Neurophysiological Mechanisms of Social Communication Deficits in Children with Autism: A Parent-Child Synchrony Perspective

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Abstract

Social communication impairment constitutes a core symptom of autism spectrum disorder. Previous research has predominantly interpreted this core symptom through individual factors such as deficits in social attention or empathic ability, thereby neglecting the fundamentally interpersonal nature of social communication. Interpersonal synchrony theory posits that behavioral and physiological synchronization between interaction partners serves as a crucial factor in maintaining and promoting interpersonal communication. Therefore, this study proposes to integrate artificial intelligence and functional near-infrared spectroscopy hyperscanning technology to investigate the characteristics and neurophysiological mechanisms of parent-child synchrony in autism, and to analyze its relationship with social communication impairments in children. This conceptual framework offers theoretical elucidation for the pathological mechanisms underlying social communication impairment from a novel parent-child synchrony perspective, while providing technical support for early screening of autism spectrum disorder.

Full Text

The Neurophysiological Mechanism of Social Communication Impairments in Children with Autism: A Perspective from Parent-Child Synchrony

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Abstract

Social communication impairment is a core symptom of autism spectrum disorder (ASD). Previous research has predominantly interpreted this core symptom through individual factors such as deficits in social attention or empathy, overlooking the inherently interpersonal nature of social communication. Interpersonal synchrony theory posits that behavioral and physiological synchrony between interacting parties is essential for maintaining and enhancing interpersonal communication. Therefore, this study aims to integrate artificial intelligence with functional near-infrared spectroscopy hyperscanning technology to investigate the characteristics and neurophysiological mechanisms of parent-child synchrony in children with autism and to analyze its relationship with their social communication impairments. This framework could provide a theoretical explanation for elucidating the pathological mechanisms of social communication impairments from the novel perspective of parent-child synchrony and offer technical support for the early screening of autism.

Keywords: autism spectrum disorder, social communication impairment, parent-child synchrony, early screening

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1. Problem Statement

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by core symptoms of social communication impairment, repetitive and restrictive behaviors, and narrow interests, representing one of the most common developmental disorders in children (American Psychiatric Association, APA, 2013). According to the World Health Organization (WHO, 2024), the global prevalence of autism in children is approximately 1%. The latest survey from the U.S. Centers for Disease Control and Prevention (CDC, 2024) reports that the prevalence among American children has reached as high as 1 in 36. In 2020, *Neuroscience Bulletin* published the first nationwide study revealing a prevalence rate of 0.7% among Chinese school-aged children aged 6–12, indicating that approximately 1 in 142 children in China has autism (Zhou et al., 2020). Autism symptoms typically emerge in infancy and persist throughout life, with unclear etiology and no effective pharmacological treatments. Autism severely threatens children's ability to live independently, access education, and establish healthy social relationships (Van Heijst & Geurts, 2015). As the core symptom, social communication impairment represents the greatest obstacle for children with autism to reintegrate into society and achieve high-quality lives. Therefore, investigating the mechanisms underlying this core symptom and developing effective early screening and intervention strategies have become central issues in autism research.

Previous studies have primarily understood social communication impairments in children with autism from an individual perspective, attributing the core deficits to reduced social attention (Del Bianco et al., 2021; Haskins et al., 2022), impaired theory of mind or empathy (Griffin et al., 2021; Jaisle et al., 2023), and motor skill deficiencies (Monier & Droit-Volet, 2019). These studies have revealed the unique characteristics of information processing and social cognition in children with autism, providing important clues for understanding social communication impairments. However, recent research has found that deficits in these areas do not fully determine the quality of social interactions in children with autism. Social communication impairment is more likely a complex interpersonal interaction problem rather than merely an individual issue of the child with autism (Bowsher-Murray et al., 2022; Murat Baldwin et al., 2022).

From an interpersonal interaction perspective, interpersonal synchrony theory posits that successful social interaction depends not only on individual social abilities but also on the coordination and synchrony between interacting partners in facial expressions, movements, speech, and even physiological responses and brain activation levels (Feldman, 2007, 2012). Interpersonal synchrony is considered fundamental to social communication, not only facilitating connection and emotional resonance between interaction partners but also influencing individuals' social-cognitive and socio-emotional capacities. Existing research has demonstrated that interpersonal synchrony plays a crucial role in parent-child interactions among typically developing children (Davis et al., 2018; DePasquale, 2020), while children with autism may show significant deficits in this regard. For instance, children with autism exhibit lower levels of motor synchrony, facial expression synchrony, and physiological and neural synchrony during parent-child interactions compared to typically developing children (Kruppa et al., 2021; Valentovich et al., 2018; Wang et al., 2021). This suggests that social communication impairments in children with autism may stem not only from their own social-cognitive and emotion regulation deficits but also from their difficulty in establishing synchrony with others during interactions.

During early development, the family represents the most important environment for children with autism, with parents serving as their primary interaction partners (Pacia et al., 2022). Research indicates that the quality of parent-child interactions significantly impacts the development of social skills in children with autism, with emotional bonding, interaction patterns, and physiological synchrony all influencing children' s social capacities (DePasquale, 2020). Parents often need to invest more effort in adjusting their interaction styles to accommodate the special needs of children with autism, while a lack of parent-child synchrony may further exacerbate children' s social difficulties. Therefore, studying the behavioral, physiological, and neural synchrony of children with autism in parent-child interactions can provide a new perspective for revealing the pathological mechanisms underlying the core symptom of social communication impairment.

