each sequence length (e.g., two trials of a two-digit sequence, two trials of a three-digit sequence, two trials of a four-digit sequence, etc.). If the child correctly recalled the digit sequence for at least one out of the two trials at a given sequence length, then the experimenter would move to the next sequence length. However, if the child got both trials incorrect at a given digit sequence length, then the task ended.

Appendix 2.III

Details on Faces Task Administration

Consistent with previous uses of this task (e.g., Bowman et al., 2022; Xia et al., 2024; Xie et al., 2019), children saw the face set that best matched their own race as reported by their parent. There were four face sets consisting of Black actors, East Asian actors, and two sets of White actors that are counterbalanced across White children (76.59% of the full final sample received the White actors; of this sample: 50.92% saw White Face set 1, 51.46% saw White Face Set 2). The face sets consisted of unique actors that each displayed emotional expressions in all emotion conditions (see Figure S2.III.1.). There were five unique East Asian actors, four unique Black actors, and nine unique White actors distributed across the two White face sets with one actor repeated across both White sets. Within each face set, participants saw each actor express each of the 6 emotions 10 times (except where one actor was presented 20 times across each emotion in the Black face set given the overall paucity of Black actor stimuli available in broader Nim Stim faces, Tottenham et al., 2009) for a total of 300 trials in the experiment. ERPs were time-locked to the onset of the face stimulus. During task administration, children took multiple short breaks during which they placed stamps on a piece of paper, rested their eyes, or wiggled and stretched their arms and legs.

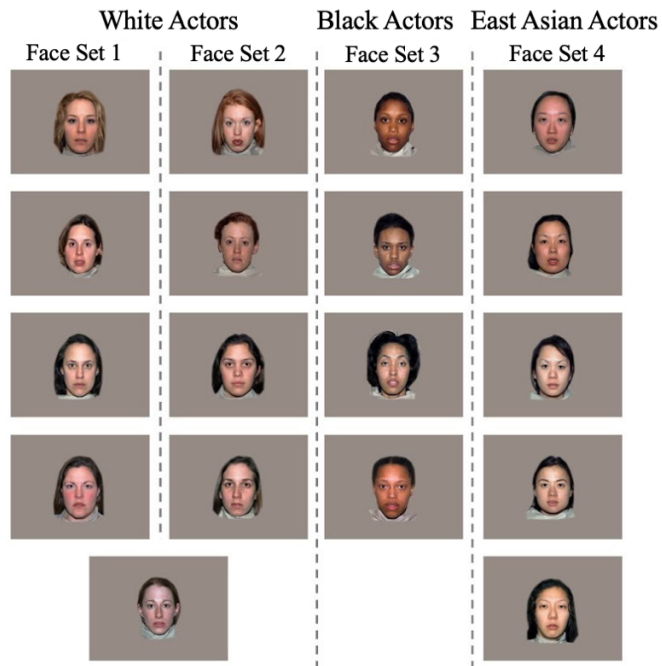


Figure S2.III.1. Actors were grouped into different face sets by race condition, shown to different participants across the sample. Children saw the face set that best matched their own race as reported by their parent or that best matched the faces children frequently saw as reported by their parents at the time of test—either a set of White faces, Black faces or East Asian faces.

Appendix 2.IV

Details on EEG Recording, Processing, and Analysis

Continuous EEG data was recorded throughout the ERP experiment using BrainVision Recorder (Version 1.21.0393, Brain Products GmbH, Gilching, Germany), actiCHamp (2020c) amplifier (actiCHamp, Brain Products GmbH, Gilching, Germany), and a 64-channel montage High Precision fabric ActiCap Snap cap (ActiCAP Snap, Brain Products GmbH, Gilching, Germany) that positioned actiCAP slim electrodes in line with the international 10-20 system (actiCAP slim, Brain Products GmbH, Gilching, Germany). Data were bandpass filtered from 0-140 Hz and referenced to Cz during recording. A photodiode was used to measure the delay of the monitor at the face location. Before all signal processing and analyses, the stimulus event codes were shifted to reflect the true stimulus onset time at the location of the face. Data were digitized at a 500 Hz sampling rate for 50 participants and the remaining 95 were digitized at 1000 Hz (and down sampled to 500 Hz during initial processing steps).

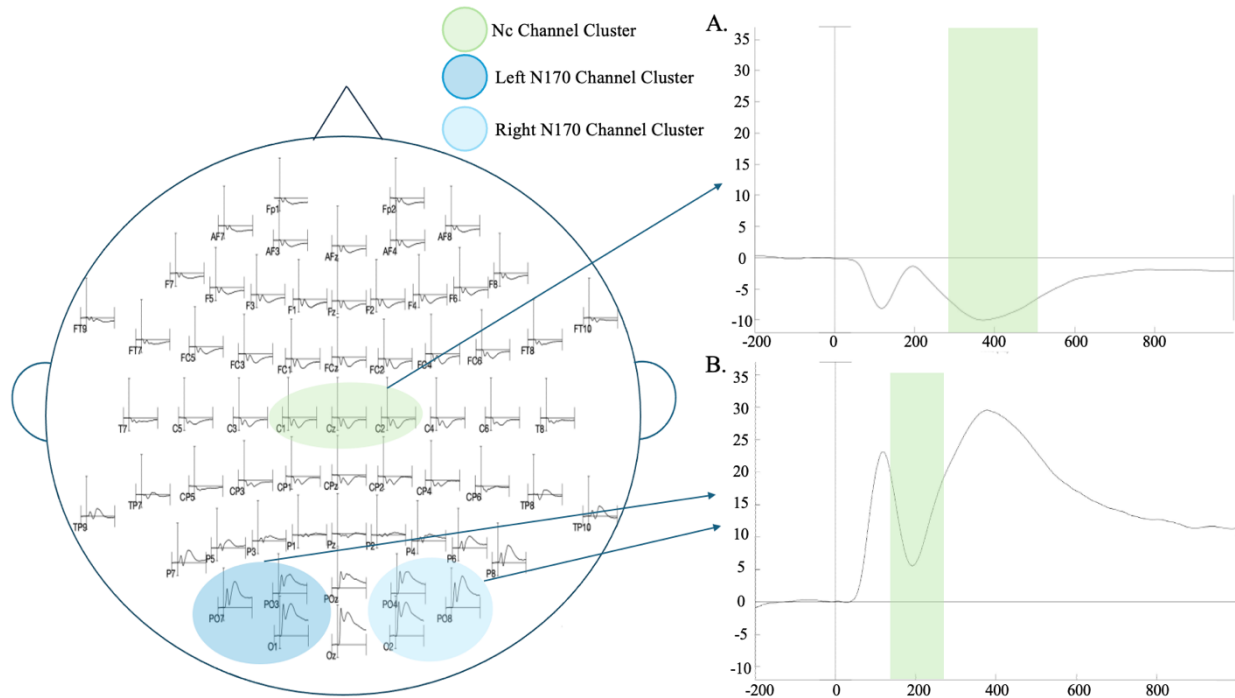


Figure S2.IV.1. Topography of waveforms across all 64 electrodes. Nc electrodes highlighted in green, N170 electrodes highlighted in dark blue for the left cluster and light blue for the right cluster. Panel A (top) shows grand average waveform collapsed across all conditions and electrodes for Nc. Panel B (bottom) shows grand average waveform collapsed across all conditions and electrodes for N170. Green vertical bars depict epoch of analysis.

Appendix 2.V

Continuous EEG Egregious Artifact Rejection Protocol

(also published in Xia et al., 2024)

‘Continuous EEG Egregious Artifact Rejection (CEEAR)’ refers to the process in which we visually inspect the continuous EEG data to identify egregious artifacts (i.e., noisy sections in the data) to be rejected (removed) from the analyses. These egregious artifacts are typically caused by 1) motion (e.g., child moved their head or stretched); 2) muscle tension (e.g., jaw clenching) or 3) other electrical noise (e.g., high impedance level from one electrode or malfunctioning ground/reference electrode). The goal of CEEAR is to prepare our data to be entered into a subsequent, more automated process of Independent Component Analysis (ICA) to eventually identify and remove eye blinks (see ICA Blink Component Identification Protocol below for more details).

We include our detailed CEEAR protocol below. In this protocol, we discuss how to set up a workstation, and what counts as ‘egregious artifact’. We also show screenshots of example EEG segments containing artifact that should be removed during this process. We use EEGLAB to visualize artifacts and mark them for rejection in subsequent preprocessing steps.

Continuous EEG Egregious Artifact Rejection (CEEAR) Protocol

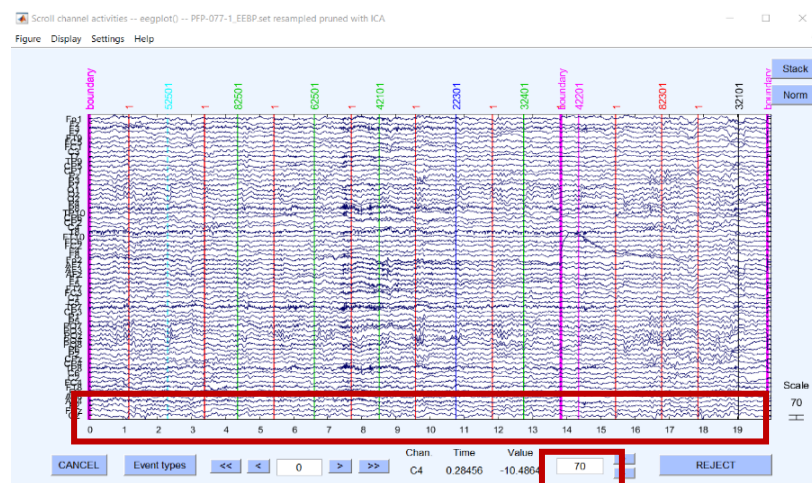
NOTE before you begin: It is **absolutely essential** that you do not complete any continuous EEG artifact rejection tasks when you are tired, or if you are in a distracting environment. Continuous EEG artifact rejection is an extremely important process that ensures

good data quality and produces data for analyses. If mistakes are made, we lose valuable data and we risk publishing erroneous results.

Step 1. Setting up your continuous EEG artifact rejection workstation:

- Setting up EEGLAB:
 - Go to EEGLAB → Plot → Channel Data (Scroll) to plot the continuous EEG data

- In the left corner, change the vertical viewing scale to 70 μ V (small red box)



- In Settings, change Time Range to Display to 20 seconds (large red box)
- Note: these are the settings we use to identify artifact based on visual inspection. You must use the same parameter settings for all continuous EEG artifact rejection projects.

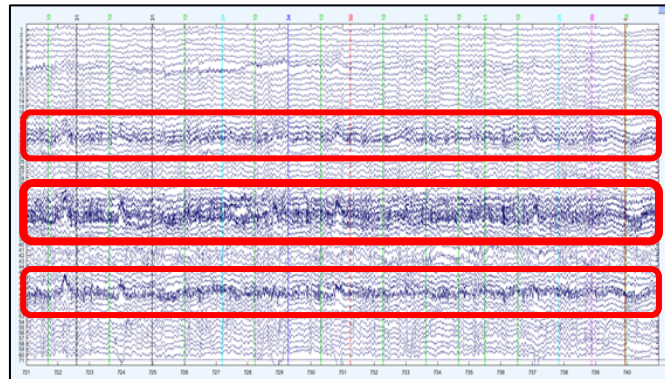
- Additional things to prepare for:
 - A scratch pad for you to write down notes about noisy channels or questionable segments

- Open this protocol on a different screen – it will be easier for you to see both the EEG data scroll and the protocol (the squiggly lines are hard to read on a smaller screen).
- But if you don't have an external monitor, still have this protocol open in the background, so you can refer back to it whenever in need.

Step 2. Determine artifact-containing segments in continuous EEG data

Now that you are all set up with EEGLAB, you are ready to scroll through the continuous EEG data file to identify the artifacts and mark them on the EEG data scroll. To mark the artifacts on continuous EEG, click and drag your cursor on the continuous data (it will be highlighted; see pictures below for examples) until the end of the artifact you identified.

The very first step you need to do before starting to highlight and identify artifacts for rejection is to click through the entire EEG data scroll to 1) calibrate your expectations for a general idea of how noisy the data



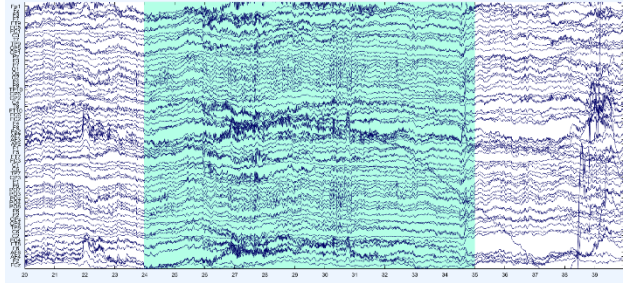
file is, and 2) write down consistently noisy channels (i.e., channels with high frequency noise throughout 50% or more of the recording; see example of channels with high frequency noise on the right) on your scratch pad for channel interpolation.

- This step is very important, because even though the goal is to be as standardized as possible in our identification of artifacts (see sections to come), we need to recalibrate to every EEG data scroll in the service of preserving the most task-evoked brain data. That is, leaving in ‘messy’ data at this step does not compromise overall data quality because this data will be further processed in an automated and standardized artifact identification and rejection process in a later step. Thus, if you have a particularly ‘messy’ data file, you may not be able to identify clearly where artifact starts and ends, and it is better to leave more data in than to remove it in this subjective artifact identification step. Whereas if you have a particularly ‘clean’ data file, identification of clear artifact will be easier to identify, and we can feel more confident in removing artifact during this step which will help improve accuracy during the subsequent ICA processing step (see Luck, 2014).

Relatedly, we follow different rules when identifying artifact that is occurring during task-evoked brain activity versus during non-task ‘breaks’. As noted above, we want to avoid excessive removal of artifact during task-related EEG because this current continuous EEG artifact rejection process is subjective, and we prefer to leave task-related data to get artifact-edited during a later, objective, automated processing step (once it is epoched).

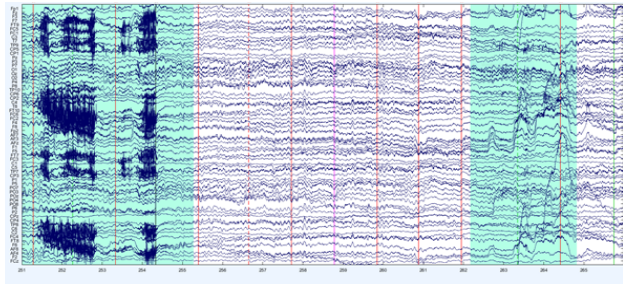
- **During task** (e.g., during the presentation of fixation crosses and face stimuli): we are more lenient to preserve as much task-related brain data as possible. However, if you see the following, you must flag and remove the following egregious artifact to improve the quality of the ICA (see Luck, 2014):

- Data with **more than 15** noisy channels (high frequency noise with faster-occurring peaks, which



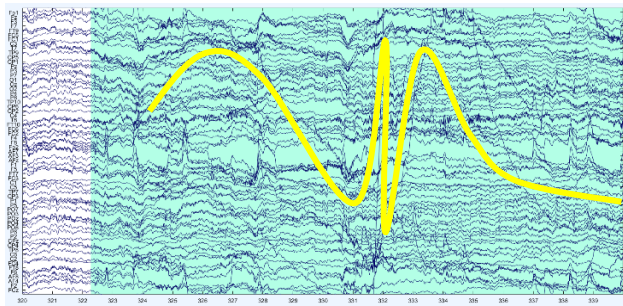
usually are visualized with darker data sections, see example on the right)

- ‘Dark’ data sections that obstruct many other channels (see example on the right)



- Note: these are often muscle tension created from jaw clenching)

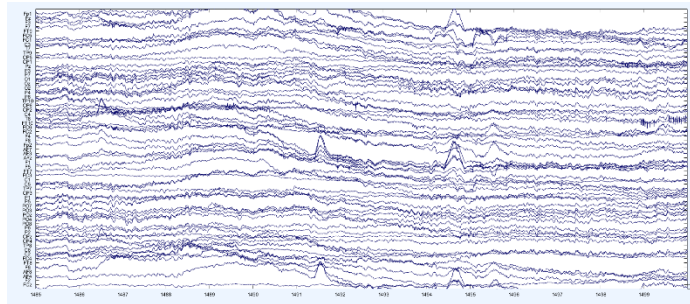
- Data with **5 or more** ‘wandering channels’ (channels that are not in line with their designated space in EEGLAB, see example yellow channel on the right)



- Note: From the example on the right, the yellow highlighted channel is ‘wandering’ because its oscillations are at a scale far beyond typical for brain-related voltage changes and it moves far outside the bounds of its allotted space in the EEG data scroll.
- If there’s one channel that is consistently wandering throughout more than 50% of the recording, first write it down on your scratch pad for channel

interpolation; then when you are counting wandering channels in a given segment of data you will not include this channel in your tally (because it will already get flagged for interpolation), and you need to find 5 or more *additional* wandering channels for the segment to qualify for artifact rejection.

- We also flag and remove everything when all channels are ‘drifting’. Channel drifting is a special

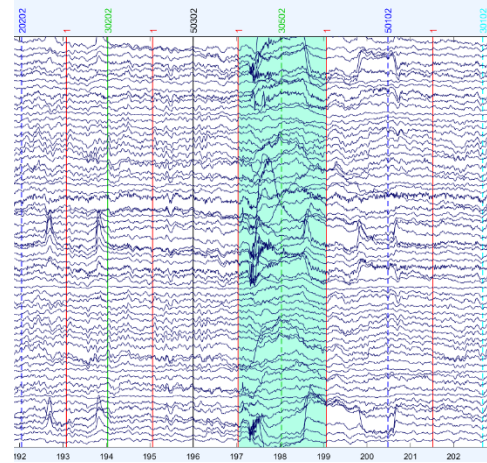


case where none of the three criteria described above really applies (i.e., data seemed to be not noisy, didn't have dark sections, and didn't have 5 or more wandering channels), but there seems to be a weird ‘trend’ that influenced every electrode (see example on the right).

- Note: Channel drifting can be due to sweat. It can also be residuals of a previously egregious artifact caused by large movements.
- ***General notes about continuous rejection during task:***
 - Do **NOT** remove any segments that fit the following:
 - Data with 4 or fewer noisy channels
 - If there were only 4 or fewer noisy channels, we can then interpolate them – so we can preserve more trials
 - Noise that lasts 0.5 second or less

- Short bursts of the noise are okay. Our processing steps later can help with this
- Frequent blinks or saccades
 - Blinks are preserved for Independent Component Analysis (ICA). We use ICA to correct for blinks, because it would be wasteful to remove all the EEG data in a segment containing blinks when there are now processes that can identify a blink ‘component’, remove that ‘component’ from the data, and preserve the rest of the brain data for analysis. We need blinks to be retained in the data in order for the ICA to be most accurate at identifying these blink ‘components’.
 - If you have to remove a blink because the data containing the blink is noisy/messy, remove the entire blink (do NOT cut the blink in half)
 - Saccades could be related to some underlying cognitive processes (e.g., people shift their gaze as directed by attentional processes), so we don’t want to take out the sections of brain data that contain gaze shifts at this stage, with this subjective process. If the saccades are causing artifact at levels that meet set thresholds for removal during later processing steps, they will get flagged then. Retain them here for now.