Building on basic theoretical research, translating research findings into clinical practice represents another important challenge for autism researchers. Currently, early screening for autism primarily relies on scale assessments focusing on individual behavioral characteristics. Commonly used screening tools include first-level screening instruments such as the Checklist for Autism in Toddlers (CHAT), Modified CHAT (M-CHAT), and CHAT-23 (Baron-Cohen et al., 1992; Robins et al., 2001; Wong et al., 2004), as well as second-level screening tools like the Autism Behavior Checklist (ABC; Krug et al., 1980) and the Clancy Autism Behavior Scale (CABS; Clancy et al., 1969). Diagnostic assessments rely on instruments such as the Autism Diagnostic Interview-Revised (ADI-R; Lord et al., 1994) and the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord et al., 2012). However, these screening tools suffer from issues such as time-consuming evaluation, subjectivity, and high professional requirements for clinicians, affecting screening efficiency and accuracy (Cai et al., 2022; Zhao et al., 2023).

In recent years, technological advances have enabled researchers to develop more objective screening tools by integrating eye-tracking, electroencephalography (EEG), and magnetic resonance imaging (MRI). For example, eye-tracking studies have found significant abnormalities in face viewing patterns and attention to social scenes in children with autism (Liu et al., 2016; Wen et al., 2022). EEG research has shown differences in EEG power spectra during resting and task states in children with autism (Kang et al., 2020). MRI studies have revealed abnormalities in brain volume, extra-axial cerebrospinal fluid volume, and resting-state functional connectivity patterns in children with autism (Reiter et al., 2021; Shen et al., 2018; Sun et al., 2021). However, most existing studies rely on basic tasks in laboratory settings, such as viewing emotional pictures or simple social scenes, lacking capture and analysis of children’ s behavioral performance in real social situations, which limits their clinical applicability.

Therefore, this study aims to explore the behavioral synchrony (motor and facial expression synchrony) and its neurophysiological mechanisms in children with autism during parent-child interactions from the perspective of interpersonal synchrony theory, revealing the mechanisms underlying social communication impairments. Based on these findings, this study will also explore the feasibility of using parent-child synchrony as an objective indicator for early autism screening, providing theoretical and technical support for developing more clinically applicable objective screening tools. This research will not only deepen understanding of social communication impairments in autism but also provide new screening approaches for clinical practice.

2.1 Autism Social Communication Impairment and Parent-Child Behavioral Synchrony

Previous research has identified numerous individual factors that may contribute to social communication impairments in children with autism, with particular attention paid to social attention patterns, emotional or empathic abilities, and motor skills (Del Bianco et al., 2021; Griffin et al., 2021; Monier & Droit-Volet, 2019). Some empirical studies have supported these factors, yet other research suggests that none of these individual factors are deterministic causes of social communication impairments in children with autism (Bowsher-Murray et al., 2022; Murat Baldwin et al., 2022). Taking social attention patterns as an example, social motivation theory posits that abnormal development of reward-related neural mechanisms in individuals with autism leads to reduced sensitivity to social rewards while showing abnormal preferences for certain non-social rewards (Chevalier et al., 2012; Yi et al., 2022). Specifically, this manifests as less attention to faces, particularly the eye region, and more attention to non-social stimuli (such as geometric patterns, mechanical objects, etc.) (Kwon et al., 2019; Wang et al., 2021). This dual abnormality creates significant challenges in social interactions: on one hand, they struggle to obtain expected reward experiences from social interactions; on the other hand, abnormal preferences for non-social stimuli may further weaken their motivation to engage in social activities (McNaughton & Redcay, 2020). This insensitivity to social stimuli combined with excessive attention to non-social stimuli is considered one of the core mechanisms underlying social difficulties in individuals with autism (Chevallier et al., 2012).

However, research on typically developing parent-child dyads has found that during positive parent-child interactions, children should allocate more attention to the toys used in the interaction rather than to their parents' facial regions (Deák et al., 2018). For example, Yu and Smith (2017) used eye-tracking to record gaze behavior in 51 toddlers aged 11–24 months while playing with toys together with their parents. The study found that joint attention between toddlers and parents was not achieved by following each other's gaze but by attending to each other' s hand movements while manipulating objects. Furthermore, the study revealed that differences in hand-eye coordination between parents and children were closely related to their joint attention performance, with dyads showing higher hand movement coordination achieving joint attention more frequently. This finding challenges the view that understands autism social communication impairments solely from the perspective of children' s individual social attention patterns, suggesting that attention allocation in social interactions may be influenced by context and interaction partners rather than just children' s individual attention preferences. Therefore, social communication impairments in children with autism may need to be understood within the broader context of social interactions rather than being attributed solely to their social attention patterns. The meaning of social interactions emerges from the interaction process and the individuals involved, a concept known as "participatory sense-making" (Fuchs

& Jaegher, 2009). Consequently, beyond the child' s own factors, differences in basic psychological states such as perception, thinking, intentions, and beliefs between children with autism and their interaction partners may make it difficult for them to find common ground during interactions. The double empathy problem perspective suggests that because individuals with autism process and experience the world differently from neurotypical individuals, they also have different norms and expectations, making it difficult for both parties to empathize with each other during interactions and leading to social failure (Bolis et al., 2018; Milton, 2012). These challenging findings regarding individual child factors and the theoretical perspective of the double empathy problem both suggest that we should shift from an individual perspective to an interpersonal interaction perspective to re-examine the mechanisms of social communication impairments in autism.

Interpersonal synchrony is an important indicator of interpersonal interaction quality, referring to the process during which interaction partners coordinate their eye contact, facial expressions, body movements, and even physiological responses and brain activity levels (Feldman, 2007; Harrist & Waugh, 2002). Interaction partners' basic psychological states change in real time. To accurately understand each other' s intentions and achieve effective social interaction, individuals need to promptly adjust their movements and emotional expressions to synchronize with their partners. For example, during a parent-child joint block-building activity, the mother first builds part of the structure, then uses verbal and gestural cues to guide the child to complete the next part while continuously shifting her gaze between the child' s actions and the blocks. If the child focuses only on the blocks while ignoring the mother' s verbal, motor, and attentional cues, their interaction quality will certainly suffer. Similarly, when a child experiences strong positive emotions while playing with blocks and expresses them through speech or smiles, if the mother fails to provide timely feedback on the child' s emotional and verbal information, this will also damage parent-child interaction quality. Empirical research has found that early development of children' s socio-emotional abilities and social communication skills is greatly influenced by emotional synchrony (Davis et al., 2018; Feldman, 2015; Scholtes et al., 2021) and motor synchrony (Bowsher-Murray et al., 2022; Hoehl et al., 2021) during interpersonal interactions.

In fact, interpersonal synchrony is an important aspect of early autism screening. China' s "Expert Consensus on Early Identification, Screening, and Intervention for Children with Autism Spectrum Disorder" (Li, 2017) identifies the "Five No' s" behaviors—no/limited looking, no/limited responding, no/limited pointing, no/limited speaking, and inappropriate behavior—as early behavioral markers of social communication impairment in autism, particularly emphasizing that these autism warning signs should be identified within interpersonal interactions. Furthermore, the importance of interpersonal synchrony is also confirmed in autism diagnostic and assessment tools. Standardized diagnostic instruments such as the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord et al., 2012) and the Autism Diagnostic Interview-Revised (ADI-R; Lord et al., 1994) specifically focus on behavioral synchrony in interpersonal interaction contexts.

2.2 Neurophysiological Mechanisms of Parent-Child Synchrony in Autism

The autonomic nervous system (ANS) provides physiological support for ongoing social interactions and individuals' emotional responses (Porges & Furman, 2011). Among various indicators reflecting ANS function, respiratory sinus arrhythmia (RSA) has received the most attention in parent-child synchrony research (DePasquale, 2020; Miller et al., 2023). RSA refers to the degree of periodic and regular changes in sinoatrial node automaticity due to changes in vagal tone during respiration, reflecting the ANS' s regulatory role in social and emotional information processing (Porges, 2007). Research suggests that children with autism may have abnormal ANS function (Baker et al., 2020; Corbett et al., 2019). Specifically, compared to typically developing children, children with autism show lower RSA levels at rest (Condy et al., 2017; Neuhaus et al., 2014) and often exhibit abnormal RSA reactivity during social interactions (Corbett et al., 2019; Fenning et al., 2018). For example, Neuhaus et al. (2016) compared RSA levels in 8–11-year-old children with autism and typically developing children during positive parent-child interactions (joint toy play). They found that typically developing children not only had higher overall RSA levels during interactions but also showed gradually increasing RSA levels as the positive interaction progressed. In contrast, children with autism maintained consistently low RSA levels throughout and lacked dynamic changes. This abnormal ANS function may affect the social abilities of children with autism, making it difficult for them to adapt to the dynamic changes in social contexts during parent-child interactions, thereby damaging interaction quality and weakening physiological synchrony between parents and children.

However, only one study has examined RSA synchrony between children with autism and their interaction partners during social interactions (Wang et al., 2021). The results showed that RSA synchrony in children with autism during a cooperative drawing task with their parents was significantly lower than that in typical parent-child dyads. Further analysis revealed that more severe autism symptoms and more internalizing psychopathology (such as anxiety and depression) in children, along with poorer parent-child interaction quality, were associated with lower parent-child RSA synchrony. This study provides preliminary evidence for understanding physiological synchrony in children with autism during social interactions and suggests that social difficulties in children with autism may be related to their inability to establish and maintain physiological synchrony with interaction partners.

In addition to the ANS, the central nervous system' s brain also plays a crucial role in social information processing, understanding others' intentions, emotional states, and behavioral actions (Ratliff et al., 2022; Li et al., 2018). During interpersonal interactions, synchrony in different physiological systems between interaction partners may have different meanings. For example, ANS synchrony may primarily reflect the degree of synchronized arousal between partners, while synchrony between two interacting brains may more strongly reflect cognitive synchrony processes (Quiñones-Camacho et al., 2020). Research on inter-brain synchrony can help us more comprehensively and deeply understand the neural mechanisms underlying behavioral synchrony in autism parent-child dyads.

Brain-to-brain synchrony, or neural synchrony, represents a new direction in interpersonal synchrony research that has gradually developed with advances in "hyperscanning" technology (Montague et al., 2002), which can simultaneously monitor brain activity in two or more individuals during social interactions. During interpersonal interactions such as cooperative button-pressing tasks (Kruppa et al., 2021; Miller et al., 2019) or more natural behaviors like mutual gaze (Hirsch et al., 2017), hand-holding (Goldstein et al., 2018), free conversation (Nguyen et al., 2021), and cooperative drawing (Neugyen et al., 2020), the brain activity of interaction partners shows synchronized patterns.