- If an identified segment of artifact ends right at the start of a trial, consider marking the end of the segment 0.5 seconds before the trial start event marker. We use a ‘pre-trial baseline’ in our calculation of ERPs, and so we



want to avoid removing pre-trial baselines as much as possible. In contrast, if the pre-trial baseline period is contaminated with egregious artifact, we remove the fixation and the stimulus trial all together rather than leaving a trial without a corresponding baseline (see example on the right: fixation period after marker 1 prior to 30502 is noisy, so we removed the trial of 30502).

- **During break** (e.g., when no fixations or faces are shown): we can be more aggressive in identifying and removing artifacts. Our removal of data here will not affect our eventual analysis of the task-related EEG because we will ‘epoch around’ (segment out) our task-related EEG for further preprocessing and analysis in later steps. So, there is not a risk of removing ‘good’ EEG data when artifact-editing during task breaks. There is however a risk of leaving in ‘bad’ or ‘noisy/messy’ EEG during these break sessions because it will affect the quality of our subsequent ICA, which is trying to identify individual ‘components’ in the

data that represent blinks so that these blink components can be removed. If you leave in ‘noise’, the ICA has a harder time finding the target ‘blink signal’.

- To remove non-task (break) EEG, start at the beginning of a ‘break’ event marker (e.g., 99). Click and highlight from the start of the break to 0.5

seconds prior

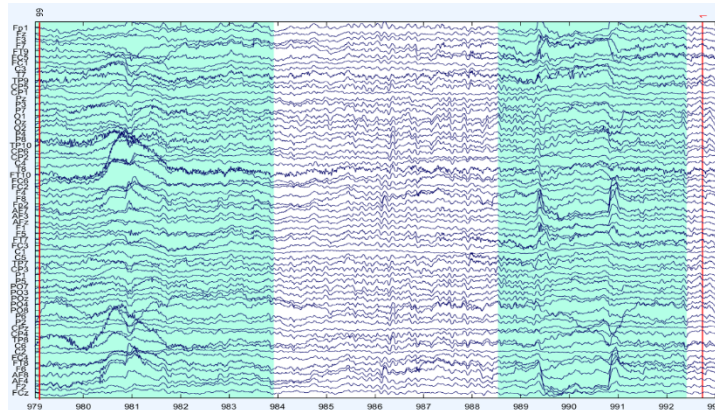
to the start of

the next task-

related marker

(e.g., 1). This

entire break



segment will then be removed.

- You can retain segments of data within a break only if they are perfectly ‘clean’ (i.e., no ‘dark spots’, 0 wandering or noisy channels, 0 drift; see example on the right). In this case, highlight all sections of the break ‘around’ the clean segment to retain just the clean segment (and remember to leave 0.5 seconds prior to the start of the next task-related trial marker). You may also leave in segments of data within a break if they contain blinks but are otherwise ‘clean’ (it will be helpful to have more ‘blink signals’ for the ICA to identify).

- ICA will also benefit from more data to process. So, in this egregious artifact rejection process, we walk a fine line of cutting

out noise (that could be mistakenly treated as an independent component) and leaving in good data (so there's more data to work with).

- Note that 'clean' segments in a break are rare because on breaks, participants tend to move around, stretch, do other activities etc. Thus, 'break' data is typically especially full of egregious artifact and should be removed unless is truly perfectly clean.

Appendix 2.VI

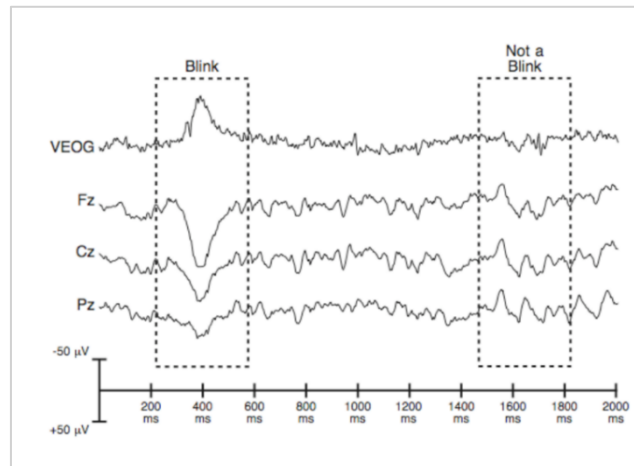
Independent Component Analysis (ICA) Blink Component Identification Protocol

(also published in Xia et al., 2024)

We followed the following steps and criteria to perform ICA and select blink components

(suggested by Luck, 2014):

- Perform ICA in EEGLAB using
binica function
- Recall that a blink consists of short
duration high amplitude peaks that
are either positive or negative going
(usually they are paired). They look
like the figure on the right in a raw

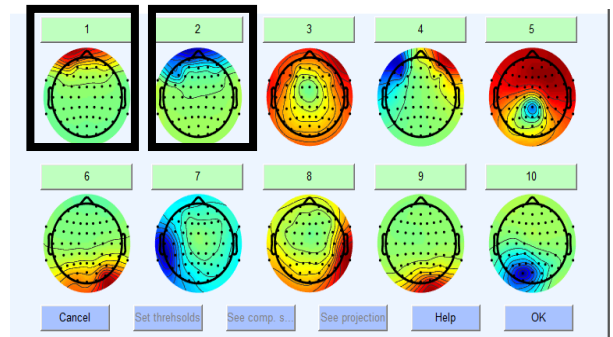


EEG recording: Blinks are generated by the eyes and therefore should be most visible in the electrodes around the eyes (i.e., frontal electrodes), and they occur in both eyes at the same time. Blinks can occur anytime, but they should be consistently distributed throughout an EEG recording session. We want to identify the Independent Component (IC) from the ICA that captures a blink, which means we need to look at the time course of an IC's activation (analogous to the time course of a blink's voltage deflection), and distribution of a given IC, to confirm it has these 'blink-like' characteristics. That is, the distribution should be maximally near the eyes, and the time course should show deflections that occur when blinks occur and have the same wave shape as the blinks.

- We use the plots generated in EEG lab to make this verification and identify only the ICs that reflect blink-like voltage changes for removal.

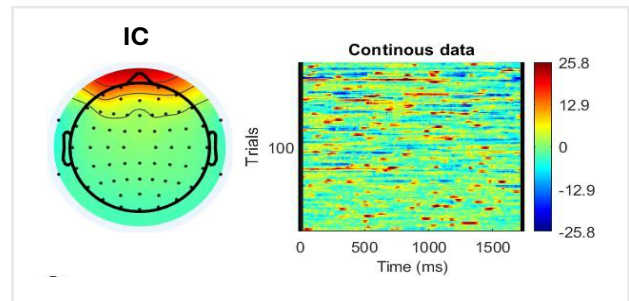
- Blink components should be present in the first 10 components plotted following binica
 - If no clear blink component is observable in the first 10 components plotted, return back to Continuous EEG Egregious Artifact Rejection protocol and further reject segments of data until ICA returns clear blink components in the first 10 components
- To identify potential blinks from topo map:

- Red or blue regions (representing peak positive or negative amplitude) should be centralized around frontal eye channels (Fp1, Fp2, AF3, AF4, AF7, AF8)



- Red/blue should span across left, center, and right frontal channels (not concentrated on one side—blinks occur in both left and right eyes)
 - Black boxes in figure on right show ‘potential blink components’ that would be considered for removal

- Click on a ‘potential blink component’ (that meets criteria specified above) to bring up additional information to



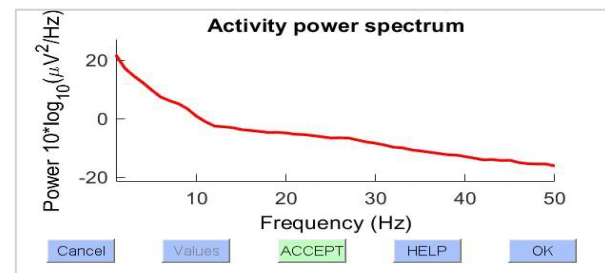
further evaluate it for removal. To be considered as a blink, the scalp map must show a strong far-frontal projection (as demonstrated by IC1 in the left panel of the figure on the right). Further, in the ‘Continuous Data’ plot to the right of the

scalp map that plots time across the x-axis, trial number in the y-axis and amplitude in the color bar, we should see short bursts of amplitude that are randomly but relatively evenly distributed across the entire plot. This distribution is likely associated with blinks which occur as short duration peaks, randomly but consistently throughout the EEG recording.

- Note: Use the color of the independent component in the scalp map to guide your evaluation of the Continuous Data plot. If the scalp map shows peak positive amplitude (red), you should be evaluating whether there are short bursts of red (positive) amplitude throughout the recording (this is exemplified in the figure with IC1 and Continuous Data plot above).

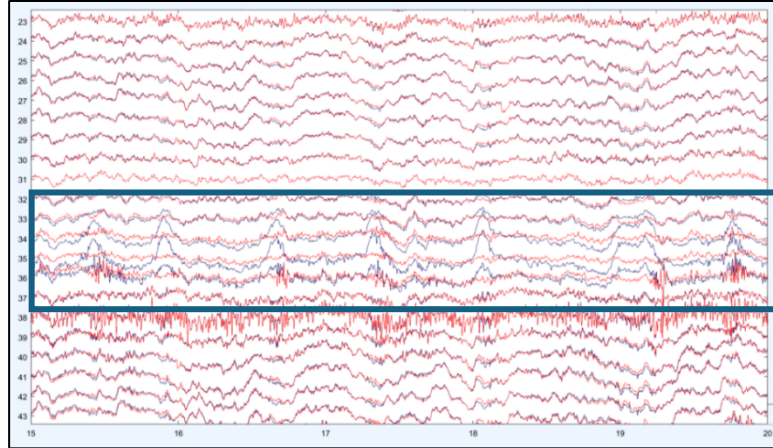
Whereas if the scalp map shows peak negative amplitude (blue), you should be

evaluating whether there are short bursts of blue (negative) amplitude throughout the recording.



- Activity power spectrum should show smooth, decreasing frequency spectrum with an early peak (see example in figure to the right)

- Once a blink component is identified and confirmed, reject this component and then inspect the continuous data before and after



rejection of this component (example shown on the right, inside blue box):

- Dark blue lines represent data before rejection
- Red lines represent data after rejection
- In segments where there are clear blinks, you should expect to see that these blinks are ‘flattened’ in red.

Appendix 2.VII

Linear Mixed Effect Data Preparation and Model Selection

Data preparation for LME analysis

To allow for use of LME analysis, individual trials in the ERP faces experiment were given unique event marker codes at time of collection (in line with specifications in Heise et al., 2022). Event markers corresponding to emotion condition and actor were inserted via the stimulus presentation software used, E-Prime version 3.0 (Psychology Software Tools, 2016). After data collection, markers were replaced with a 5- digit code representing emotion, actor, and presentation condition. This allows us to gain trial-level ERP data. We used an ‘exact match’ method to calculate the difference waves for the LME (in line with prior work: Heise, Mon, & Bowman, 2022; Xia et al., 2024). This involves pairing trials that matched on actor and presentation number. In instances of missing ERP data (e.g., one of the trials is removed during artifact rejection), that trial-level difference wave will not be included in further analyses.

LME Model Selection

As guided by recommendations made by Barr et al (2013) and consistent with prior work using LME with child ERP data (Xia et al., 2024; Heise et al., 2025), we aimed to include as many random effects as possible with the model still converging and without a singular fit. We would not want to have a singular fit because this would indicate overfitting of the model and would produce coefficients that are not interpretable.

We began with the maximal model, which was a 2-level random slopes and random intercepts model in which the outcome was children’s mean amplitude difference waves for N170 or Nc at the trial level; fixed effects were emotion difference condition (i.e., Angry-Neutral, Fear-Neutral, Happy-Neutral, Angry40-Neutral, Fear40-Neutral, Angry100-Angry40,

Fear100-Fear40) by ToM interaction, language covariate, executive functioning covariate, child age, child sex, and trial presentation number; a random intercept for subject; and random by-subject slopes for emotion difference condition and presentation number. We included language and executive functioning as covariates because these variables have been shown to be related to ToM in children both theoretically and empirically (Ahmed & Stephen Miller, 2011; Henry et al., 2013; Hughs & Ensor, 2007; Miller, 2006). Additionally, due to using the ‘exact match’ method for difference wave analysis, this accounted for actor and electrode channel, and thus we did not include them in our model (Heise, Mon, & Bowman, 2025). The effect of presentation number on our outcome could vary across different emotion conditions, so we included trial presentation number in our model. This maximal model failed to converge.

To determine the order of removal of random effects, we examined the intraclass correlation coefficient (ICC) of presentation number ($ICC = 0.003$) and emotion ($ICC = 0.0001$) (Brauer & Curtin, 2018). We first removed the random by-subject slopes for emotion due to emotion having a lower ICC. The second model had N170 or Nc mean amplitude difference waves at the trial level as the outcome; fixed effects were emotion difference condition by ToM interaction, language covariate, executive functioning covariate, child age, child sex, and trial presentation number; random effects were a random by-subject slopes for presentation number. This model also failed to converge.

In our next model, we eliminated the random by-subject slopes for presentation number and instead included a random by-subject slope for emotion. The third model consisted of the outcome as the N170 or Nc mean amplitude difference waves at the trial level; fixed effects were emotion difference condition by ToM interaction, language covariate, executive functioning

covariate, child age, child sex, and trial presentation number; random effects were a random by-subject slopes for emotion. This model also failed to converge.

In our final model, we removed the random by-subject slopes for presentation number and emotion and included a random intercept for subject. Our final model was a 2-level random slope and random intercept model in which the outcome was children's mean amplitude difference waves for N170 or Nc at the trial level; fixed effects were emotion difference condition by ToM interaction, language covariate, executive functioning covariate, child age, child sex, and trial presentation number; random intercept for subject. The LME assumptions of linearity and a normal distribution of residuals for the final model were confirmed based on visual inspection, and homogeneity of variance was confirmed with a Levene's test ($ps > 0.35$). A normal distribution of residuals was confirmed based on visual inspection because the number of samples in our final dataset exceeded 5000 (Royston, 1995).

Final Overall LME model:

Level 1 (within-subjects):

$$\text{MeanAmplitudeTrialDifferenceWaves}_{ij} = \beta_{0j} + \beta_{1j}\text{Emotion}_{ij} + \beta_{2j}\text{PresentationNumber}_{ij} + \epsilon_{ij}$$

Level 2 (between-subjects):

$$\beta_{0j} = \gamma_{00} + \gamma_{01}(\text{Emotion} * \text{ToM})_j + \gamma_{02}\text{ChildEF}_j + \gamma_{03}\text{Age}_j + \gamma_{04}\text{Language}_j + u_{0j}$$

$$\beta_{1j} = \gamma_{10} \text{ (coefficient of the fixed effect of Emotion)}$$

$$\beta_{2j} = \gamma_{20} \text{ (coefficient of the fixed effect of Presentation Number)}$$

i represents trial-level estimates

j represents subject-level estimates

γ_{00} represents grand-mean/intercept

γ_{01} represents coefficient of the interaction between Emotion and ToM

γ_{02} represents coefficient of the fixed effect of Child EF

γ_{03} represents coefficient of the fixed effect of Child Age

γ_{04} represents coefficient of the fixed effect of Child Language

u_{0j} represents Subject-level deviation from the mean (i.e., random intercept for Subject)

ϵ_{ij} represents error residuals where $\epsilon_j \sim N(0, \sigma^2)$

We separated out by emotion difference wave and created 7 different LME models for each emotion (e.g., angry100 – 40, fear100- 40, angry40-neutral, fear40-neutral, fear100-neutral, angry100-neutral, happy100-neutral). Each model was a 2-level random slope and random intercept model in which the outcome was children's mean amplitude difference waves for N170 or Nc at the trial level; fixed effects were ToM, language covariate, executive functioning covariate, child age, child sex, and trial presentation number; random intercept for subject. This process is repeated for all seven emotion difference wave conditions in separate models (e.g., angry100 – 40, fear100- 40, angry40-neutral, fear40-neutral, fear100-neutral, angry100-neutral, happy-neutral). For all focal analyses, we corrected for multiple comparisons using False Discovery Rate (FDR) and we report the adjusted p-values.

Final LME model per emotion condition:

Level 1 (within-subjects):

$$\text{MeanAmplitudeTrialDifferenceWaves}_{ij} = \beta_{0j} + \beta_{1j}\text{PresentationNumber}_{ij} + \beta_{2j}\text{PresentationNumber}_{ij} + \epsilon_{ij}$$

Level 2 (between-subjects):

$$\beta_{0j} = \gamma_{00} + \gamma_{01}(\text{residualized ToM})_j + \gamma_{02}\text{Age}_j + u_{0j}$$

$$\beta_{1j} = \gamma_{10} \text{ (coefficient of the fixed effect of Presentation Number)}$$

i represents trial-level estimates

j represents subject-level estimates

γ_{00} represents grand-mean/intercept

γ_{01} represents coefficient of the fixed effect of residualized ToM

γ_{02} represents coefficient of the fixed effect of Child Age

u_{0j} represents Subject-level deviation from the mean (i.e., random intercept for Subject)

ϵ_{ij} represents error residuals where $\epsilon_j \sim N(0, \sigma^2)$

Appendix 2.VIII

Preliminary Analyses

Table S2.VII.1. Preliminary analysis: bivariate Pearson correlations showing relation between N170 or Nc and behavioral variables

		<i>r</i>	<i>p</i>
Mean Amplitude Left N170	Age	0.21	0.08
Mean Amplitude Left N170	EF	0.28	.03*
Mean Amplitude Left N170	KBIT Language Matrices	0.18	0.15
Mean Amplitude Left N170	KBIT Language Verbal	0.19	0.11
Mean Amplitude Left N170	SERT	-0.13	0.27
Mean Amplitude Left N170	Sex	0.19	0.13
Mean Amplitude Left N170	ToM	0.15	0.23
Mean Amplitude Right N170	Age	0.20	0.10
Mean Amplitude Right N170	EF	0.06	0.65
Mean Amplitude Right N170	KBIT Language Matrices	0.09	0.45
Mean Amplitude Right N170	KBIT Language Verbal	0.16	0.19
Mean Amplitude Right N170	SERT	-0.09	0.48
Mean Amplitude Right N170	Sex	0.28	0.04*
Mean Amplitude Right N170	ToM	-0.06	0.64
Mean Amplitude Nc	Age	-0.16	0.19
Mean Amplitude Nc	EF	-0.19	0.11
Mean Amplitude Nc	KBIT Language Matrices	-0.20	0.10
Mean Amplitude Nc	KBIT Language Verbal	-0.30	0.02*
Mean Amplitude Nc	SERT	-0.04	0.72
Mean Amplitude Nc	Sex	-0.13	0.29
Mean Amplitude Nc	ToM	-0.23	0.06
Sex	EF	0.03	0.83

Sex	KBIT Language Matrices	0.11	0.38
Sex	KBIT Language Verbal	0.03	0.82
Sex	SERT	-0.08	0.51
Sex	ToM	0.22	0.04*
Age	EF	0.47	<.001*
Age	KBIT Language Matrices	0.68	<.001*
Age	KBIT Language Verbal	0.34	0.004*
Age	SERT	0.38	0.001*
Age	Sex	0.22	0.07
Age	ToM	0.49	<.001*
EF	KBIT Language Matrices	0.37	0.002*
EF	KBIT Language Verbal	0.39	<.001*
EF	SERT	0.36	0.002*
EF	ToM	0.46	<.001*
KBIT Language Matrices	SERT	0.34	0.004*
KBIT Language Matrices	ToM	0.49	<.001*
KBIT Language Verbal	KBIT Language Matrices	0.31	0.009*
KBIT Language Verbal	ToM	0.38	0.001*
KBIT Language Verbal	SERT	0.23	0.06

Appendix 2.IX

Preliminary Analyses: N170 and Nc responses to emotional and neutral faces

To characterize the ERP responses elicited by the face stimuli and to determine whether our sample demonstrated the expected modulation of ERP amplitudes by facial emotion, we conducted a series of preliminary analyses comparing responses across emotion conditions using raw (non-difference wave) ERP amplitudes. These analyses were intended to provide context for the primary research questions examining associations between ERP responses and children's theory of mind, and were not designed to test our primary hypotheses.

Nc

There was a significant main effect of emotion on Nc mean amplitude, $\beta = 12.79$, $SE = 0.21$, $p < .0001$. Pairwise comparison statistics are listed in the table below, and waveforms are plotted in figures. In general, results revealed larger Nc amplitude for emotional faces (i.e., angry, fearful), compared to neutral, as well as differences in Nc amplitude among emotion conditions (e.g., Nc amplitude to angry faces were larger than happy faces and both reduced-intensity fear and angry conditions). Additionally, full-intensity fearful faces elicited larger Nc amplitudes than happy faces and both reduced-intensity emotion conditions. When emotional expressions were grouped by valence, negative faces (average of full-intensity angry and fearful) elicited significantly larger Nc amplitudes than positive (happy) faces.

Pairwise Contrast	β	SE	p
Nc Happy100-Neutral	0.03	0.18	.99
Nc Angry100-Neutral	-1.2	0.21	< .0001*
Nc Fear100-Neutral	-0.79	0.21	.0007*
Nc Fear40-Neutral	-0.04	0.21	.99
Nc Angry40-Neutral	-0.06	0.21	.99
Nc Angry100-Happy100	-1.24	0.2	< .0001*
Nc Angry100-Fear40	-1.17	0.21	< .0001*
Nc Angry100-Angry40	-1.14	0.21	< .0001*

Nc Angry100-Fear100	-0.41	0.28	.34
Nc Fear100-Happy100	-0.82	0.2	.0009*
Nc Fear100-Fear40	-0.75	0.21	.004*
Nc Fear100-Angry40	-0.73	0.21	.006*
Nc Happy100-Fear40	0.07	0.29	.99
Nc Happy100-Angry40	0.09	0.3	.99
Nc Fear40-Angry40	0.02	0.29	.99
Nc Negative-Positive	-1.13	0.34	<.0001*

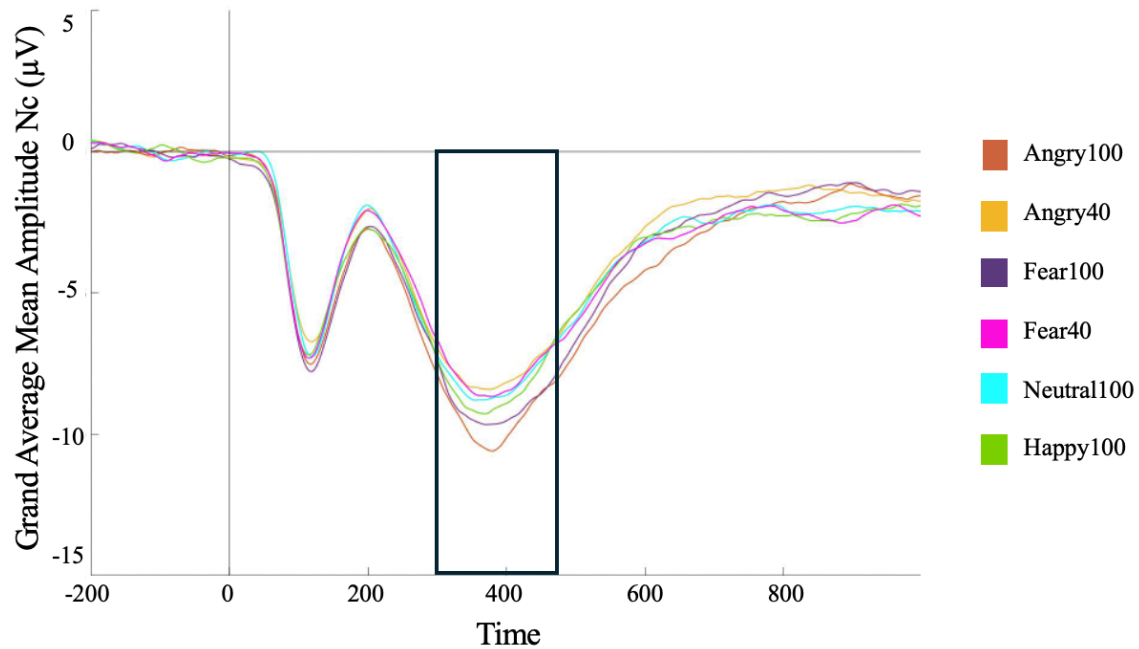


Figure S2.VII.1. Grand-average Nc ERP waveforms for all participants by facial emotion condition. Full-intensity angry and full-intensity fearful faces elicited the largest (i.e., most negative) Nc mean amplitudes, consistent with previous findings that larger Nc amplitudes reflect greater attentional allocation.

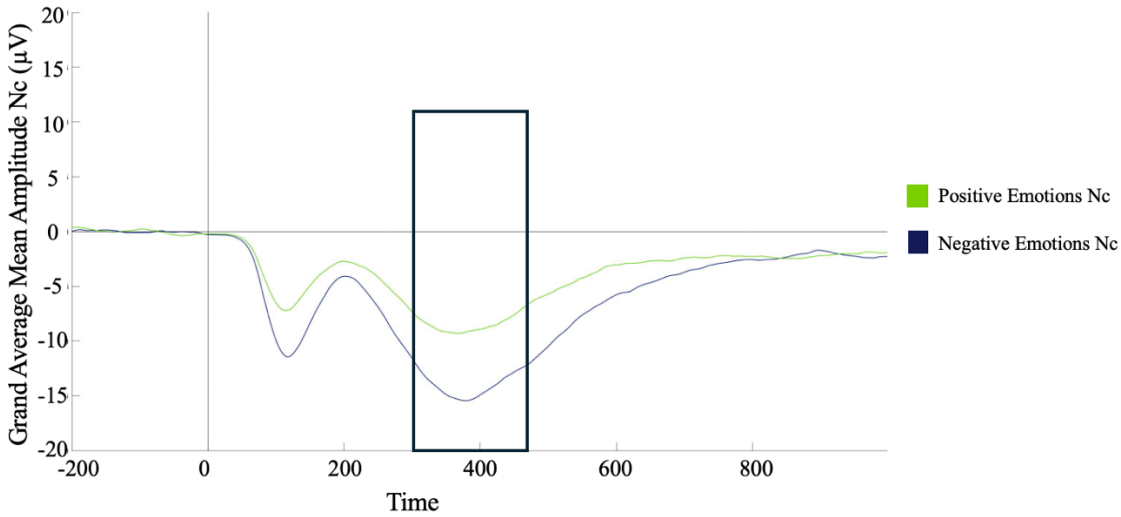


Figure S2.VII.2. Grand-average Nc ERP waveforms for all participants comparing positive (happy) and negative (full-intensity angry and full-intensity fearful) facial emotion conditions. Negative facial emotions elicited larger (i.e., more negative) Nc amplitudes than positive facial emotions, a pattern consistent with greater attentional resources being allocated to negative faces.

N170

Previous research has suggested that smaller (i.e., less negative) N170 amplitudes reflects greater neural specialization for face processing (Bentin et al., 1996; Sadeh & Yovel, 2010; Xia et al., 2024). To examine whether N170 responses differed across facial emotion conditions, we conducted a linear mixed-effects analysis of N170 mean amplitude. There was a significant main effect of emotion on N170 mean amplitude, $\beta = 33.07$, $SE = 0.40$, $p < .001$. Pairwise comparison statistics are listed in the table below, and waveforms are plotted in figures. In general, results revealed smaller N170 mean amplitude for emotional faces (i.e. angry, happy, reduced-intensity angry) compared to neutral, as well as differences in N170 amplitude among emotion conditions (e.g., N170 amplitude to angry faces were smaller compared to N170 amplitudes to full-intensity fearful, reduced-intensity fearful, and happy faces). Full-intensity fearful and happy faces elicited

smaller N170 amplitudes than reduced-intensity fearful faces. When emotional expressions were grouped by valence, negative faces (average of full-intensity angry and fearful) elicited significantly smaller N170 amplitudes than positive (happy) faces.

Pairwise Contrast	β	SE	p
N170 Happy100-Neutral	0.8	0.22	.002*
N170 Angry100-Neutral	1.61	0.22	< .0001*
N170 Fear100-Neutral	0.47	0.29	.13
N170 Fear40-Neutral	-0.8	0.28	.28
N170 Angry40-Neutral	1.47	0.22	< .0001*
N170 Angry100-Happy100	0.82	0.21	.002*
N170 Angry100-Fear40	2.37	0.23	< .0001*
N170 Angry100-Angry40	0.15	0.31	.98
N170 Angry100-Fear100	1.14	0.21	< .0001*
N170 Fear100-Happy100	0.32	0.28	.68
N170 Fear100-Fear40	1.23	0.22	< .0001*
N170 Fear100-Angry40	-0.99	0.41	.34
N170 Happy100-Fear40	1.56	0.22	< .0001*
N170 Happy100-Angry40	-0.67	0.32	.26
N170 Angry40-Fear40	2.22	0.22	< .0001*
N170 Negative-Positive	1.23	0.52	.01*

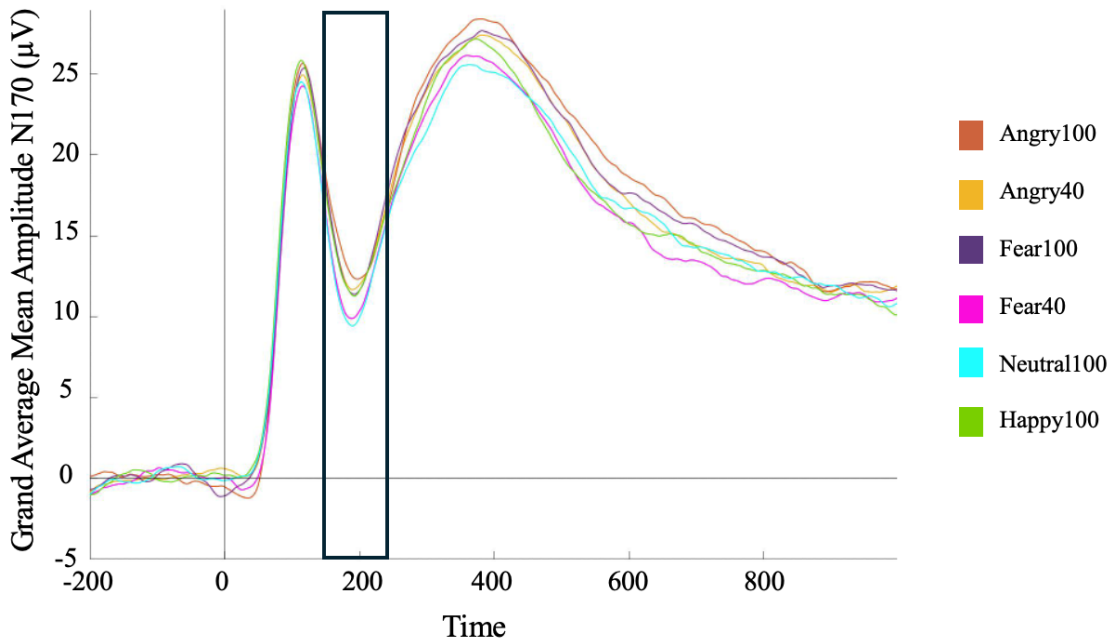


Figure S2.VII.3. Grand-average N170 ERP waveforms for all participants by facial emotion condition. Full-intensity angry faces elicited the smallest (i.e., least negative) N170 mean amplitudes, whereas neutral faces elicited the largest (i.e., most negative) N170 mean amplitudes. Previous research has suggested that reduced N170 amplitudes reflect greater neural specialization for face processing.

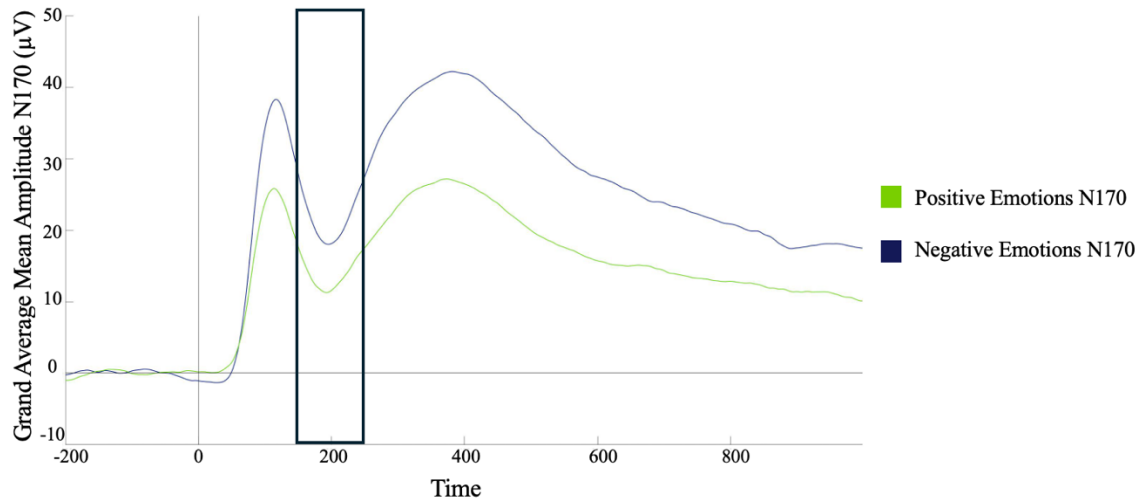


Figure S2.VII.4. Grand-average N170 ERP waveforms for all participants comparing positive (happy) and negative (full-intensity angry and full-intensity fearful) facial emotion conditions. Negative facial emotions elicited smaller (i.e., less negative) N170 amplitudes than positive facial emotions, consistent with greater neural specialization for emotionally salient faces.

Appendix X

Relation between ToM or SERT and N170/Nc

The following three tables report on the relations between ERP mean amplitude for N170 and Nc during the ERP emotional faces task and ToM behavioral performance (both on the ToM composite scale and SERT measure). This can show how the neural correlates of emotional face perception relate to behavioral ToM. We first created four larger LME models with ERP-behavior pairings as follows: N170–ToM composite, Nc–ToM composite, N170–SERT, and Nc–SERT. This was repeated for both behavioral ToM scales (ToM composite Wellman & Liu, 2004 and SERT) and for both ERP components (N170 and Nc) resulting in 4 total models. The reported values are the interaction between each emotion condition and ToM behavioral measure (see figure S2.VIII.1.).

Table S2.VIII.1. Estimated interaction effects between emotion condition and behavioral Theory of Mind (ToM) measures from four linear mixed-effects models for both ERP components (N170 and Nc). Values reflect fixed-effect interaction estimates for each emotion condition with either the ToM composite (Wellman & Liu, 2004) or SERT.

ToM Measure	ERP Component	Emotion Condition Interaction with ToM or SERT	β	SE	p
ToM Composite	N170	Fear100-Neutral*ToM	0.66	0.2	.75
		Happy100-Neutral*ToM	-0.03	0.21	.9
		Angry40-Neutral*ToM	-0.17	0.21	.43
		Fear40-Neutral*ToM	0.4	0.21	.06
		Angry100-40*ToM	-0.36	0.2	.09
		Fear100-40*ToM	-0.08	0.4	.69
		Fear100-Neutral*ToM	-26	0.2	.2

SERT	Nc	Happy100-Neutral*ToM	-0.14	0.3	.5
		Angry40-Neutral*ToM	-0.46	0.2	.02*
		Fear40-Neutral*ToM	0.07	0.2	.75
		Angry100-40*ToM	0.27	0.27	.17
		Fear100-40*ToM	-0.007	0.2	.97
	N170	Fear100-Neutral*SERT	0.22	0.34	.52
		Happy100-Neutral* SERT	0.45	0.33	.89
		Angry40-Neutral* SERT	-0.16	0.33	.63
		Fear40-Neutral* SERT	0.41	0.34	.22
		Angry100-40* SERT	-0.61	0.34	.07
		Fear100-40* SERT	-0.49	0.33	.14
	Nc	Fear100-Neutral* SERT	-0.2	0.32	.53
		Happy100-Neutral* SERT	-0.32	0.32	.32
		Angry40-Neutral* SERT	-0.4	0.32	.21
		Fear40-Neutral* SERT	-0.38	0.33	.24
		Angry100-40* SERT	0.33	0.32	.3
		Fear100-40* SERT	0.12	0.36	.7

We then created separate models estimated for each emotion condition (e.g., angry40-neutral, fear40-neutral, fear100-neutral, angry100-neutral, happy100-neutral, angry100-angry40, fear100-fear40, neutral condition) and each ERP–behavior pairing (N170–ToM composite, Nc–ToM composite, N170–SERT, and Nc–SERT), resulting in a total of eight models for each ERP component (N170 and Nc). There is one table showing the relations between N170 and Nc to ToM composite scale (mental state reasoning) (Table S2.VIII.2.) and another table showing the relations between N170 and Nc to SERT (mental state decoding) (Table S2.VIII.3.).

Table S2.VIII.2. Separate models showing relation between N170 or Nc and mental state reasoning (ToM)

ERP Component	Emotion Condition	β	SE	p	FDR- p
N170	Fear100-Neutral	0.25	0.52	0.63	.79
N170	Happy100-Neutral	0.37	0.43	0.39	.98
N170	Angry100-Neutral	0.09	0.52	0.85	.85
N170	Angry40-Neutral	0.7	0.45	0.12	.84
N170	Fear40-Neutral	-0.31	0.46	0.5	.83
N170	Angry100-40	-0.18	0.48	0.72	.97
N170	Fear100-40	0.05	0.49	0.99	.99
N170	Neutral	-0.66	0.37	0.18	.72
Nc	Fear100-Neutral	-0.71	0.21	0.001	.002*
Nc	Happy100-Neutral	-0.32	0.23	0.18	.42
Nc	Angry100-Neutral	-0.27	0.2	0.19	.33
Nc	Angry40-Neutral	-0.81	0.21	0.0002	.001*
Nc	Fear40-Neutral	-0.09	0.21	0.66	.77
Nc	Angry100-40	0.11	0.22	0.62	.87
Nc	Fear100-40	-0.06	0.24	0.8	.8
Nc	Neutral	.026	0.2	0.2	.32

Table S2.VIII.3. Separate models showing relation between N170 or Nc and mental state decoding (SERT)

ERP Component	Emotion Condition	β	SE	p	FDR- p
N170	Fear100-Neutral	0.22	0.8	0.78	.91
N170	Happy100-Neutral	0.28	0.6	0.64	.99
N170	Angry100-Neutral	-0.05	0.71	0.95	.95
N170	Angry40-Neutral	0.03	0.07	0.69	.97

N170	Fear40-Neutral	0.28	0.6	0.64	.92
N170	Angry100-40	-0.82	0.68	0.23	.81
N170	Fear100-40	-0.12	0.64	0.06	.42
N170	Neutral	-1.4	0.71	0.05	.4
Nc	Fear100-Neutral	-0.12	0.33	0.73	.85
Nc	Happy100-Neutral	-0.4	0.3	0.31	.54
Nc	Angry100-Neutral	0.05	0.28	0.87	.87
Nc	Angry40-Neutral	-0.35	0.32	0.28	.65
Nc	Fear40-Neutral	-0.49	0.3	0.11	.77
Nc	Angry100-40	0.4	0.29	0.18	.63
Nc	Fear100-40	0.16	0.36	0.67	.94
Nc	Neutral	0.2	0.29	0.48	.77

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Chapter 3: What supports preschoolers' prosocial development? A combination of Theory of Mind skills and how the brain responds to emotional faces.