During interpersonal interactions, the prefrontal cortex (PFC), closely associated with attention processing and mentalizing, and the temporo-parietal junction (TPJ), involved in perceiving social stimuli and forming social bonds, play particularly critical roles (Hoehl et al., 2021; Lougheed & Keskin, 2021; Nguyen et al., 2021). The joint social attention system theory proposed by Gvirts and Perlmutter (2020) suggests that these two brain regions constitute the neural foundation of social interaction: they not only participate in individuals' joint attention processing of external stimuli but also support real-time mutual understanding of each other' s behaviors and emotional states, thereby playing a key role in maintaining and promoting social interactions.

Currently, only two studies have examined inter-brain synchrony in children with autism. In one study, researchers used functional near-infrared spectroscopy (fNIRS) hyperscanning technology to examine inter-brain synchrony in 16 parent-child dyads with children aged 5–11 years with autism during cooperative button-pressing and independent button-pressing tasks (Wang et al., 2020). The results showed that inter-brain synchrony in the prefrontal cortex was significantly higher during the cooperative task than during the independent task. Additionally, weaker inter-brain synchrony was associated with more severe autism symptoms in children. This study was the first in the autism field to examine inter-brain synchrony and pioneered a new direction for elucidating autism core symptoms from the perspective of inter-brain synchrony during interpersonal interactions. Subsequently, Kruppa et al. (2021) used the same technology and found similar results: autism parent-child dyads showed above-chance-level prefrontal cortex synchrony during both cooperative and competitive tasks. Although these results provide preliminary evidence that lower inter-brain synchrony in children with autism may be a neural mechanism of social communication impairment, these two studies have several limitations, including small sample sizes and lack of comparison with typical parent-child dyads. The most serious issue is the selection of experimental tasks: both studies used computer-based button-pressing tasks, which differ substantially from real social interactions (Chen et al., 2023; Zampella et al., 2020). Whether these findings can be generalized to neural synchrony patterns in natural interpersonal interactions of children with autism remains unclear. A recent study examined inter-brain synchrony in adults with autism during natural interactions and found that weaker TPJ synchrony between adults with autism and their interaction partners during conversation was associated with more severe social communication impairments (Quiñones-Camacho et al., 2021). This finding provides preliminary evidence for the relationship between inter-brain synchrony in natural interactions and social communication impairment in autism. However, no studies have examined neural synchrony in children with autism in naturalistic contexts. Thus, investigating inter-brain synchrony during real social interactions is crucial for understanding the neural mechanisms of interpersonal interaction and social communication in children with autism.

2.3 Early Screening for Social Communication Impairments in Autism

Social communication deficits in autism emerge during early childhood, and early screening can promptly identify abnormal behaviors in children, providing support for early diagnosis and intervention to help children benefit maximally from early intervention. The American Academy of Pediatrics (AAP) recommends that, in addition to routine developmental monitoring and screening, all toddlers should be screened for autism during well-child visits at 18–24 months. Although autism can be diagnosed in children as young as 2 years old, in the United States, most children are not diagnosed until after age 4 (CDC, 2024). In China, the situation is even less ideal, with only a handful of pediatricians, child health physicians, and psychiatrists able to effectively identify autism.

The main obstacle to early screening and diagnosis of autism is the limited number of observable, objective indicators in infants and toddlers. Currently, early screening for autism primarily relies on clinicians taking medical histories and conducting behavioral observations, with screening tools mainly consisting of questionnaires and scales (Cai et al., 2022; Zhao et al., 2023). Specifically, early screening for autism typically involves two stages. First-level screening aims to identify suspected ASD cases from the general child population, with commonly used tools including the Checklist for Autism in Toddlers (CHAT; Baron-Cohen et al., 1992) and its revised versions (M-CHAT; Robins et al., 2001), as well as the CHAT-23 (Wong et al., 2004; Gong et al., 2015). For children who screen positive at the first level, second-level screening is conducted using more specialized assessment tools. Commonly used tools at this stage include the Autism Behavior Checklist (ABC; Krug, 1978), Clancy Autism Behavior Scale (CABS; Clancy, 1969), Screening Tool for Autism in Two-Year-Olds (STAT; Stone et al., 2000), and Autism Spectrum Quotient for Children (AQ-Child; Auyeung et al., 2008). If second-level screening remains positive, diagnostic assessment tools are used for confirmation, including the Autism Diagnostic Interview-Revised (ADI-R; Lord et al., 1994), Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord et al., 2012), and Childhood Autism Rating Scale (CARS; Lu et al., 2004). However, these screening tools face numerous challenges in clinical application. First, the screening process involves multiple steps including scale completion, history taking, clinical observation, and comprehensive scoring, making the overall assessment time-consuming and affecting screening efficiency. Second, accurate early screening requires clinicians to have solid professional knowledge of developmental characteristics and clinical manifestations of children with autism, necessitating systematic professional training to ensure doctors can proficiently use screening tools and make accurate judgments about observed child behaviors. However, limited by clinical workload and training resources, implementing systematic screening training presents practical difficulties. Therefore, developing objective and precise auxiliary tools for early autism screening and constructing a multi-dimensional risk assessment system have become urgent needs in current clinical practice.