Abstract

What supports the development of preschoolers prosociality? Theory and research highlight the role of social-cognitive skills such as Theory of Mind (ToM) in supporting children's helping, sharing, and comforting behaviors. However, better ToM does not consistently predict greater prosociality and, in some cases predicts increased antisocial or aggressive behavior. Additional factors must therefore be present to help explain the relation between social-cognitive skills and real-world prosocial tendencies. The present study investigates the role of a particularly relevant perceptual process— emotional face perception—given it provides cues that can inform both mental-state inferencing and appropriate prosocial action. We test the hypothesis that preschoolers' prosocial tendencies are predicted by a combination of their behavioral ToM skills and how their brains respond to emotional faces. We examined typically developing 3- to 5-year-old children's (N = 92) event-related potentials (ERPs; specifically, N170, Nc, and P1) to pictures of emotional faces. In a moderation model, we tested whether preschoolers' mean ERP amplitudes interacted with their behavioral ToM skills (assessed with a modified Wellman & Liu, 2004 scale) to predict their prosocial tendencies (assessed with the Parent Rating of Prosocial Behavior). We found that better ToM predicted higher prosocial ratings *only* for children with enhanced P1 amplitudes to emotional faces. For children with reduced P1 amplitudes, there was a negative trend of better ToM predicting lower prosocial ratings. Findings suggest that how the brain has tuned to automatically and vigilantly attend to faces is a key factor linking children's ToM skills with their real-world prosocial activities.

Introduction

What supports the development of prosociality (helping, sharing, comforting)? Prosocial behaviors emerge early in life and play a central role in children's social adjustment, peer relationships, school achievement, and personal well-being (Dunn & Cutting, 1999; Eisenberg et al., 2015). Starting in toddlerhood, children begin to respond to others' needs (Brazzelli, Pepe, & Grazzani, 2022), yet there is substantial variability in how frequently and effectively they do so. Therefore, it is vital to understand the processes that give rise to individual differences in prosociality. Broadly, prosocial action requires that children recognize when someone is in need, interpret the meaning of that need, and generate an appropriate response. These abilities draw on multiple interacting systems, including children's emerging social-cognitive skills and their sensitivity to others' perceptual and emotional cues.

Theory and empirical research point to the importance of a particular social-cognitive skill in the development of prosociality: Theory of Mind (ToM), defined as the ability to attribute mental states, including beliefs, intentions, and desires, to oneself and others, as well as to understand that these mental states may differ from one's own (Rakoczy, 2022). Early theoretical accounts propose that these social perspective-taking abilities promote empathic concern and prosocial responding (Hoffman, 2000). ToM is also considered to be a necessary cognitive basis to elicit prosocial behavior because it requires an understanding of the psychological states of others (Qiu et al, 2024). To initiate a prosocial action, a child must first recognize when someone is in need to determine how to best help. This engagement in prosocial behavior is therefore dependent on the understanding of others' mental states (having an accurate ToM). Existing theoretical perspectives posit that children who have a better ability to understand their own and others' internal states are more equipped to interpret the cause of others' distress and therefore

more motivated to engage in prosocial actions (Eggum et al., 2011). Empirically, ToM has been linked to prosocial behavior starting in early childhood, such that a better, more advanced ToM is positively correlated with more prosocial behavior (Cassidy et al., 2003; Eggum et al., 2011; Gross et al., 2015; Wu and Su, 2014). Additionally, individual differences in false-belief understanding and mental-state reasoning have been associated with greater helping, sharing, and comforting in early childhood (Over & Carpenter, 2009; Paulus, 2014). A recent large meta-analysis in 2-to-19-years-old found that there was a significant positive correlation between prosocial behavior and ToM (Qiu, et al., 2024). Thus, ToM has been shown to support prosocial behavior by supporting children's interpretation of others' mental states, which ultimately can lead to helping, comforting or sharing behaviors.

However, empirical relations between ToM and prosocial behaviors are not straightforward. The meta-analysis of 24 studies reported a small positive correlation between ToM and prosocial behavior ($r = .24$), suggesting that ToM is associated with only a modest amount of variance in prosocial behavior (Qiu, et al., 2024). Additionally, because the studies analyzed spanned a broad age range from early childhood to adolescence, the observed positive association between ToM and prosocial behavior may capture general maturation in social cognitive capacities across age groups rather than indicating that ToM is a primary driver of prosocial behavior. Indeed, individual studies show that better ToM does not always predict increased prosociality (Imuta, et al., 2016) and sometimes predicts antisocial or aggressive behaviors (O'Toole et al., 2017). Taken together, empirical evidence suggests that ToM does not on its own represent a complete foundation for development of prosocial behavior.

One possibility is that these conflicting and inconsistent findings point to additional factors that facilitate and influence a link between children's social-cognitive skills (i.e., ToM)

and their real-world prosocial behavior. In particular, *perceptual processes* are theorized as a central contributor to prosociality, given they support extraction of relevant personal information (e.g. facial expressions, body posture), which inform decision-making in prosocial behaviors (Paulus, 2014). Critically, comprehensive models of prosocial development implicate perceptual and motivational processes that operate alongside ToM to influence how social information is detected and acted upon (e.g., Paulus, 2014; Vaish & Hepach, 2020). These comprehensive models highlight that prosocial responding is not likely to be driven by any single system in isolation; rather, it is posited to reflect the dynamic interplay between children's broader social-cognitive ToM skills as well as the perception of others' personal cues that interact with and inform social-cognitive processing to motivate prosocial actions.

One such factor that may play both perceptual and motivational roles in supporting prosocial behavior is emotional face perception. Children who more rapidly or efficiently attend to and perceive emotional facial expressions may be better able to detect cues of others' distress or need, thereby providing the social input necessary for perspective-taking abilities to guide behavior. Facial expressions can elicit motivational behavior, either as it relates to approach or avoidance (Radke et al., 2015; Schultheiss et al., 2005). In adults, attention to emotional facial expression that allow one to perceive others' distress cues can motivate empathic concern and promote helping and comforting behaviors (Eisenberg et al., 2006; Marsh, Kozak, & Ambady, 2007). Empirically, researchers have found that children's better emotion understanding was positively related to children's prosocial behaviors concurrently (Denham et al., 2014; Ensor & Hughes, 2005) and longitudinally such that children's better performance on emotion-understanding tasks at age 2 predicted later helping and sharing behaviors at age 4 (Ensor et al., 2011; see also Spinrad & Eisenberg, 2010). Also, in adults, increased sensitivity to fearful facial

expressions predicted their increased prosocial behavior (Marsh, Kozak, & Ambady, 2007).

Therefore, existing research demonstrates positive links between abilities to perceive emotional expressions and prosocial behaviors.

Critically, perception of emotional faces fits well within the broader complex model of factors supporting prosocial development, in particular in relating to social-cognitive and perspective-taking abilities. For example, attention to and efficient decoding of emotional facial expressions represent key perceptual processes that provide the social input upon which ToM operates (Haynes & Rees, 2006). Theoretically, accurately perceiving and discriminating emotional expressions provides critical information to help infer mental states and predict future action, thus supporting decisions to help, comfort or share (Adolphs, 2002; Eggum et al., 2010). Empirically, research has found that preschoolers who allocate more attentional resources to emotional faces also showed better behavioral ToM (Pestana et al., Under Review). Notably, perceiving emotional facial cues alone may not lead to prosocially responsive behavior unless those cues are interpreted within a broader understanding of others' mental states. Thus, individual differences in emotional face perception, particularly the degree to which children attend to emotional expressions, may *interact* with individual differences in ToM abilities to predict prosocial behavior. When these processes function together—both accurately inferring underlying mental states as well as attending to and decoding others' emotional cues—they may collectively influence helping, sharing and comforting prosocial behaviors.

The present study provides the first direct test of the possibility that individual differences in children's prosocial development are the product of an interaction between children's emotional face perception and their ToM. Specifically, we test the central hypothesis that individual differences in how the brain specializes or 'tunes' to perceive and process

emotional facial expressions interacts with children's emerging behavioral ToM skills to support individual differences in their prosocial tendencies.

Existing behavioral and neuroscientific research supports our hypothesis. For example, the neural system supporting face processing develops as early as 6-7 months of age (Johnson et al., 1991; Kestenbaum & Nelson, 1990; Leppänen & Nelson, 2012) and undergoes substantial tuning and specialization across infancy and childhood, becoming increasingly sensitive to socially relevant facial cues (Leppänen & Nelson, 2009; Scott & Monesson, 2010). Importantly, this system also shows meaningful individual differences in children's attention to and perception of differences in emotional faces, which can be shaped by children's social experiences (e.g., parents' emotionality, maternal anxiety, etc.) (Xia et al., 2024; Bowman et al., 2022). Most relevant, these individual differences in the attention-related neural correlates of emotional face perception to differing emotional expressions can directly relate to social cognition, including ToM (Pestana et al., Under Review). Given that neural systems involved in processing emotional facial expressions are specialized to rapidly detect and prioritize socially relevant cues, individual differences in how these systems have tuned over early childhood may interact with children's ToM to influence prosocial responding. Specifically, mental-state reasoning may be most strongly associated with increased prosocial behaviors among children who have a neural system that is especially sensitive and perceptually attuned to others' emotional facial cues.

To empirically examine this possibility and to capture individual differences in face- and emotion-perception process at the neural level, the present study uses Event Related Potentials (ERP) to examine children's neural responses during emotional face perception. ERPs offer a sensitive measure of individual differences in the extent to which neural systems are tuned to

process emotional facial expressions. Specifically, there are existing ERP components (N170, Nc, and P1) that have specific functions tied to emotional face perception and attention to faces. The N170 has been linked to expertise and familiarity with faces (de Haan et al., 2002; Halit et al., 2003). A reduced N170 amplitude has been considered to reflect more neurospecialization for face processing (Halit et al., 2003; de Haan et al., 2002; Xia et al., 2024). The Nc is related to increased allocation of attention to emotional faces (Carver et al., 2003; de Haan et al., 2004). A larger Nc amplitude indicates more attention to facial processing (Dennis, Malone, & Chen, 2009; Taylor-Colls & Fearon, 2015). The P1 is related to initial allocation of attention to facial expressions (Batty & Taylor, 2006; Taylor et al., 2001; Taylor et al., 2004). The P1 has been used to assess early and automatic stages of attentional processing and has been linked to vigilance (Gupta et al., 2019; Luna et al., 2023). A larger P1 indicates more initial attentional orienting. The present study will examine these three ERP components as indices of emotional face perception. Building on the conceptual framework outlined above, we test whether individual differences in how the brain has tuned to perceive emotional faces may moderate the association between children's behavioral ToM abilities and their prosocial tendencies. Specifically, we hypothesize that a child with an especially sensitive face-processing neural system may be better equipped to assess others' emotions and interpret their internal mental states to support prosocial actions.

In the present study, we collected ERP data during an emotional faces task, in which children passively viewed photos of emotional faces. We additionally collected behavioral data on children's ToM performance (Wellman & Liu, 2004 composite scale) and parent-reported questionnaire data on children's engagement in prosocial behaviors, including helping, sharing, comforting, and cooperation (Laible et al., 2017). We also included children's language ability

and executive functioning, given their empirical and theoretical implications in ToM (Henry et al., 2013; Hughs & Ensor, 2007; Miller, 2006), to use as covariates in our statistical models to better target individual differences in ToM specifically. Taken together, the results of this study will shed light on inconsistencies in relations between ToM and prosocial behavior, highlight the role of face and emotion perception in prosocial activities, and overall advance our understanding of the foundations of prosocial development.

Methods

Participants

A total of 162 typically developing 3-to-5-year-old children participated in this study (82 girls, 80 boys, $Mage = 4.5$ years, $SD = 0.86$). Children were recruited from a research database and were compensated for the one-time visit with small toys and a monetary gift card. All children were right-handed and had no history of neurodevelopmental disorders. Seventy children were excluded from ERP analyses for the following reasons: timing error in stimuli presentation ($n = 4$), technical error ($n = 2$), sibling participated prior ($n = 1$), child was later diagnosed with Autism Spectrum Disability ($n = 1$), refusal to wear EEG cap ($n = 9$), child did not complete executive functioning data ($n = 3$), child did not complete language data (KBIT) ($n = 16$), parent did not complete prosociality questionnaire for child (PRPB) ($n = 7$), and child's ERP data was excessively noisy as objectively quantified with aSME (Luck et al., 2021) ($n = 27$). Thus, 92 participants were included in analyses (49 girls, 43 boys, $Mage = 4.58$ years, $SD = 0.76$). An a priori power analysis was conducted using G*Power 3.1 to determine the sample size needed to detect the hypothesized interaction effect in the focal moderation analyses. Assuming a small-to-moderate effect size ($f^2 = 0.16$), $\alpha = .05$, and 80% power, the analysis indicated that a minimum sample of $N = 92$ participants was required.

Participants' demographics reflected those of the community from which they were drawn (Sacramento, California Region). The largest percentage of children's parent-reported race/ethnicity was White Not-Hispanic/Latinx (51%), with the remainder being multi-racial, Asian/Pacific Islander, African American, and Hispanic/Latinx (see Supplemental Appendix 3.I for additional demographic details). Median household income was \$100K or greater (range: \$5K-\$100k+). The median highest educational attainment for either parent was a master's degree (range: high school to Ph.D, J.D., or M.D).

The Institutional Review Board approved all methods used in this study. Parents gave informed consent and children provided assent.

Measures

All behavioral measures were well-established and previously used in research with preschool children. Below, we provide brief descriptions of each measure, with further details available in Supplementary Appendix 3.II.

Parent Rating of Prosocial Behavior (PRPB) (Laible et al., 2017)

To assess prosocial behavior, parents completed Laible's Parent Rating of Prosocial Behavior questionnaire (Laible et al., 2017) evaluating their child's engagement across multiple domains of prosocial behavior. Questionnaire items included the essential aspects of the four central prosocial domains: (a) Helping (e.g. my child cleans up surroundings), (b) Sharing (e.g. my child shares his/her toys or play), (c) Comforting (e.g. my child says something to comfort an unhappy child or adult) and (d) Cooperation (e.g., cooperates with you or another child). There were 19 items; all items were rated on a seven-point Likert-scale ranging from never to always (see Supplemental Appendix 3.II for questionnaire details). Although the measure comprises four subscales, for the final analyses we summed responses across all 19 items to create a total

prosocial behavior score. For final analyses, the Likert scale was recoded to a numerical scale, which ranged from 1 = never to 7 = always (max score = 133, higher scores = more prosocial behavior). The 19-item PRPB measure demonstrated good internal consistency in the current sample ($\alpha = .89$).

Theory of Mind Composite – (Wellman & Liu, 2004)

A composite of ToM tasks tested children's reasoning of others' mental states, actions and desires. Six of the vignettes were taken from the Wellman and Liu (2004) ToM scale, including diverse desires, diverse beliefs, knowledge access, contents false belief, explicit false belief, belief emotion. We also included two additional false-belief tasks to create this ToM composite scale (Wimmer & Perner, 1983) (max score: 8; higher scores = more mental state reasoning). All tasks had warm-up and control questions, which children had to answer correctly to pass the task (additional details can be found in Chapter 2, Methods).

Covariate measures

Kaufman Brief Intelligence Test (Kbit) – Verbal and Nonverbal Intelligence

As a measure of verbal and nonverbal intelligence, we administered the verbal and matrices tasks from the Kaufman Brief Intelligence Test (KBIT) (Kaufman & Kaufman, 1990). Children were asked to choose an image from a grid that either matched the meaning of a target word (verbal task) or correctly completed a pattern (matrices task) (higher scores = greater verbal intelligence). The task was concluded once children received a score of 0 for 4 consecutive trials or if they reached the end of the 60 prompts. A composite was created by standardizing scores from each task and averaging them to form a single measure of overall verbal and nonverbal intelligence.

Executive Functioning Composite

We additionally created an EF composite scale consisting of two tasks: the Dimensional Change Card Sort (DCCS) and Forward Digit Span (Wechsler, 1974; Zelazo, 2006). In the DCCS task, children were first asked to sort cards depicting red boats, blue boats, red rabbits, and blue rabbits according to shape across five trials. On each trial, the experimenter restated the sorting rule, labeled the test card by its color, and then asked the child to sort. Children who correctly sorted five consecutive cards by shape (e.g., rabbits placed with rabbits, boats with boats) proceeded to the post-switch phase. In this phase, children were required to sort the same cards by color (e.g., red cards placed in the red tray, blue cards in the blue tray), requiring them to shift from the initial rule. In the forward digit span task, children are asked to recall and repeat aloud sequences of up to eight digits, with two trials administered for each sequence length (max score = 16). A single EF composite measure was created as an average of the standardized proportion scores for both tasks (DCCS and forward digit span were correlated, $r(88) = .33$, $p = .002$) (higher scores = greater EF ability).

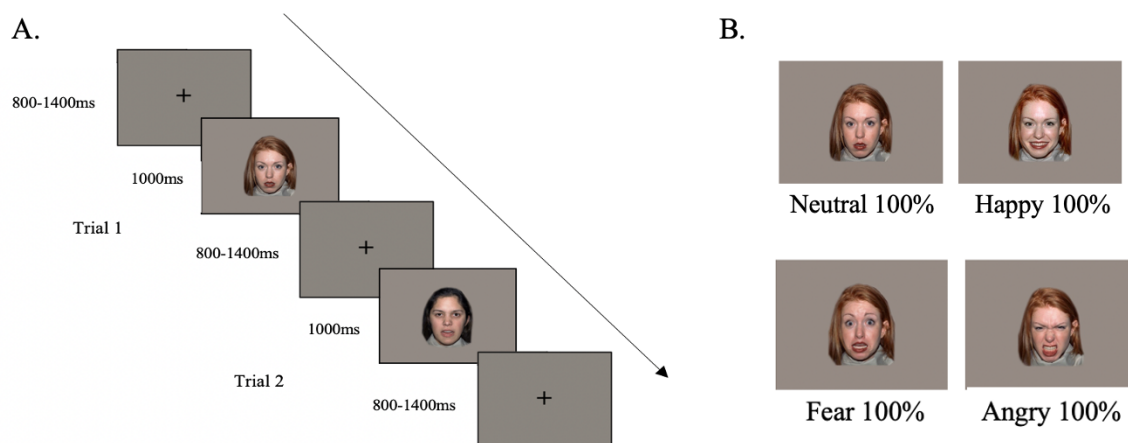
ERP Facial Emotion Perception Task

The ERP facial emotion task has been previously used to study N170, Nc, and P1 amplitude in children (Bowman et al., 2022; Xia et al., 2024; Xie et al., 2019). During the task, preschoolers passively viewed emotional faces in six categories: full intensity happy, angry, and fearful faces; reduced intensity angry and fearful faces; and neutral faces (50 trials of each emotion category; 300 trials total) (see Supplemental Appendix 3.III for full details of task). Although ERP data were collected for six emotional face conditions, only the full-intensity emotional faces (angry, fear, happy and neutral) were included in analyses to maximize emotional salience and ensure more robust and reliable neural responses across participants (see figure 3.1 for task schematic). Faces were grouped into sets —White, Black, and East Asian (see

supplemental appendix 3.III)—and children were shown the face set that best matched their own race or that best matched the faces children most frequently saw, as reported by parents at the time of test. The ERP experiment lasted approximately 30 minutes including short breaks. Faces were presented for 1000 ms and were preceded by a fixation cross for 800 – 1400 ms and were presented in a randomized order via E-Prime Version 3.0 (Psychology Software Tools, Pittsburgh, PA). Stimulus presentation was random for each participant with the stipulation that no stimuli from the same emotion condition repeated consecutively.

Figure 3.1

ERP Emotional Faces Stimuli



Note. ERP experimental design illustrating inter-trial interval stimulus duration (A) and examples of emotion conditions (B). Face stimuli consisted of emotional faces, including full intensity angry, fearful, and happy faces, and neutral faces, taken from the Nim Stim data set (Tottenham et al., 2009).

EEG Recording, Processing, and Analysis

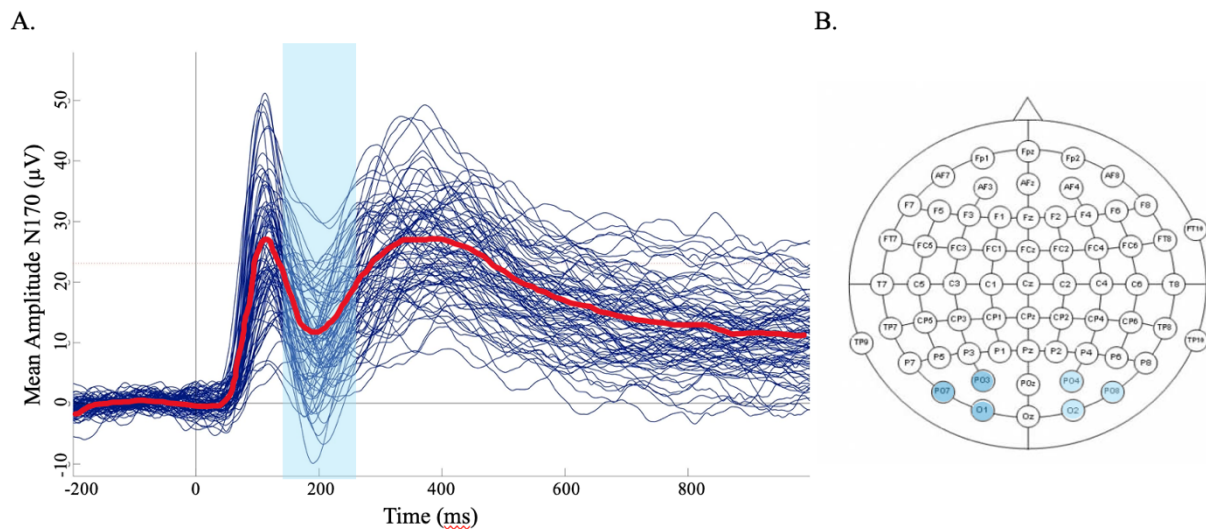
Continuous EEG data were recorded throughout the experiment using BrainVision Recorder (Version 1.21.0393, Brain Products GmbH, Gilching, Germany), and a 64-channel

montage in line with the international 10-20 system. Data were analyzed offline in MATLAB version 2019a (MATLAB, 2019) using EEGLAB version 2019_0 (Delorme & Makeig, 2004) and ERPLAB version 8.01 (Lopez- Calderon & Luck, 2014), processed in line with previous ERP research (e.g., Batty & Taylor, 2006, Xia et al., 2024). A photodiode was used to measure the delay of the monitor at the face location. Before all signal processing and analyses, the stimulus event codes were shifted to reflect the true stimulus onset time at the location of the face. Continuous EEG was bandpass filtered using a Butterworth filter (0.1-30 Hz) and visually inspected for any egregious artifacts, which were then rejected (see supplemental 3.V for continuous rejection protocol; validated in prior research with preschoolers, Xia et al., 2024). Consistently noisy channels were flagged for interpolation to improve the accuracy of Independent Components Analysis (ICA), which identifies blink components that are subsequently removed (Ullsperger & Debener, 2010) (see supplemental 3.VI for ICA protocol, validated in prior research with preschoolers, Xia et al., 2024). Data were rereferenced to the average of all 64 channels. In line with previous research, trials were epoched from -200 ms to 1000 ms, baseline corrected, and epochs containing any channel that exceeded -120 to 120 μ V or for which sample-to-sample μ V exceeded 100 μ V were automatically rejected in ERPLAB (de Haan et al., 2004; Batty & Taylor, 2006). After epoching and artifact rejection, subjects contributed an average of 172.85 trials ($SD = 51.39$ trials, range = 60 – 272; average of 28.97 trials per condition; number of trials per condition did not differ, $F(3, 364) = 0.25, p = .86$). Number of contributed trials was unrelated to participant sex ($F(1, 86) = 0.09, p = .76$) and race/ethnicity ($F(1, 86) = 0.09, p = .77$) but was related to age ($F(1, 86) = 10.3, p = .002$). We included age in the final models to account for this relation.

Selection of electrodes and time windows for ERP components were informed by previous studies on emotional face processing (Hoyniak et al., 2019) and match those of prior uses of this exact task with preschool children (Xia et al., 2024). For each ERP component, a time window was constrained by previous research and finalized by visual inspection. The N170 had a time window of 150-240 ms (see figure 3.2; Hoyniak et al., 2019); Nc had a time window of 300 - 500 ms (see figure 3.3; Peltola et al., 2009; Pestana et al., 2025); and P1 had a time window of 85 - 145 ms (see figure 3.4, Batty & Taylor, 2006; Kuefner, De Heering, & Rossion, 2009).

Figure 3.2

N170 mean amplitude individual differences

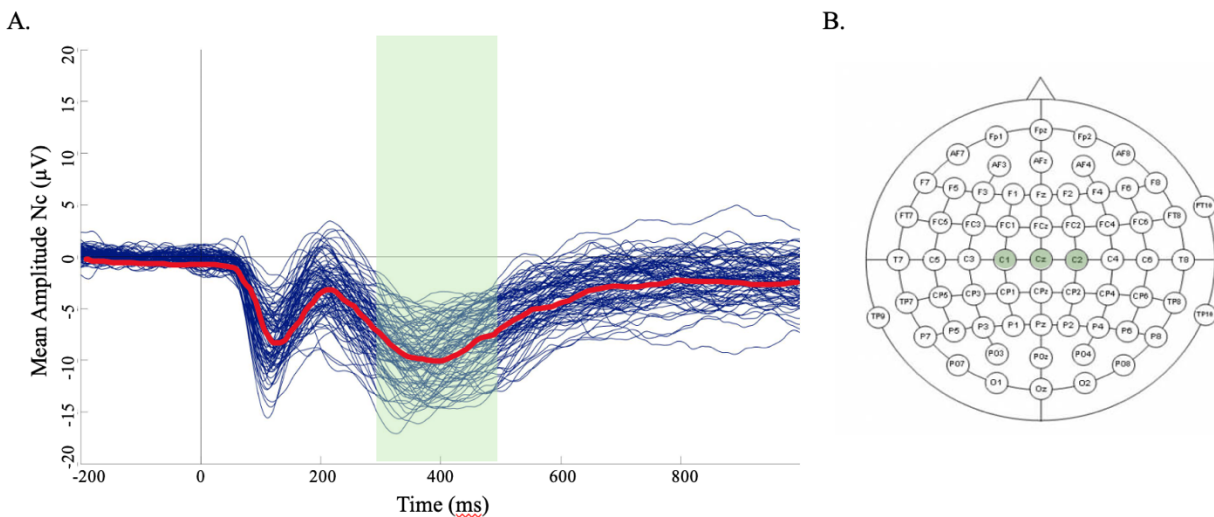


Note: Figure above shows the individual variability in children's N170 mean amplitude. Each thin line represents an individual participant's ERP component with thick red line indicating the grand mean average. Waveforms are shown for an average of all emotions. The blue shaded box in A depicts the time window in which mean N170 amplitude was extracted. Figure B shows the

channels that were extracted for N170, which included sites: PO8, PO4, O2, PO7, PO3, and O1. Labels indicate the international 10-20 electrode positions with respect to our electrode montage.

Figure 3.3

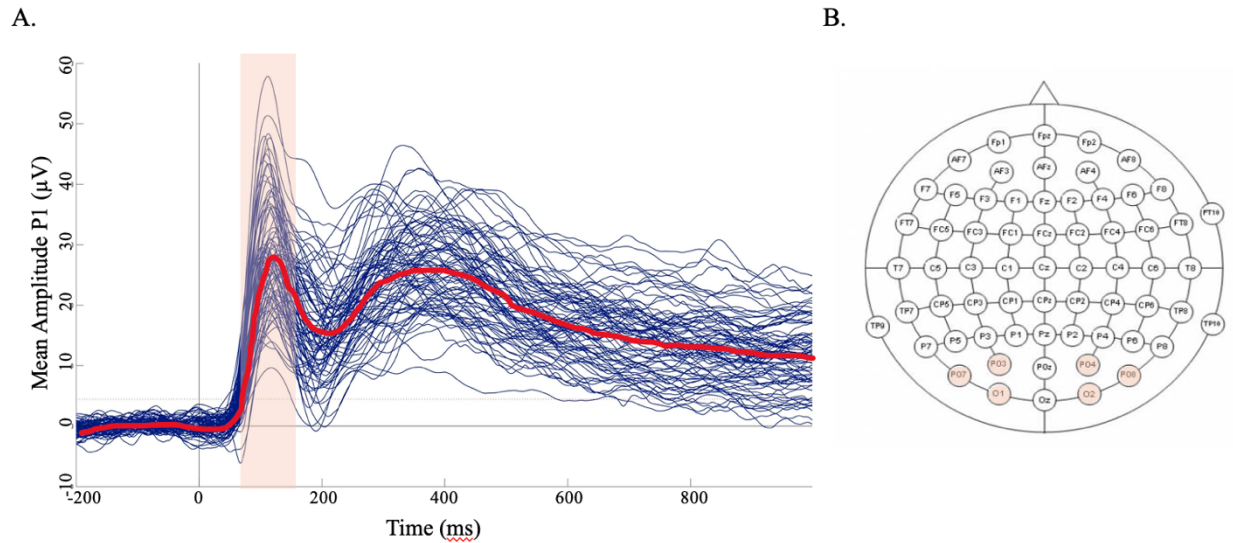
Nc mean amplitude individual differences



Note: Figure above shows the individual variability in children's Nc mean amplitude. Each thin line represents an individual participant's ERP component with thick red line indicating the grand mean average. Waveforms are shown for an average of all emotions. The green shaded box in A depicts the time window in which mean Nc amplitude was extracted. Figure B shows the channels that were extracted for Nc including: posterior and occipital sites C3, Cz, C4. Labels indicate the international 10-20 electrode positions with respect to our electrode montage.

Figure 3.4

P1 mean amplitude individual differences



Note: Figure above shows the individual variability in children’s P1 mean amplitude. Each thin line represents an individual participant’s ERP component with thick red line indicating the grand mean average. Waveforms are shown for an average of all emotions. The blue shaded box in A depicts the time window in which mean P1 amplitude was extracted. Figure B shows the channels that were extracted for P1, which included sites: PO8, PO4, O2, PO7, PO3, and O1. Labels indicate the international 10-20 electrode positions with respect to our electrode montage.

Single-participant ERP data quality was calculated using the analytic standardized measurement error (aSME) to determine participant exclusion based on low data quality (Luck et al., 2021). The aSME was calculated per participant for each of the three components of interest, and outliers were identified using the sum of the 3rd quartile and 1.5 times inter-quartile range (IQR) in any condition for a given component (N170, Nc, P1). Participants with an outlying value in any of the conditions for a given component were excluded from analysis of that component. For the N170, this metric excluded 24 participants, for Nc it excluded 16

participants, and for P1 it excluded 25 participants; together for both tasks 27 participants were excluded from analysis (13 participants were the same across N170, Nc and P1 exclusions) (see appendix 3.VII for details on aSME values for excluded participants).

Data Analysis Plan

All analyses were conducted in R (version 4.1.3; R Core Team, 2024) and plots of the moderation results were created in the `interact_plot` function in the `interactions` Package v1.2 (Long & Long, 2021). Preliminary analyses were conducted in R using the `rcorr` function v5.2-4 in the `Hmisc` package (Harrell, 2026). We used bivariate Pearson's correlations and t-tests to determine whether individual differences in children's reported sex assigned at birth, race, age, or parental income were related to the ERP components. For all analyses, we use an alpha criterion of $p < .05$. For all focal analyses, we corrected for multiple comparisons using False Discovery Rate by using the `Stats p.adjust` function (R Core Team, 2024) and we report the corrected p -values.

The focal analyses consisted of moderation models to determine whether children's ToM composite (as predictor) interacted with ERP amplitudes to each facial-expression condition (fearful, angry, happy, and neutral) (as moderators) to predict children's prosociality (as outcome). We examined ERP amplitudes for each facial expression condition separately rather than calculating emotional-minus-neutral difference waves, allowing us to test whether the ToM and prosociality association varied as a function of neural responses to specific facial expressions without treating neutral faces as an emotion-free baseline. We used the R `Stats` package `summary.lm` function v3.6.2 (R Core Team, 2024) and the `lm.beta` function v1.7-3 (Behrendt, 2023). A total of 12 separate moderation models were tested (4 Nc emotion conditions (fear, angry, happy, neutral), 4 N170 emotion conditions (fear, angry, happy, neutral), 4 P1 emotion

conditions (fear, angry, happy, neutral) X 1 ToM variable X 1 outcome variable of PRPB prosociality). We corrected for multiple comparisons using FDR and report both the original and adjusted p-values. Significant moderation results were followed up with a simple slopes test, and we examined the effect of the predictor at three levels of the moderator (denoted as 1 SD above the mean, mean, and 1 SD below the mean) as consistent with prior work (Mirabile et al. 2009; Wang et al. 2018) using the *sim.slopes* function as part of the QuantPsyc package v1.6 (Fletcher, 2010). Children's EF composite and KBIT were residualized for both PRPB variable and ToM variable. Child age and sex were entered as covariates in final models, and sex was dummy-coded. To avoid multicollinearity in moderation analysis, the predictors were mean-centered (Aiken and West, 1991).

Results

Preliminary Analyses

Preliminary analyses were conducted to determine the placement of covariates of age, sex, EF, and KBIT in the focal analyses. Bivariate correlations confirmed that ToM composite was related to PRPB, KBIT, and EF ($r_s > 0.24$, $p_s < .02$, see supplemental appendix 3.VIII for correlation tables) and that KBIT was related to PRPB and EF ($r_s > 0.31$, $p_s < .002$). This confirmed the need to control for this domain general variance for EF and intelligence (verbal and nonverbal) in both the ToM and PRPB variables. We did so by creating residualized variables for ToM and PRPB that accounted for variance in both KBIT and EF in each of these respective variables, as is done in prior work (Bowman et al., 2019; Müller et al., 2012). Age was related to all target variables of ToM, PRPB, as well as the P1 ERP component ($r > 0.19$, $p < .04$), confirming the need to include age as a covariate in focal regression models. Independent sample t-tests showed that PRPB, ToM, and the ERP variables did not significantly differ by sex

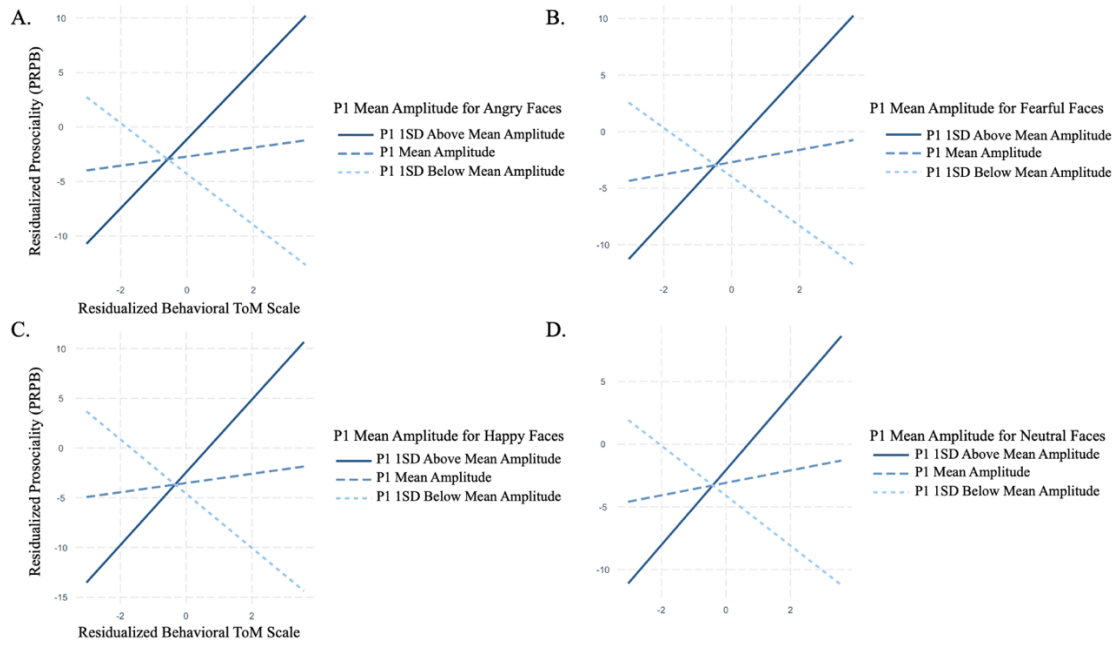
($ts > -1.8$, $ps > .07$), with the exception of Nc (Males ($M = -8.01$, $SD = 2.35$) vs. Females ($M = -9.05$, $SD = 2.64$), $t(105.48) = -2.16$, $p = .03$). We included sex as a covariate in focal models to be conservative but note that patterns do not change when sex was removed.

Focal Analyses

Planned focal analyses tested whether ERP mean amplitudes (N170, Nc and P1) to emotional and neutral faces combined with children's behavioral ToM ability to predict children's prosociality. Focal moderation analyses revealed that P1 mean amplitude to all faces (angry, fearful, happy, and neutral) and ToM interacted to predict children's prosociality. Specifically, child ToM predicted more prosociality, but only when children exhibited a greater (more positive) P1 mean amplitude to all faces (see Figure 3.5). See Table 3.1 for statistics corrected for multiple comparisons across all 12 models using False Discovery Rate (FDR). Interestingly, there is also a downward trend, such that more advanced ToM predicted less prosociality in children with a smaller P1 mean amplitude in all four emotion and neutral conditions, but this did not reach significance for any condition. Therefore, ToM was not significantly related to child prosociality at low or mean levels of P1 mean amplitude. Additionally, when collapsed across all emotions, this model also was significant, such that in children who had higher ToM composite scores and a larger P1 mean amplitude to 'all emotions' combined had reports of greater prosociality (see Table 3.1).