In recent years, with scientific and technological advances, researchers have combined eye-tracking, EEG, and MRI technologies to develop some objective autism screening tools (see reviews by Chang et al., 2024; Li et al., 2022; Zhu et al., 2024). Regarding eye-tracking screening indicators, numerous studies have shown that children' s abnormal visual preferences and gaze characteristics, such as reduced fixation on faces and their core regions (especially the eye area), decreased attention to social scenes, and increased attention to non-social scenes, can serve as important indicators for early autism screening. For example, Liu et al. (2016) found that analyzing children' s scanning patterns of faces, particularly core regions, during static face recognition tasks could effectively distinguish children with autism aged 4–11 from typically developing children. Similarly, in dynamic face recognition tasks, children with autism showed significantly reduced fixation time on the eyes, nose, mouth, and cheeks of faces when viewing dynamic videos, particularly on the mouth and body, effectively distinguishing them from healthy controls (Wan et al., 2019). Additionally, researchers have consistently found that children with autism show a greater tendency to fixate on repetitive geometric patterns and significantly less attention to various social scenes when comparing their gaze preferences for geometric figures versus social scenes (Moore et al., 2018; Pierce et al., 2016; Wen et al., 2022).

Regarding EEG screening indicators, researchers have combined EEG data with machine learning techniques to develop various early screening indicators. For example, Kang et al. (2020) collected EEG data from children aged 3–6 during resting state and while viewing face pictures, calculating relative power in δ, , α, β, and γ frequency bands. The results showed that children with autism had significantly higher EEG power in the band and significantly lower power in β and γ bands compared to healthy controls. Furthermore, using relative power from these five frequency bands combined with a Support Vector Machine (SVM) algorithm could effectively distinguish healthy children from children with autism.

In terms of MRI screening, autism is believed to be closely related to abnormal brain volume growth during early development, making brain volume differences a potential auxiliary indicator for early screening (Hazlett et al., 2017). For instance, Shen et al. (2018) used structural MRI (sMRI) to measure extra-axial cerebrospinal fluid volume and brain volume in 159 children with autism aged 2–4 years and 77 typically developing children. The study found that, after controlling for brain volume, body weight, sex, and age, children with autism showed a significant 15.1% increase in extra-axial cerebrospinal fluid volume compared to typically developing children. Additionally, using extra-axial cerebrospinal fluid volume, brain volume, and head circumference as feature vectors combined with machine learning algorithms could effectively predict autism diagnosis. Moreover, resting-state functional MRI (rsfMRI) studies have shown that resting-state functional connectivity patterns can also serve as potential biomarkers for autism (Reiter et al., 2021; Sun et al., 2021).

Although current autism screening tools based on eye-tracking, EEG, and MRI technologies have made some progress, the experimental task designs of these tools still have limitations. Most existing studies focus on basic emotion recognition and visual preference tasks (such as comparisons between geometric figures and social scenes) and use static pictures as stimuli. Although some recent studies have begun to attempt introducing real social scenes, their task designs remain limited to children passively observing others' emotions and behaviors in social situations, failing to fully capture children' s dynamic characteristics in real interactions. Therefore, there is currently a lack of effective tools that automatically extract objective indicators based on children' s emotional and behavioral performance in real social situations for autism screening. This limitation severely restricts the ecological validity of screening tools and their promotion value in clinical practice.

Notably, children' s social skills are primarily formed and developed through real interpersonal interactions, especially parent-child interactions. Therefore, developing early screening tools for autism using parent-child synchrony as an objective indicator can provide new ideas and technical support for clinical practice. However, as a screening tool, its core lies in having objective and quantifiable indicators. Consequently, how to quantitatively assess behavioral and neurophysiological synchrony in real-time parent-child interactions, particularly extracting automated and standardized evaluation indicators, has become an important technical challenge for current research.

In research on motor synchrony indicators, previous studies have primarily used structured behavioral tasks (e.g., cooperative button-pressing) and then calculated the time difference in joint button-pressing responses between interaction partners as a quantitative indicator of behavioral synchrony—that is, the shorter the time difference, the higher the degree of motor synchrony (Kruppa et al., 2021; Wang et al., 2020). However, such structured behavioral tasks suffer from insufficient ecological validity, making it difficult to reflect the characteristics of interpersonal interactions in natural contexts. To overcome this limitation, recent studies have begun to focus on synchrony in real interpersonal interactions, such as motor synchrony during free play and free conversation (Chen et al., 2023; Zampella et al., 2020). However, the accompanying problem is the inability to objectively quantify the degree of motor synchrony. Since interpersonal interactions in natural contexts are irregular, complex, and full of uncertainty, synchrony can only be estimated through researchers' behavioral coding of interaction videos, a method that is highly subjective and inefficient. Although many studies have shown that poor motor synchrony in children with autism during interpersonal interactions may be a pathological mechanism of their social communication impairment (Fitzpatrick et al., 2017; Kaur et al., 2018), the subjectivity of current assessment methods severely limits the application of these research conclusions in autism early screening practice.

To address these issues, recent advances in computer science and artificial intelligence have provided new possibilities for objective quantification of interpersonal synchrony. The multi-person pose estimation model based on AlphaPose (regional multi-person pose estimation, RMPE) offers technical support for objectively calculating motor synchrony between interaction partners in real interaction contexts (Fang et al., 2017, 2022; Li et al., 2019). AlphaPose is a staged detection model that uses a top-down approach, first detecting human regions in images or video information and marking them with rectangular boxes, then applying human pose estimation algorithms to detect key points in the detected human regions for pose estimation. A recent study applied this technology to objectively quantify motor synchrony between toddlers with autism and their teachers during free play (Chen et al., 2023). The results showed that, compared to typically developing children, toddlers with autism exhibited lower motor synchrony with teachers in upper limbs and trunk, approaching random levels, and that motor synchrony levels were significantly negatively correlated with autism symptoms. This study suggests that machine learning techniques can be used to analyze the degree of motor synchrony between parents and children during real interactions.