Figure 3.5

Overall moderating effect of P1 mean amplitude to faces on the relation between child ToM and prosociality



Note. Greater ToM is related to greater child prosociality, but only when children exhibit high (more positive) levels of P1 mean amplitude to all faces shown to child. This pattern was consistent across all emotion (angry, fearful, and happy) and neutral conditions.

Table 3.1

Moderation models show that the combination of enhanced neural responses to emotional faces (indexed by P1) and ToM predicts childhood prosociality.

Interaction term of P1 × ToM predicting child prosociality	Overall Model Statistics	Relations between ToM and child prosociality at levels of P1 moderator
P1 Angry Faces and ToM	$b = 0.28, SE = 0.11, t = 2.64,$ $p = .009, FDR-corrected p =$.01, $F^2 = 0.17$	<i>High P1:</i> $b = 0.61, SE = 0.26,$ $CI\ 95\% = [0.08, 1.13]$ <i>Mean P1:</i> $b = 0.17, SE = 0.16,$ $CI\ 95\% = [-0.16, 0.49]$

		<i>Low P1: $b = -0.28$, $SE = 0.2$, CI 95% = $[-0.69, 0.13]$</i>
P1 Fearful Faces and ToM	$b = 0.3$, $SE = 0.11$, $t = 2.79$, $p = .006$, <i>FDR-corrected</i> $p = .01$, $F^2 = 0.19$	<i>High P1: $b = 0.62$, $SE = 0.24$, CI 95% = $[0.15, 1.09]$ Mean P1: $b = 0.16$, $SE = 0.17$, CI 95% = $[-0.19, 0.48]$ Low P1: $b = -0.33$, $SE = 0.24$, CI 95% = $[-0.81, 0.15]$</i>
P1 Happy Faces and ToM	$b = 0.35$, $SE = 0.11$, $t = 3.21$, $p = .001$, <i>FDR-corrected</i> $p = .004$, $F^2 = .21$	<i>High P1: $b = 0.67$, $SE = 0.27$, CI 95% = $[0.16, 1.17]$ Mean P1: $b = 0.12$, $SE = 0.17$, CI 95% = $[-0.21, 0.45]$ Low P1: $b = -0.43$, $SE = 0.22$, CI 95% = $[-0.87, 0.009]$</i>
P1 Neutral Faces and ToM	$b = 0.27$, $SE = 0.11$, $t = 3.21$, $p = .01$, <i>FDR-corrected</i> $p = .02$, $F^2 = 0.16$	<i>High P1: $b = 0.53$, $SE = 0.24$, CI 95% = $[0.04, 1.01]$ Mean P1: $b = 0.11$, $SE = 0.16$, CI 95% = $[-0.22, 0.44]$ Low P1: $b = -0.31$, $SE = 0.23$, CI 95% = $[-0.77, 0.15]$</i>
P1 'All Emotion' Faces and ToM	$b = 0.34$, $SE = 0.12$, $t = 2.94$, $p = .004$, <i>FDR-corrected</i> $p = .01$, $F^2 = 0.19$	<i>High P1: $b = 0.7$, $SE = 0.27$, CI 95% = $[0.16, 1.23]$ Mean P1: $b = 0.17$, $SE = 0.18$, CI 95% = $[-0.19, 0.52]$ Low P1: $b = -0.37$, $SE = 0.24$, CI 95% = $[-0.84, 0.11]$</i>

Note. High P1 = 1 SD above the mean, Low P1 = 1 SD below the mean.

Neither the Nc nor the N170 yielded significant moderation models: The interaction terms involving ToM and any of Nc and N170 mean amplitude to angry, fearful, neutral, or happy faces respectively did not reach significance either corrected or uncorrected for multiple comparisons (uncorrected $ps > .06$, $ts > -0.9$). See supplemental appendix 3.IX for null tests.

Discussion

This study investigated the moderating role of the neural correlates of emotional face perception in the relation between children's behavioral ToM and their prosocial behavior. Specifically, we examined individual differences in preschool children's reported prosocial tendencies as predicted by the *interaction* of children's behavioral ToM performance and their ERP mean amplitude (N170, Nc and P1) to fearful, angry, happy, and neutral facial expressions. Our findings offer a comprehensive empirical test of a model of prosocial development that includes core theoretical components of social cognition and perception, giving critical insight into the development of prosocial behavior, and helping to clarify how variability in children's emotional face perception and their emerging ToM may shape children's tendencies to engage in prosocial actions.

Children's P1 to emotional faces moderates the relation between ToM and prosocial behavior

Results revealed that children's increased attention to all emotional and neutral faces (as indexed by a larger P1) in combination with a higher behavioral ToM composite score predicted more prosocial behavior in children. These results demonstrate that the relation between ToM and prosociality is not straightforward, but rather dependent on an interaction between children's ToM skills and individual differences in how children's brains respond to emotional faces. Specifically, better ToM performance predicted greater prosocial tendencies, but only for children who exhibited increased automatic attentional resources to faces, as indexed by larger P1 amplitudes. There was also a visible contrasting trend such that for children with higher ToM performance and lower levels of attention to emotional faces (a smaller P1 amplitude) had *fewer* prosocial tendencies. The significant moderation effect supports a key interpretation of social

cognitive and prosocial development: sufficient attentional engagement (as indexed by larger P1 neural responses) to facial expressions is necessary for ToM abilities to predict prosocial action.

Indeed, results of the present study are in line with the possibility that early and automatic attentional processes supporting face perception play a critical role in shaping how social-cognitive skills are used in real-world interactive social contexts. Consistent with developmental models of prosocial behavior, early perceptual processes are theorized to play a central role in supporting prosocial responding, as they allow children to extract socially relevant information from cues such as facial expressions and body posture, which then guide decisions to help, share, or comfort others (Paulus, 2014). Critically, comprehensive models of prosocial development propose that these perceptual and motivational processes operate alongside inferring others' mental states to shape how social information is detected and acted upon (Paulus, 2014; Vaish & Hepach, 2020). In the context of our findings, early, automatic attentional engagement with faces (as indexed by the P1 ERP component) may reflect precisely this perceptual sensitivity, providing the initial processing necessary for children to recognize relevant social cues. Children who demonstrate greater early attention to faces may therefore be better able to infer others' mental states from their perceptual input, which in turn enhances their likelihood of engaging in prosocial behavior. These results support the idea that prosocial responding emerges from the dynamic interplay between perceptual and social-cognitive systems, rather than from ToM or attention to faces in isolation. Such findings set the stage for important future research to examine how individual variability in neural responses to emotional faces develops over infancy and early childhood. Longitudinal work investigating how later ToM and prosocial behavior are predicted by such early individual differences in how the neural system for face and emotion

perception tunes and specializes over the first years of life can offer critical insight into the foundations of prosocial development and its complex emergence from these interacting factors.

Early but not later ERP indices of emotional face perception moderate a link between ToM and prosocial tendencies

Notably, the effect of emotional face perception as a moderator in the relation between ToM and prosocial behavior was specific to the early-occurring P1 component and was not observed for later ERP components such as the N170 or Nc. The P1 component is an early positive ERP peak (85-145 ms after stimulus onset) and is thought to reflect early visual attentional vigilance to faces (Di Russo et al., 2002; Batty & Taylor, 2002). Because it arises so early and is sensitive to attentional modulation, larger P1 amplitudes are interpreted as greater initial allocation of visual attention to socially relevant cues, such as emotional faces (Luck & Hillyard, 1994; Di Russo et al., 2002; Itier & Taylor, 2004) and may therefore index early attentional engagement with emotional expressions. By contrast, the N170, which peaks later than P1 (150-240 ms after stimulus onset), is more consistently associated with familiarity and decoding of faces rather than initial attention (Bentin et al., 1996; de Haan et al., 2002; Halit et al., 2003), and the Nc is a later component (300-500 ms after stimulus onset) reflecting broader, allocation of attention rather than rapid attentional vigilance (Dennis, Malone, & Chen, 2009; Taylor-Colls & Fearon, 2015). The significant moderating effect of the early P1 component points to a critical role for early, automatic attentional processes—rather than later-stage processing—in shaping the relation between ToM and prosocial behavior. Future work using the current task could examine even later components such as the LPP (occurring 600-1000 ms after stimulus onset) to determine whether this moderation is truly restricted to early attentional

processes or whether it might emerge again during more sustained, attentional processing (Dennis & Hajcak, 2009; Kennedy & Montreuil, 2021).

P1 is observed across many different facial expressions as a moderator in the relation between ToM and prosocial behavior

Interestingly, the moderating effect of P1 on the relation between ToM and prosocial behavior was observed across all emotional face categories tested including angry, fearful, happy, and neutral expressions. This pattern suggests that a key contributor to variability in children's prosocial tendencies may be children's attention to facial expressions more broadly, rather than attention to a singular emotion or set of emotions over others. This broader pattern of findings is in line with prior research. Behaviorally, toddlers' understanding of emotions overall, including happy, sad, angry, and fearful, combined with their ToM and language ability, contributes to prosocial actions (Brazzelli et al., 2022). This finding aligns with the present results, suggesting that general sensitivity to facial cues, rather than emotion-specific processing, may be a key contributor to prosocial tendencies. Additionally, neural responses to all emotional faces (angry, fearful, sad, happy) including neutral faces mediated a relation between childhood empathy and adolescent prosocial behavior, again showing a role of emotional facial expressions more broadly in the development of prosocial behaviors (Flournoy et al., 2016). It is important to note that neutral faces can be interpreted in socially relevant ways depending on the context (Suess et al., 2014) and thus can offer useful information in social cognitive and prosocial processes. Our finding that attention to neutral faces in combination with ToM ability predicts children's prosocial tendencies is consistent with the notion that attention to facial expressions more generally (emotional and neutral) plays a critical role in prosociality. Future research could extend the current paradigm by including a more diverse and balanced set of positive and

negative facial expressions (e.g., happy, excitement, joy, fear, anger, sadness, etc.) to further unpack how attention to different facial expressions interacts with ToM to predict prosocial tendencies. It would also be useful to add non-social stimuli (e.g., houses, cars) to determine if the automatic attention that moderates the relation between ToM and prosocial tendencies is specific to social/facial cues, or about attentional vigilance more broadly.

Limitations and Future Directions

The present results suggest that increased neural responses supporting attention to emotional faces is a moderator in the relation between ToM and prosocial behavior in preschoolers. Here we discuss additional limitations and motivate future work.

First, incorporating more ecologically valid methods, such as live, interactive measures of emotion perception and coded behavioral assessments of prosocial responding, would strengthen the ecological validity of these findings. It may also be beneficial to use a more comprehensive assessment of ToM that examines children's ability to predict others' mental states and explain how mental states are relevant in these depicted scenarios (such as the Comprehensive Assessment of ToM; Heise & Bowman, 2025). Additionally, prosocial behavior reflects not only social-cognitive ability but also motivation (e.g., empathy, concern for others) and thus including direct measures of these factors would help clarify whether the observed effects are driven by motivation or their interaction.

In addition, the cross-sectional design limits conclusions about directionality. It remains unclear whether early attentional sensitivity facilitates the use of ToM in prosocial behavior, or whether more socially skilled children become increasingly attentive to faces over time, which ultimately influences their prosocial development. Longitudinal research is needed to test these developmental pathways. The generalizability of the findings may also be limited by

characteristics of the current sample, highlighting the need for replication in more diverse populations and other developmental contexts (e.g. younger children, children who have problems with face processing, etc.). Additionally, although P1 responses to emotional faces were associated with ToM and prosociality, similar relations were not observed for the other ERP components examined. Future work should investigate whether these null associations reflect differences in the processes indexed by these components or task-specific characteristics. Finally, prosociality was assessed using parent report, which captures children's behavior across everyday contexts but may be influenced by parent perceptions and may not fully capture children's prosocial behavior across settings (Lagatutta et al., 2012). Future research would benefit from incorporating behavioral or observational measures of prosociality and distinguishing among different forms of prosocial behavior (e.g., helping, comforting, sharing), which may show distinct relations with attention to faces and ToM.

Conclusion

A vital aspect of social behavior is the ability to perceive other's facial expressions, which convey critical information about others' internal mental states and promote prosocial action. In summary, the present findings highlight the importance of the neural response to early attention to faces in shaping the link between ToM and prosocial behavior in preschoolers. Specifically, the P1 ERP component in response to emotional faces moderated this relation, suggesting that rapid attentional engagement with faces may facilitate the translation of social-cognitive abilities into prosocial action. Notably, this effect was not specific to particular emotional expressions, pointing to a broader role of attention to social cues rather than emotion-specific processing. These findings suggest that individual differences in how the brain 'tunes' to attend to emotional facial cues plays an important role in individual differences in ToM and

prosocial behavior. This study highlights the role of face and emotion perception in prosocial activities, and overall advances our understanding of the foundations of prosocial development.

The present findings make an important contribution to the literature by moving beyond approaches that examine ToM in isolation, instead highlighting the critical role of neural processing of social input in shaping prosocial behavior. Although there are some findings linking the connection between ToM and prosocial behaviors, this relation is not direct or straightforward. Research has found that better ToM does not always predict increased prosociality (Imuta, et al., 2016) and sometimes predicts antisocial/aggressive behaviors (O'Toole et al., 2017). Therefore, other factors must be necessary to connect children's social-cognitive skills (i.e., ToM) to their real-world prosocial behavior. Developmental models increasingly emphasize that children's social behavior arises from the integration of multiple systems, including perceptual, cognitive, and motivational processes (Paulus, 2014; Vaish & Hepach, 2020). By demonstrating that early neural sensitivity to faces (indexed by P1) moderates the ToM–prosociality link, this study underscores the value of a multi-level approach that combines neural and behavioral measures to better understand social development. Possible implications include the idea that supporting children's ability to detect and attend to socially relevant information may enhance the extent to which their social-cognitive skills translate into real-world prosocial actions.

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Supplemental Materials

Index

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Appendix 3.I

Participant Demographics

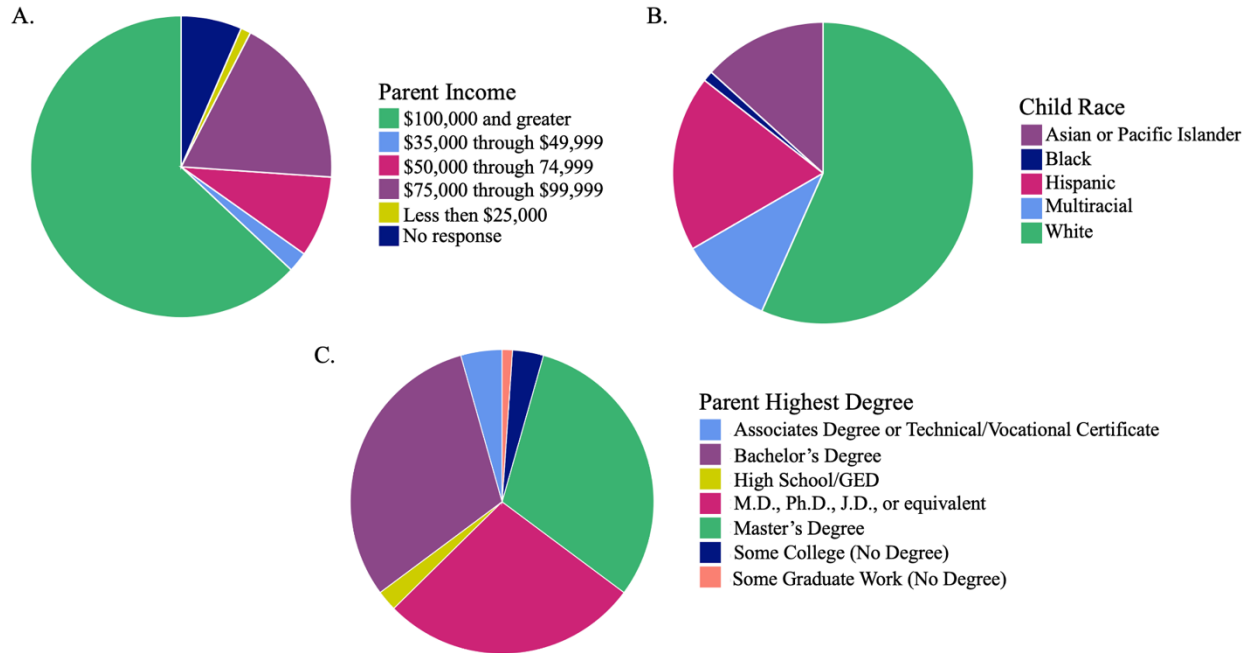


Figure S3.I.1. Demographic Information by parent's income (A), child's race (B), and parent's highest degree level (C). Demographic information was gathered by parent report for final sample (N = 92)

Children's race was reported as follows: 56.7% were White (18.9% are Mexican or other Hispanic/Latinx heritage), 13.3% were Asian or Asian American, 10% were multiracial (30% were Hispanic or Latinx as well as another race other than White), and 1.11% were Black. Parental education was also reported: 2.2% of children had parents with a high-school equivalent of education, 4.4% had at least 1 parent with an Associate's degree, 3.3% had some college education but no degree, 30.8% had at least 1 parent with a Bachelor's degree, 30.8% has at least one parent with a Master's Degree, 1.1% had some graduate work but no degree, and 27.5% had at least 1 parent with a doctorate degree (M.D., Ph.D., J.D.). Family income was also reported;

63% of families earned greater than \$100k, 18.5% families earned \$75- \$99k, 8.7% earned \$50-74k, 2.17% earned \$35-49k, 1.09% earned less than \$2k, and 6 families did not report income.

Appendix 3.II

Behavioral Measures

Parent Rating of Prosocial Behavior (PRPB) Questionnaire – (Laible et al., 2017)

Parents reported on children's prosocial behavior using a questionnaire assessing behaviors such as helping, sharing, and comforting others. Items were rated on a Likert scale, with higher scores indicating greater prosocial tendencies. Responses were averaged to create a composite score of prosocial behavior.

Figure S3.II.1. The exact PRPB questionnaire is listed below.

My child...

	Never	Once in a while	Not very often	Not often or rarely	Often	Very often	Always
1. Cleans up surroundings	☐	☐	☐	☐	☐	☐	☐
2. Shows another child how to do things	☐	☐	☐	☐	☐	☐	☐
3. While doing something collaborates with another child	☐	☐	☐	☐	☐	☐	☐
4. Accepts to share the toy that he/she is playing with or some other thing (sharing)	☐	☐	☐	☐	☐	☐	☐
5. Accepts to give or share his/her toy with another child who is distressed	☐	☐	☐	☐	☐	☐	☐
6. Gives the thing that he/she is playing with at that moment	☐	☐	☐	☐	☐	☐	☐
7. When a child hurts himself/herself comforts that child	☐	☐	☐	☐	☐	☐	☐
8. Cooperates with you or another child	☐	☐	☐	☐	☐	☐	☐
9. Helps a child who is distressed	☐	☐	☐	☐	☐	☐	☐
10. If he has lots of toys or good enough toys that other children can play he/she will let them play with those toys	☐	☐	☐	☐	☐	☐	☐
11. Exchange his/her toys if the other child has a toy that he/she wants	☐	☐	☐	☐	☐	☐	☐
12. Help another child when there is a need for extra help	☐	☐	☐	☐	☐	☐	☐
13. Shares his/her toys or play	☐	☐	☐	☐	☐	☐	☐
14. If another child is scared, unhappy, or afraid comforts that child	☐	☐	☐	☐	☐	☐	☐
15. Helps you clean up surroundings	☐	☐	☐	☐	☐	☐	☐
16. Hugs or kisses the unhappy child or adult	☐	☐	☐	☐	☐	☐	☐
17. Shares his/her food	☐	☐	☐	☐	☐	☐	☐
18. Says something to comfort an unhappy child or adult	☐	☐	☐	☐	☐	☐	☐
19. Helps another child or adult to clean up something spilled or dropped	☐	☐	☐	☐	☐	☐	☐

Theory of Mind Composite (ToM composite) – Mental State Reasoning (Wellman & Liu, 2004)

This ToM composite was meant to assess mental state reasoning ability in preschoolers (Wellman & Lui, 2004). The vignettes included: diverse desires (that others will have and act on different desires), diverse beliefs (that others will have and act on different beliefs), knowledge access (that others may not have the same knowledge), contents false-belief (that others may have false beliefs about the contents of an object), explicit false-belief (that others will act on false beliefs they hold about the location of an object), belief emotion (that others' emotions are based on their beliefs, even if those beliefs are false), and real vs. apparent emotions (that expressed emotions can be different than real emotions). However, the real versus apparent emotion task was excluded from the ToM composite, as reliability analyses indicated stronger internal consistency without it ($\alpha = .78$) compared to when it was included ($\alpha = .62$), a finding that aligns with previous research (Calero et al., 2013; McElwain et al., 2018). Coefficient alpha indicated that the ToM composite had moderate internal consistency ($\alpha=0.78$), in line with prior research (Bowman et al., 2017; Sabbagh et al., 2009).

Kaufman Brief Intelligence Test (Kbit) – Verbal and Nonverbal Intelligence (Kaufman & Kaufman, 1990)

Children received a score of 1 for a correct response and 0 for an incorrect one. There were 60 possible trials for a max score of 60, where higher scores indicate better verbal and nonverbal intelligence.

Executive Functioning Composite (Wechsler, 1974; Zelazo, 2006)

For the Dimensional Change Card Sort (DCCS) task, children were first asked to sort cards depicting red boats, blue boats, red rabbits, and blue rabbits according to shape across five trials. On each trial, the experimenter restated the sorting rule, labeled the test card by its color,

and then asked the child to sort. Children who correctly sorted five consecutive cards by shape (e.g., rabbits placed with rabbits, boats with boats) proceeded to the post-switch phase. In this phase, children were required to sort the same cards by color (e.g., red cards placed in the red tray, blue cards in the blue tray), requiring them to shift from the initial rule.

In the digit span task, children were asked to repeat sequences of numbers spoken aloud by the experimenter in the same order presented. The task began with a practice trial consisting of a two-digit sequence. If the child responded correctly, the test phase began, consisting of two trials at each sequence length, starting with two digits and increasing by one digit per level up to a maximum of eight digits. Children advanced to the next level if they correctly recalled at least one of the two trials at a given sequence length. The task was discontinued when the child failed both trials at the same level.

Appendix 3.III

Details on Faces Task Administration

Consistent with prior implementations of this task (e.g., Bowman et al., 2022; Xia et al., 2024; Xie et al., 2019), children were presented with the set of faces that best matched their race, as reported by their parent. Four face sets were used, consisting of Black actors, East Asian actors, and two sets of White actors that were counterbalanced across White participants. Overall, 80% of the final sample viewed White actor stimuli; within this group, 47.3% were assigned to White Face Set 1 and 52.7% to White Face Set 2. Each face set included unique actors displaying emotional expressions across all conditions (see Figure S3.III.1). Specifically, there were five East Asian actors, four Black actors, and nine White actors distributed across the two White face sets, with one actor appearing in both sets.

Within each face set, participants viewed each actor expressing each of the six emotions ten times. An exception was made for the Black face set, in which one actor was presented twenty times per emotion due to the limited availability of Black actor stimuli in the broader NimStim set (Tottenham et al., 2009). This resulted in a total of 300 trials. Event-related potentials (ERPs) were time-locked to the onset of each face stimulus. During the task, children were given multiple short breaks, during which they could place stamps on paper, rest their eyes, or stretch and move their bodies to maintain engagement.

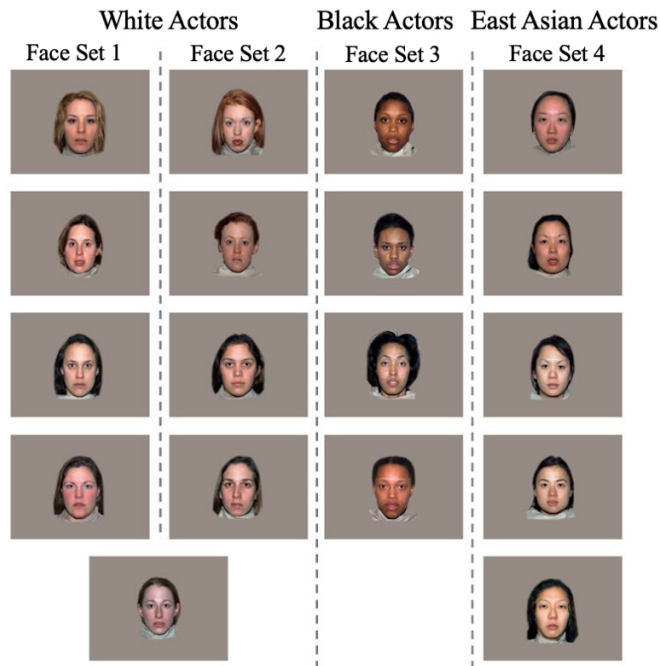


Figure S3.III.1. Children saw the face set that best matched their own race as reported by their parent or that best matched the faces children frequently saw as reported by their parents at the time of test. Actors were grouped into different face sets by race condition, shown to different participants across the sample. The figure shows examples of each actor displaying a neutral expression.

Appendix 3.IV

Details on EEG Recording, Processing, and Analysis

Continuous EEG data was recorded throughout the ERP experiment using BrainVision Recorder (Version 1.21.0393, Brain Products GmbH, Gilching, Germany), actiCHamp (2020c) amplifier (actiCHamp, Brain Products GmbH, Gilching, Germany), and a 64-channel montage High Precision fabric ActiCap Snap cap (ActiCAP Snap, Brain Products GmbH, Gilching, Germany) that positioned actiCAP slim electrodes in line with the international 10-20 system (actiCAP slim, Brain Products GmbH, Gilching, Germany). Data were bandpass filtered from 0-140 Hz and referenced to Cz during recording. Data were digitized at a 500 Hz sampling rate for 50 participants and the remaining 95 were digitized at 1000 Hz (and down sampled to 500 Hz during initial processing steps)

Appendix 3.V

Continuous EEG Egregious Artifact Rejection Protocol

(also published in Xia et al., 2024)

‘Continuous EEG Egregious Artifact Rejection (CEEAR)’ refers to the process in which we visually inspect the continuous EEG data to identify egregious artifacts (i.e., noisy sections in the data) to be rejected (removed) from the analyses. These egregious artifacts are typically caused by 1) motion (e.g., child moved their head or stretched); 2) muscle tension (e.g., jaw clenching) or 3) other electrical noise (e.g., high impedance level from one electrode or malfunctioning ground/reference electrode). The goal of CEEAR is to prepare our data to be entered into a subsequent, more automated process of Independent Component Analysis (ICA) to eventually identify and remove eye blinks (see ICA Blink Component Identification Protocol below for more details).

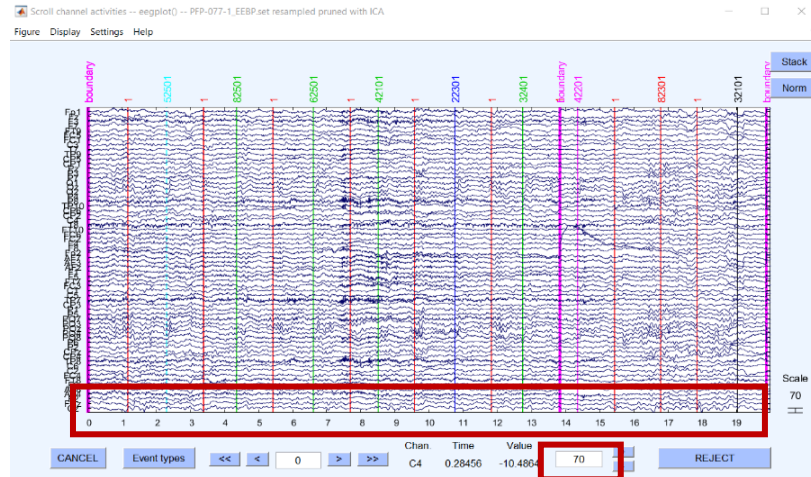
We include our detailed CEEAR protocol below. In this protocol, we discuss how to set up a workstation, and what counts as ‘egregious artifact’. We also show screenshots of example EEG segments containing artifact that should be removed during this process. We use EEGLAB to visualize artifacts and mark them for rejection in subsequent preprocessing steps.

Continuous EEG Egregious Artifact Rejection (CEEAR) Protocol

NOTE before you begin: It is **absolutely essential** that you do not complete any continuous EEG artifact rejection tasks when you are tired, or if you are in a distracting environment. Continuous EEG artifact rejection is an extremely important process that ensures good data quality and produces data for analyses. If mistakes are made, we lose valuable data and we risk publishing erroneous results.

Step 1. Setting up your continuous EEG artifact rejection workstation:

- Setting up EEGLAB:
 - Go to EEGLAB → Plot → Channel Data (Scroll) to plot the continuous EEG data
 - In the left corner, change the vertical viewing scale to 70 μ V (small red box)
 - In Settings, change Time Range to Display to 20 seconds (large red box)
 - Note: these are the settings we use to identify artifact based on visual inspection. You must use the same parameter settings for all continuous EEG artifact rejection projects.
- Additional things to prepare for:
 - A scratch pad for you to write down notes about noisy channels or questionable segments
 - Open this protocol on a different screen – it will be easier for you to see both the EEG data scroll and the protocol (the squiggly lines are hard to read on a smaller screen).

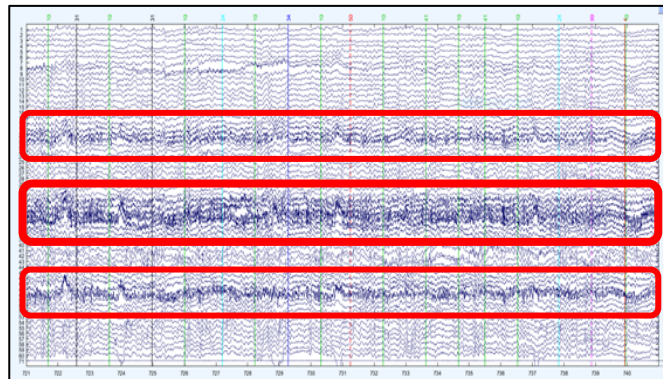


- But if you don't have an external monitor, still have this protocol open in the background, so you can refer back to it whenever in need.

Step 2. Determine artifact-containing segments in continuous EEG data

Now that you are all set up with EEGLAB, you are ready to scroll through the continuous EEG data file to identify the artifacts and mark them on the EEG data scroll. To mark the artifacts on continuous EEG, click and drag your cursor on the continuous data (it will be highlighted; see pictures below for examples) until the end of the artifact you identified.

The very first step you need to do before starting to highlight and identify artifacts for rejection is to click through the entire EEG data scroll to 1) calibrate your expectations for a general idea of how noisy the data



file is, and 2) write down consistently noisy channels (i.e., channels with high frequency noise throughout 50% or more of the recording; see example of channels with high frequency noise on the right) on your scratch pad for channel interpolation.

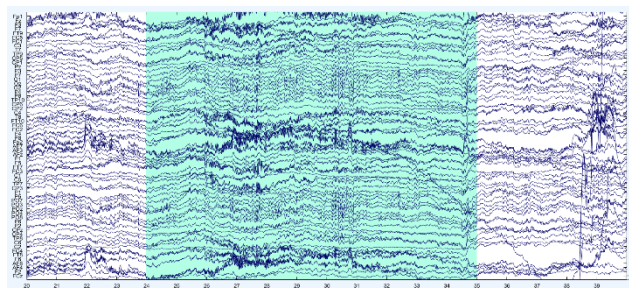
- This step is very important, because even though the goal is to be as standardized as possible in our identification of artifacts (see sections to come), we need to recalibrate to every EEG data scroll in the service of preserving the most task-evoked brain data. That is, leaving in 'messy' data at this step does not compromise overall data quality because

this data will be further processed in an automated and standardized artifact identification and rejection process in a later step. Thus, if you have a particularly ‘messy’ data file, you may not be able to identify clearly where artifact starts and ends, and it is better to leave more data in than to remove it in this subjective artifact identification step. Whereas if you have a particularly ‘clean’ data file, identification of clear artifact will be easier to identify, and we can feel more confident in removing artifact during this step which will help improve accuracy during the subsequent ICA processing step (see Luck, 2014).

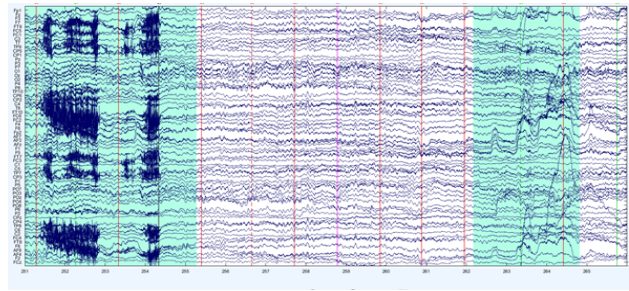
Relatedly, we follow different rules when identifying artifact that is occurring during task-evoked brain activity versus during non-task ‘breaks’. As noted above, we want to avoid excessive removal of artifact during task-related EEG because this current continuous EEG artifact rejection process is subjective, and we prefer to leave task-related data to get artifact-edited during a later, objective, automated processing step (once it is epoched).

- **During task** (e.g., during the presentation of fixation crosses and face stimuli): we are more lenient to preserve as much task-related brain data as possible. However, if you see the following, you must flag and remove the following egregious artifact to improve the quality of the ICA (see Luck, 2014):

- Data with **more than 15** noisy channels (high frequency noise with faster-occurring peaks, which usually are visualized with darker data sections, see example on the right)

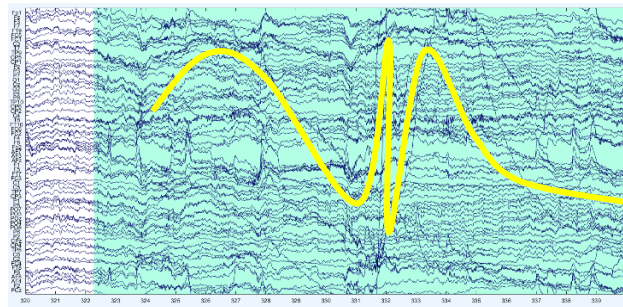


- ‘Dark’ data sections that obstruct many other channels (see example on the right)



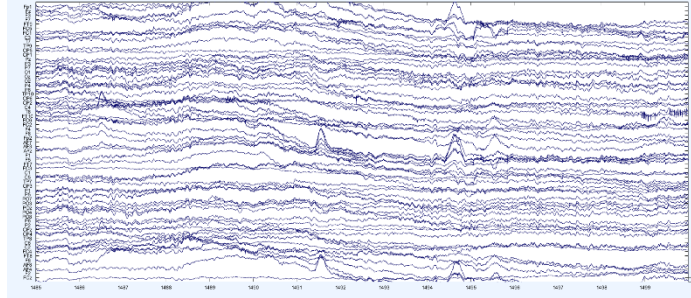
- Note: these are often muscle tension created from jaw clenching)

- Data with **5 or more** ‘wandering channels’ (channels that are not in line with their designated space in EEGLAB, see example yellow channel on the right)



- Note: From the example on the right, the yellow highlighted channel is ‘wandering’ because its oscillations are at a scale far beyond typical for brain-related voltage changes and it moves far outside the bounds of its allotted space in the EEG data scroll.
- If there’s one channel that is consistently wandering throughout more than 50% of the recording, first write it down on your scratch pad for channel interpolation; then when you are counting wandering channels in a given segment of data you will not include this channel in your tally (because it will already get flagged for interpolation), and you need to find 5 or more *additional* wandering channels for the segment to qualify for artifact rejection.

- We also flag and remove everything when all channels are ‘drifting’. Channel drifting is a special case

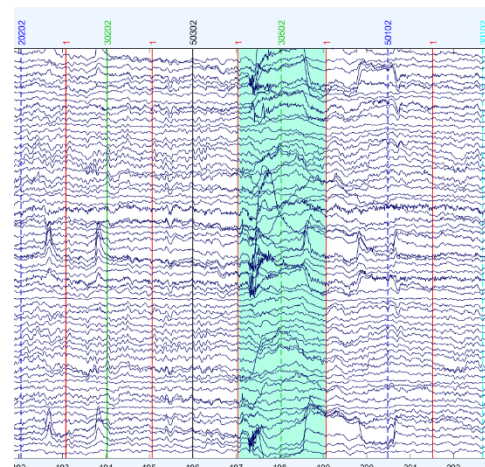


where none of the three criteria described above really applies (i.e., data seemed to be not noisy, didn’t have dark sections, and didn’t have 5 or more wandering channels), but there seems to be a weird ‘trend’ that influenced every electrode (see example on the right).

- Note: Channel drifting can be due to sweat. It can also be residuals of a previously egregious artifact caused by large movements.
- ***General notes about continuous rejection during task:***
 - Do **NOT** remove any segments that fit the following:
 - Data with 4 or fewer noisy channels
 - If there were only 4 or fewer noisy channels, we can then interpolate them – so we can preserve more trials
 - Noise that lasts 0.5 second or less
 - Short bursts of the noise are okay. Our processing steps later can help with this
 - Frequent blinks or saccades
 - Blinks are preserved for Independent Component Analysis (ICA). We use ICA to correct for blinks, because it would be wasteful to remove all the EEG data in a segment

containing blinks when there are now processes that can identify a blink ‘component’, remove that ‘component’ from the data, and preserve the rest of the brain data for analysis. We need blinks to be retained in the data in order for the ICA to be most accurate at identifying these blink ‘components’.

- If you have to remove a blink because the data containing the blink is noisy/messy, remove the entire blink (do NOT cut the blink in half)
- Saccades could be related to some underlying cognitive processes (e.g., people shift their gaze as directed by attentional processes), so we don’t want to take out the sections of brain data that contain gaze shifts at this stage, with this subjective process. If the saccades are causing artifact at levels that meet set thresholds for removal during later processing steps, they will get flagged then. Retain them here for now.
- If an identified segment of artifact ends right at the start of a trial, consider marking the end of the segment 0.5 seconds before the trial start event marker. We use a ‘pre-trial baseline’ in our

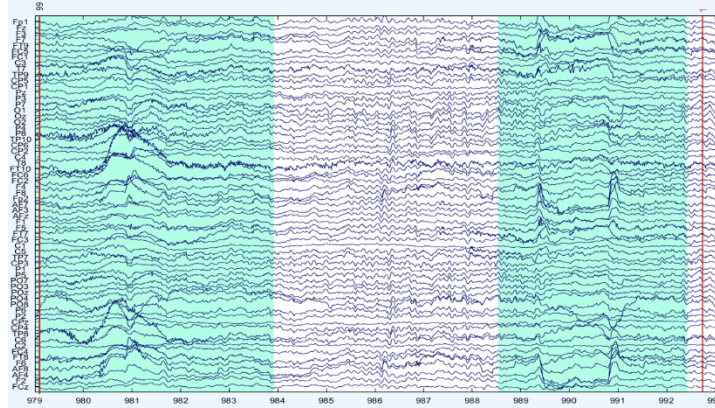


calculation of ERPs, and so we want to avoid removing pre-trial baselines as much as possible. In contrast, if the pre-trial baseline period is contaminated with egregious artifact, we remove the fixation and the stimulus trial all together rather than leaving a trial without a corresponding baseline (see example on the right: fixation period after marker 1 prior to 30502 is noisy, so we removed the trial of 30502).