Additionally, no studies have yet explored the quantitative computation of facial expression synchrony. Although some studies have found that children with autism show lower facial expression synchrony during interpersonal interactions compared to typical parent-child dyads, and that facial expression synchrony levels are significantly negatively correlated with autism symptoms (Ting & Weiss, 2017; Valentovich et al., 2018), these studies have all assessed facial expression synchrony through behavioral coding. How to objectively and quantitatively analyze interaction partners' facial expressions is also an important technical challenge.

The recent facial action coding system—FaceReader—can automatically identify and analyze six basic emotions (happiness, sadness, anger, surprise, fear, disgust) and neutral emotional states, with an average recognition accuracy of up to 99% for different types of facial expressions (Stöckli et al., 2018). Research has shown that this system can effectively recognize facial emotions in Chinese individuals (Shi & Li, 2018). However, no studies have yet applied this system to research on autism parent-child dyads. Regarding physiological and neural synchrony indicators, no studies have yet applied them to autism screening practice.

3 Research Framework

Guided by interpersonal synchrony theory, this study will combine multi-person pose estimation, automatic facial expression recognition, physiological measurement, behavioral coding, and fNIRS hyperscanning technology to explore the behavioral synchrony and its neurophysiological mechanisms in children with autism during natural interactions with their parents, and to investigate the possibility of using parent-child synchrony as an objective indicator for early screening of social communication impairments in autism. Study 1 will comprehensively assess facial expression and body movement synchrony in autism parent-child dyads during free interactions through behavioral experiments, examining the characteristics of parent-child behavioral synchrony and testing its relationship with children's social communication impairments. Study 2 will use physiological polygraphy and fNIRS hyperscanning technology to examine RSA synchrony and inter-brain synchrony in autism parent-child dyads during interactions, clarifying the neurophysiological mechanisms of parent-child behavioral synchrony and its impact on social communication impairments in children with autism. Study 3 will use a longitudinal design and machine learning methods to explore the predictive value of early behavioral and neurophysiological synchrony between high-risk autism toddlers and their parents for autism diagnosis one year later, to validate the feasibility of using parent-child synchrony as an objective indicator for early autism screening. The overall research framework is shown in Figure 1 [Figure 1: see original paper].

3.1 Study 1: The Relationship Between Parent-Child Behavioral Synchrony and Social Communication Impairment

Study 1 will investigate the behavioral synchrony (including motor and emotional synchrony) between children with autism and their parents during free interactions and test its relationship with children' s social communication impairments. Currently, researchers favor using structured and rhythmic behavioral tasks such as cooperative button-pressing, hand-clapping, and joint drumming to create interpersonal synchrony scenarios (Fitzaptrick et al., 2017; Fulceri et al., 2018), as these highly structured tasks make it relatively easy to assess behavioral synchrony in interpersonal interactions. However, the behavioral synchrony demonstrated in these tasks is intentional synchrony, which differs substantially from spontaneous synchrony that occurs naturally in real-world settings. Real interpersonal interactions are more complex, unstructured, and full of uncertainty, making it difficult to effectively generalize relevant findings to real interactions (Georgescu et al., 2020; Zampella et al., 2020). To truly understand the characteristics of synchrony between children with autism and their parents during interactions, Study 1 will employ a parent-child free play task.

This study plans to recruit 100 parent-child dyads, including 50 children with autism aged 3–6 years and 50 typically developing children. Inclusion criteria for children with autism are: (1) diagnosis by a clinician according to DSM-5 criteria for autism spectrum disorder (APA, 2013); (2) diagnostic confirmation through ADOS-2 and CARS; (3) exclusion of other neurodevelopmental disorders or serious physical illnesses. Inclusion criteria for typically developing children are: (1) matching in age, sex, and IQ with children with autism; (2) no neurodevelopmental disorders, psychiatric disorders, or physical illnesses.

Upon arrival at the laboratory, parents will complete questionnaires on basic demographic information (e.g., child' s sex, birth date, time of autism diagnosis) and report on their children' s social communication abilities using the Social Responsiveness Scale, Second Edition (SRS-2; Constantino & Gruber, 2012). Subsequently, parent-child dyads will complete a 15-minute free interaction task, with video recordings capturing facial expressions and body movements during the interaction.

Data Analysis and Hypotheses

Emotional Synchrony Analysis: The facial expression analysis system will be used for automatic recognition and analysis of facial expressions during parent-child interactions. First, face finding will be performed using deep learning-based face detection algorithms to locate faces. Next, face modeling will create accurate artificial face models using nearly 500 key points. Finally, face classification will categorize expressions using artificial neural networks. This facial expression analysis system can identify, every 0.3 seconds in video data, the percentage of six basic emotions (happiness, sadness, anger, surprise, fear, disgust) and neutral emotion, as well as emotional valence and arousal, gaze direction, and other information.

Based on automatically recognized and analyzed facial expression data, parent-child facial expression synchrony will be calculated. Hierarchical Linear Modeling (HLM) will be applied to automatically extracted facial expression data from both parents and children to analyze the degree of parent-child facial expression synchrony. The specific formulas are as follows:

$$\text{Child's expression component}_t = b_0 + b_1 \times \text{time} + b_2 \times \text{parent's expression component}_t + \varepsilon_t$$
$$b_0 = \gamma_{00} + \upsilon_0$$
$$b_1 = \gamma_{10} + \upsilon_1$$
$$b_2 = \gamma_{20} + \upsilon_2$$

As shown in the formulas above, the child' s facial expression component data at time point t is the dependent variable. At Level 1, the time variable is included to control for changes in children' s facial expression components over time; the parent' s facial expression component data at the current time is included, so b_2 represents the parent-child facial expression synchrony coefficient. At Level 2, no other inter-dyad variables are included. Subsequently, Empirical Bayes coefficients (EB coefficients) representing parent-child facial expression synchrony levels (γ_{20}) are extracted from the residual data at Level 2. These coefficients quantify facial expression synchrony for each parent-child dyad. Finally, regression analysis is used to test the predictive effect of parent-child facial expression synchrony on social communication impairments in children with autism. We hypothesize that lower emotional synchrony between parents and children during free interactions will be associated with more severe social communication impairments in children with autism.

Motor Synchrony Analysis: The AlphaPose multi-person pose estimation model (Fang et al., 2017, 2022) will be used to calculate the degree of motor synchrony during parent-child interactions. The specific procedure is as follows: First, Faster Region-based Convolutional Neural Network (Faster R-CNN) will detect human regions in the input video data. Second, Regional Multi-person Pose Estimation (RMPE) will estimate poses in the detected human regions. Finally, based on previous research (Chen et al., 2023; Georgescu et al., 2020), Windowed Cross-Correlation (WCC) will quantify the degree of motor synchrony during real-time parent-child interactions. Regression analysis will similarly test the predictive effect of motor synchrony on social communication impairments in children with autism. We hypothesize that lower motor synchrony between parents and children during free interactions will be associated with more severe social communication impairments in children with autism.

3.2 Study 2: The Relationship Between Parent-Child Neurophysiological Synchrony and Social Communication Impairment

Study 2 will use multiple natural interaction contexts to validate the results of Study 1 and further explore whether motor and facial expression synchrony in autism parent-child dyads can be reflected in physiological and neural synchrony, to reveal the neurophysiological mechanisms underlying parent-child behavioral synchrony and its relationship with social communication impairments in children with autism. Since both the autonomic nervous system and the central nervous system (the brain) provide physiological support for ongoing social interactions, synchrony in arousal levels of the autonomic nervous system and brain activation levels between interaction partners may reflect joint attention to external stimuli and mutual understanding of each other' s behaviors and emotional states (Gvirts & Perlmutter, 2020; Neugyen et al., 2020). Social communication impairments in children can severely disrupt parent-child interactions, resulting in asynchronous emotional states (Ting & Weiss, 2017) and inflexible interaction behaviors (Valentovich et al., 2018). According to biobehavioral synchrony theory (Feldman, 2007, 2012), parent-child physiological and behavioral synchrony are closely connected. Therefore, children' s social communication impairments may also cause mismatches in physiological or neural activity between both parties.

The participants in this study are the same as in Study 1. During the experiment, children with autism and their parents will complete three interaction tasks (free play, cooperative drawing, and conflict topic discussion) to simulate the most common scenarios in real interactions. During parent-child interactions, BioPac MP160 physiological polygraphy will simultaneously collect heart rate and respiration data from both parents and children, while fNIRS hyperscanning technology will simultaneously record brain activity levels in both parties. The primary brain region of interest is the prefrontal cortex (PFC), as it is closely related to joint attention to external stimuli and mutual understanding of behaviors and emotions between interaction partners during interpersonal interactions (Nguyen et al., 2021; Quiñones-Camacho et al., 2020).

Data Analysis and Hypotheses

Parent-child heart rate data will be analyzed offline to calculate the degree of parent-child RSA synchrony. First, MindWare HRV software will analyze raw electrocardiogram and respiration data to obtain raw RSA values. According to heart rate variability frequency domain calculation guidelines (Task Force, 1996), R-wave time series of heart rate signals within the respiratory frequency range will be extracted. In this process, children' s bandpass filter will be set to 0.24–1.04 Hz, and parents' bandpass filter to 0.12–0.40 Hz, serving as raw RSA values during interaction tasks. The extracted RSA data will be segmented into 30-second intervals for subsequent synchrony analysis. HLM will be used to calculate parent-child RSA synchrony, with the same computational method as for facial expression synchrony in Study 1.

Inter-brain synchrony levels will be calculated. First, the Homer 2 toolbox in Matlab will preprocess the near-infrared spectroscopy data. Then, the "Motion_{{{Artifacts}}*{{By}}*}{Channel}" function will detect motion artifacts in each channel. A spline interpolation-based motion correction algorithm will correct artifacts (Scholkmann et al., 2010). Preprocessed optical density signals will then be converted to oxyhemoglobin and deoxyhemoglobin concentrations according to the modified Beer-Lambert law. Finally, the wavelet coherence function in Matlab' s Wavelet Toolbox will calculate inter-brain synchrony using wavelet transform coherence (WTC; Grinsted et al., 2004).