- **During break** (e.g., when no fixations or faces are shown): we can be more aggressive in identifying and removing artifacts. Our removal of data here will not affect our eventual analysis of the task-related EEG because we will ‘epoch around’ (segment out) our task-related EEG for further preprocessing and analysis in later steps. So there is not a risk of removing ‘good’ EEG data when artifact-editing during task breaks. There is however a risk of leaving in ‘bad’ or ‘noisy/messy’ EEG during these break sessions because it will affect the quality of our subsequent ICA, which is trying to identify individual ‘components’ in the data that represent blinks so that these blink components can be removed. If you leave in ‘noise’, the ICA has a harder time finding the target ‘blink signal’.

- To remove non-task (break) EEG, start at the beginning of a ‘break’ event marker (e.g., 99). Click and highlight from the start of the break to 0.5 seconds prior to the start of the next task-related marker (e.g., 1). This

entire break segment will then be removed.



- You can retain segments of data within a break only if they are perfectly ‘clean’ (i.e., no ‘dark spots’, 0 wandering or noisy channels, 0 drift; see example on the right). In this case, highlight all sections of the break ‘around’ the clean segment to retain just the clean segment (and remember to leave 0.5 seconds prior to the start of the next task-related trial marker). You may also leave in segments of data within a break if they contain blinks but are otherwise ‘clean’ (it will be helpful to have more ‘blink signals’ for the ICA to identify).

- ICA will also benefit from more data to process. So, in this egregious artifact rejection process, we walk a fine line of cutting out noise (that could be mistakenly treated as an independent component) and leaving in good data (so there’s more data to work with).

- Note that ‘clean’ segments in a break are rare because on breaks, participants tend to move around, stretch, do other activities etc. Thus,

‘break’ data is typically especially full of egregious artifact and should be removed unless is truly perfectly clean.

Appendix 3.VI

Independent Component Analysis (ICA) Blink Component Identification Protocol

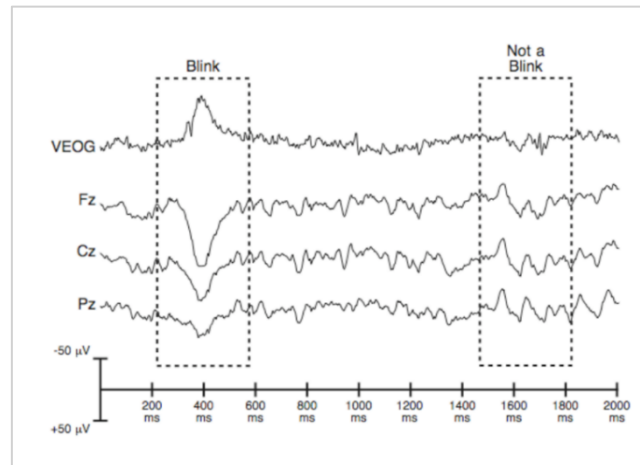
(also published in Xia et al., 2024)

We followed the following steps and criteria to perform ICA and select blink components

(suggested by Luck, 2014):

- Perform ICA in EEGLAB using binica function

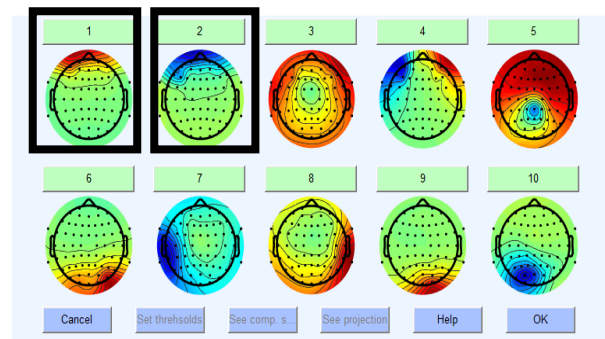
- Recall that a blink consists of short duration high amplitude peaks that are either positive or negative going (usually they are paired). They look like the figure on the right in a raw EEG recording: Blinks are generated by the eyes and therefore should be



most visible in the electrodes around the eyes (i.e., frontal electrodes), and they occur in both eyes at the same time. Blinks can occur anytime, but they should be consistently distributed throughout an EEG recording session. We want to identify the Independent Component (IC) from the ICA that captures a blink, which means we need to look at the time course of an IC's activation (analogous to the time course of a blink's voltage deflection), and distribution of a given IC, to confirm it has these 'blink-like' characteristics. That is, the distribution should be maximally near the eyes, and the time course should show deflections that occur when blinks occur and have the same wave shape as the blinks.

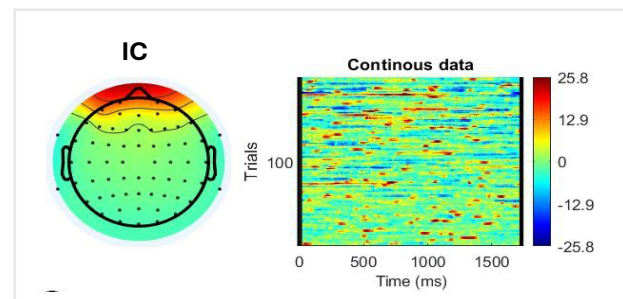
- We use the plots generated in EEG lab to make this verification and identify only the ICs that reflect blink-like voltage changes for removal.
- Blink components should be present in the first 10 components plotted following binica
 - If no clear blink component is observable in the first 10 components plotted, return back to Continuous EEG Egregious Artifact Rejection protocol and further reject segments of data until ICA returns clear blink components in the first 10 components
- To identify potential blinks from topo map:

- Red or blue regions (representing peak positive or negative amplitude) should be centralized around frontal eye channels (Fp1, Fp2, AF3, AF4, AF7, AF8)



- Red/blue should span across left, center, and right frontal channels (not concentrated on one side—blinks occur in both left and right eyes)
 - Black boxes in figure on right show ‘potential blink components’ that would be considered for removal

- Click on a ‘potential blink component’ (that meets criteria specified above) to bring up additional



information to further evaluate it for removal. To be considered as a blink, the

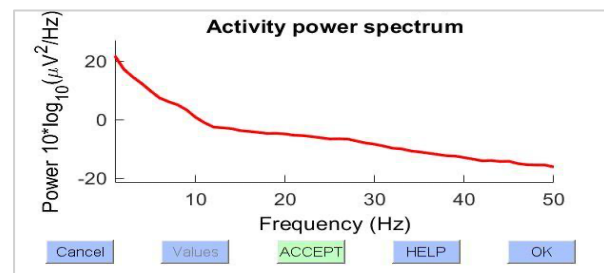
scalp map must show a strong far-frontal projection (as demonstrated by IC1 in the left panel of the figure on the right). Further, in the ‘Continuous Data’ plot to the right of the scalp map that plots time across the x-axis, trial number in the y-axis and amplitude in the color bar, we should see short bursts of amplitude that are randomly but relatively evenly distributed across the entire plot. This distribution is likely associated with blinks which occur as short duration peaks, randomly but consistently throughout the EEG recording.

- Note: Use the color of the independent component in the scalp map to guide your evaluation of the Continuous Data plot. If the scalp map shows peak positive amplitude (red), you should be evaluating whether there are short bursts of red (positive) amplitude throughout the recording (this is exemplified in the figure with IC1 and Continuous Data plot above).

Whereas if the scalp map shows peak negative amplitude (blue), you

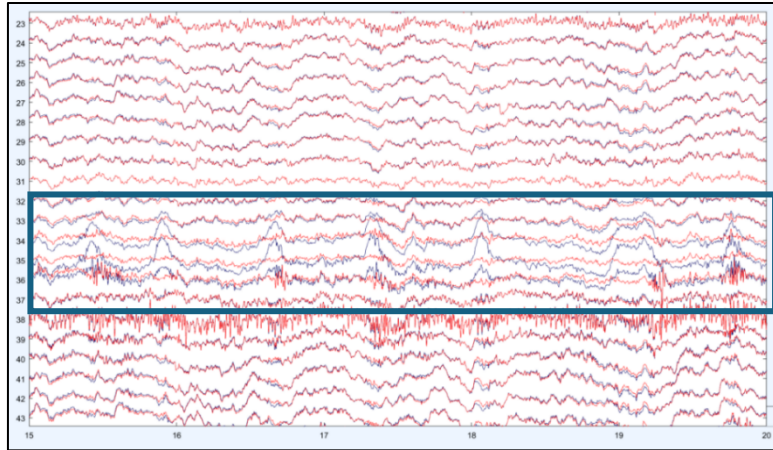
should be evaluating whether there are short bursts of blue (negative) amplitude throughout

the recording.



- Activity power spectrum should show smooth, decreasing frequency spectrum with an early peak (see example in figure to the right)

- Once a blink component is identified and confirmed, reject this component and then inspect the continuous data before and after rejection of



this component (example shown on the right, inside blue box):

- Dark blue lines represent data before rejection
- Red lines represent data after rejection
- In segments where there are clear blinks, you should expect to see that these blinks are ‘flattened’ in red.

Appendix 3.VII

Data Quality Tool: Analytic Standardized Measurement Error (aSME)

To identify individual subject ERPs of low data quality that should be excluded from analysis, ERP data quality was calculated using Analytic Standardized Measurement Error (aSME) (Luck et al, 2020). ASME is an extension of the widely used standard error of measurement (SEM) in which it further quantifies the error at the single subject level as opposed to the group level (Luck et al., 2021). Lower aSME values indicate single subject ERPs of higher data quality. We calculated aSMEs for each component of interest at the cluster level (Left cluster N170, right cluster N170, P1 cluster, Nc cluster) for each participant, per condition, which resulted in eight N170 cluster aSME values, four Nc cluster aSME values, and four P1 cluster aSME values for each participant. The aSME was calculated per participant for each of the three components of interest and outliers were identified using the sum of the 3rd quartile and 1.5 times inter-quartile range (IQR) in any condition for a given component. Participants with an outlying value in any of the conditions for a given component were excluded from analysis of that component.

Appendix 3.VIII

Preliminary Analyses

Table S3.III.1. Preliminary analysis: bivariate Pearson correlations showing relation between N170, Nc, or P1 and Age, EF, PRPB, ToM, KBIT variables (effects of sex reported in main text)

		<i>r</i>	<i>p</i>
Mean Amplitude Left N170 Angry	Age	0.11	0.26
Mean Amplitude Left N170 Fear	Age	0.12	0.20
Mean Amplitude Left N170 Happy	Age	0.02	0.82
Mean Amplitude Left N170 Neutral	Age	0.06	0.53
Mean Amplitude Left N170 All Emotion	Age	0.09	0.34
Mean Amplitude Right N170 Angry	Age	0.10	0.29
Mean Amplitude Right N170 Fear	Age	0.13	0.19
Mean Amplitude Right N170 Happy	Age	0.05	0.60
Mean Amplitude Right N170 Neutral	Age	0.09	0.34
Mean Amplitude Right N170 All Emotion	Age	0.11	0.25
Mean Amplitude P1 Angry	Age	0.22	0.03
Mean Amplitude P1 Fear	Age	0.15	0.13
Mean Amplitude P1 Happy	Age	0.13	0.18
Mean Amplitude P1 Neutral	Age	0.17	0.08
Mean Amplitude P1 All Emotion	Age	0.19	0.05
Mean Amplitude Nc Angry	Age	-0.10	0.29
Mean Amplitude Nc Fear	Age	-0.04	0.67
Mean Amplitude Nc Happy	Age	-0.10	0.33
Mean Amplitude Nc Neutral	Age	0.06	0.53
Mean Amplitude Nc All Emotion	Age	0.09	0.34
Age	PRPB	0.37	<.001
Age	ToM	0.53	<.001
Age	EF	0.48	<.001

Age	KBIT	0.58	<.001
PRPB	KBIT	0.31	<.001
PRPB	ToM	0.24	0.02
PRPB	EF	0.17	0.10
ToM	EF	0.50	<.001
ToM	KBIT	0.58	<.001
EF	KBIT	0.48	<.001

Appendix 3.IX

Moderation Analyses for N170, Nc and P1

Table S3.IX.1. Separate models showing N170, Nc or P1 as the moderator in the relation between ToM and prosocial behavior.

Interaction Predicting Prosocial Behavior	<i>b</i>	SE	t	p
Mean Amplitude Left N170 Angry & ToM	0.12	0.12	0.96	0.34
Mean Amplitude Left N170 Fear & ToM	0.21	0.12	1.75	0.08
Mean Amplitude Left N170 Happy & ToM	0.24	0.12	1.99	0.06
Mean Amplitude Left N170 Neutral & ToM	0.16	0.14	1.14	0.26
Mean Amplitude Right N170 Angry & ToM	0.11	0.12	1.03	0.31
Mean Amplitude Right N170 Fear & ToM	0.05	0.13	0.38	0.7
Mean Amplitude Right N170 Happy & ToM	0.08	0.11	0.72	0.47
Mean Amplitude Right N170 Neutral & ToM	0.08	0.11	0.66	0.51
Mean Amplitude Nc Angry & ToM	-0.12	0.31	-0.38	0.71
Mean Amplitude Nc Fear & ToM	-0.32	0.35	-0.91	0.37
Mean Amplitude Nc Happy & ToM	-0.13	0.32	-0.41	0.68
Mean Amplitude Nc Neutral & ToM	0.02	0.31	0.07	0.94
Mean Amplitude P1 Angry & ToM	0.28	0.11	2.64	.0009
Mean Amplitude P1 Fear & ToM	0.3	0.11	2.79	0.006
Mean Amplitude P1 Happy & ToM	0.35	0.11	3.21	0.001
Mean Amplitude P1 Neutral & ToM	0.27	0.11	2.48	0.01

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Chapter 4: Discussion

This dissertation examined how neural responses to emotional facial expressions relate to early social development, focusing on ToM and prosocial behavior in preschool-aged children. Across two complementary studies, the central aim was to elucidate whether and how individual differences in preschool children's neural activity supporting emotional face perception is associated not only with children's understanding of others' mental states, but also plays a key, moderating role by interacting with ToM to predict emerging prosocial tendencies. Together, the findings provide converging evidence that emotional face processing plays a critical role in early social development, and that early stages of attention to emotional faces may help shape how children reason about others' mental states and interact with others in social settings.

Neural Correlates of Emotional Faces and Theory of Mind in Preschoolers

The first study investigated whether individual differences in neural responses to emotional facial expressions, indexed by the N170 and Nc components, are associated with children's ToM abilities. This study integrated event-related potential (ERP) measures of face processing with behavioral assessments of mental-state reasoning and mental-state decoding. The results highlight a specific role for the Nc ERP component, suggesting that individual differences in how the brain allocates attention to negative emotions (fear and anger), and specifically more subtly expressed negative emotions, are meaningfully related to individual differences in preschoolers' behavioral mental-state reasoning. In contrast, no association was found between the N170 response to emotional faces and ToM, suggesting that structural face encoding may be less relevant to children's mental-state inferencing. Together, these findings indicate that later attentional engagement with emotional faces, rather than early structural face

processing, may be particularly important for the development of social-cognitive skills such as ToM.

More broadly, findings from Study 1 of the dissertation support the idea that early-emerging differences in how children attend to emotional faces are linked to how they reason about others' mental states. These results align with theoretical accounts proposing that facial perception provides a foundational role in the development of ToM, particularly in early childhood when social-cognitive skills are rapidly emerging (Bird & Viding, 2014; Biró et al., 2025).

Neural Responses to Emotional Faces, Theory of Mind, and Prosocial Behavior

The second study in the dissertation expands on Study 1 by examining whether neural responses to emotional faces (similarly assessed with ERPs) moderate the relation between ToM and prosocial behavior. Rather than focusing solely on direct associations, this study tested a more complex model in which neural indices of face processing (P1, N170, and Nc ERP components) combined with ToM translates into prosocial tendencies.

Results of Study 2 indicated that ToM was positively associated with prosocial behavior only among children who showed enhanced P1 ERP amplitudes to emotional faces. This finding is particularly notable because the P1 component is thought to reflect early visual attention and orienting processes, suggesting that the very early attention to faces in combination with increased ToM ability is important for children's prosocial behavior. In other words, children who not only reason about others' mental states but also rapidly and efficiently attend to emotional facial cues appear more likely to translate social-cognitive knowledge (ToM) into prosocial action.

The Central Role of Faces in Early Social Development

Taken together, the two studies converge on a central conclusion: the processing of emotional facial expressions plays a critical role in early social development. Across both studies, neural measures of face processing were linked to important social outcomes, either directly with ToM, or indirectly by shaping how ToM relates to prosocial behavior. Importantly, these findings highlight that not all neural markers contribute in the same way. Instead, different components appear to reflect distinct stages of processing, with early attentional mechanisms (P1) and later attentional allocation (Nc) showing particular relevance for individual differences in ToM and prosocial tendencies.

The dissertation findings highlight the central role of faces in early social development. Emotional facial expressions provide children with rich information about others' emotions, intentions, and mental states, making them a primary source of social information from early in life. As the developing brain becomes increasingly tuned to processing these socially salient cues, individual differences in neural responses to emotional faces may have important implications for social development. Across both studies, individual differences in children's neural responses to emotional faces was associated with ToM either directly or by shaping the relation between ToM and prosocial behavior. Together, these findings suggest that the developing brain's sensitivity to emotional facial expressions may represent an important mechanism through which children learn to understand and respond to others.

Future Directions

Several future directions emerge from this work. First, future research should replicate and extend these methods to younger developmental periods, including infancy, to better understand when individual differences in neural responses to emotional faces first emerge and how early they begin to shape social-cognitive development. Longitudinal designs would be

especially valuable for clarifying developmental pathways on how the brain ‘tunes’ for early face processing to later ToM and prosocial behavior.

Second, future work should move toward more naturalistic assessments of empathy and prosociality. While laboratory-based and questionnaire measures provide important control and precision, they may not fully capture how children respond to emotional cues in real-world social contexts. For example, paradigms in which an experimenter visibly experiences and recovers from distress (e.g., appearing to injure a finger) can provide a more ecologically valid context for eliciting empathic concern and prosocial behavior in preschoolers. Integrating neural measures with naturalistic behavioral paradigms would help bridge this gap and provide a more ecologically valid understanding of early social behavior.

Conclusion

In sum, across two studies, this dissertation demonstrates that neural responses to emotional facial expressions are meaningfully linked to key aspects of early social development. The findings highlight the central role of facial emotion processing in supporting both the emergence of ToM, as well as the combined effect of facial emotion processing and ToM to predict prosocial behavior. More broadly, these studies suggest that early neural attentional mechanisms to facial cues may serve as a foundational building block for children’s developing social-cognitive and prosocial abilities.

References

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