Correlation and regression analyses will explore associations between parent-child facial expression and motor synchrony and RSA synchrony and inter-brain synchrony. Additionally, the study will test the explanatory and predictive effects of parent-child behavioral and neurophysiological synchrony on social communication impairments in children with autism. Study 2 hypotheses are: (1) Parent-child emotional and motor synchrony levels will be significantly positively correlated with RSA synchrony and inter-brain synchrony levels across the three interaction tasks; (2) Lower parent-child RSA synchrony and inter-brain synchrony levels will be associated with more severe social communication impairments in children with autism.

3.3 Study 3: Application of Parent-Child Synchrony to Early Screening of High-Risk Toddlers with Autism

Study 3 will use machine learning methods, with motor, facial expression, physiological, and neural synchrony between high-risk autism toddlers and their parents as indicators, to predict autism diagnosis one year later and examine the feasibility of using objective indicators of parent-child synchrony for early autism screening. Since social communication is a real-time dynamic interactive process between interaction partners, interpersonal synchrony may be a potential mechanism underlying social communication impairments in autism (Georgescu et al., 2020; McNaughton & Redcay, 2020). Building on the theoretical research results and technical methods from Studies 1 and 2 (including AlphaPose-based multi-person pose estimation, automatic facial expression recognition, and fNIRS hyperscanning technology), Study 3 will measure motor, facial expression, physiological, and inter-brain synchrony levels in 18–24-month high-risk autism toddlers during free interactions with their parents. Machine learning techniques will then be used to predict autism diagnosis one year later.

The study plans to recruit 100 parent-child dyads, including 50 toddlers aged 18–24 months assessed by clinicians as high-risk for autism and 50 typically developing toddlers matched in age and sex with the high-risk group. According to AAP recommendations for screening all toddlers for autism during well-child visits at 18–24 months, and given that some clinical autism screening tools are applicable to this age range (e.g., the M-CHAT scale is applicable to toddlers aged 16–30 months), this study selects 18–24-month high-risk autism toddlers as participants.

High-risk autism toddlers include those with: (1) one or more siblings diagnosed with autism; (2) premature infants (<32 weeks), low birth weight (<1500 g), small-for-gestational-age or large-for-gestational-age (>95th percentile birth weight) infants assessed by clinicians as having autism risk; (3) toddlers showing "Five No' s" behaviors before age 2 according to the "Expert Consensus on Early Identification, Screening, and Intervention for Children with Autism Spectrum Disorder" and assessed by clinicians as having autism risk; (4) toddlers identified as having autism risk by clinicians after M-CHAT screening.

Study 3 consists of two phases: Phase 1 is the toddler-parent interaction experiment. This study will recruit 18–24-month high-risk autism toddlers and typically developing toddlers and their parents to complete a 15-minute parent-child free interaction task in a laboratory setting, collecting video, electrocardiogram, respiration, and brain activity data. The specific task procedures, data collection, and parent-child synchrony data analysis methods are the same as in Studies 1 and 2. Phase 2 is follow-up of autism diagnosis. One year later, the study will follow up on whether high-risk autism toddlers and typically developing toddlers receive a clinical diagnosis of autism.

Data Analysis and Hypotheses

To test the feasibility of using parent-child synchrony as an objective indicator for early autism screening, Study 3 will use the classic machine learning algorithm—Support Vector Machine (SVM)—to predict whether toddlers will be diagnosed with autism one year later. SVM was selected for its ability to effectively handle high-dimensional data (performing well even when data dimensions exceed sample size) and its strong generalization ability. The specific computational procedure is as follows: First, emotional and motor synchrony, RSA synchrony, and inter-brain synchrony data from high-risk autism toddlers and typically developing toddlers during interactions with their parents at 18–24 months will serve as core features. Principal component analysis and other methods will extract features from training data, projecting high-dimensional data into low-dimensional space to select the most significant features. Subsequently, based on extracted features, training set labels will optimize the model to construct a decision function that can distinguish high-risk autism toddlers from typically developing toddlers. To address the small sample size issue, this study will use leave-one-out cross-validation (LOOCV), cycling through left-out subjects for prediction to enhance model robustness. Finally, algorithm evaluation will use accuracy, sensitivity, specificity, and receiver operating characteristic (ROC) curve metrics to assess the trained model. This study hypothesizes that the SVM model constructed based on parent-child emotional, behavioral, physiological, and neural synchrony data can accurately classify high-risk autism toddlers and typically developing toddlers and can accurately predict whether high-risk autism toddlers will be diagnosed with autism one year later.

4 Theoretical Framework

Social communication impairment is one of the core symptoms of children with autism, and its mechanisms have long been an important focus in the field. However, traditional research has primarily explored social deficits in children with autism from an individual level, such as reduced social attention, empathy deficits, and emotion regulation disorders (Del Bianco et al., 2021; Griffin et al., 2021). Although these studies have to some extent revealed difficulties in social information processing and interaction in children with autism, they have not fully explained the mechanisms of systematic interaction failure in real social contexts. The essence of social communication is the interactive process between people; therefore, social communication impairments in children with autism should not be viewed merely as individual ability deficits but should be understood as a dynamic, relational phenomenon.

Interpersonal synchrony theory provides a novel perspective for understanding social interaction, emphasizing the coordination and consistency between individuals and their interaction partners at emotional, motor, verbal, and neurophysiological levels (Feldman, 2007, 2012). Successful social interaction depends not only on individual social-cognitive abilities but more importantly on the dynamic bidirectional coordination formed between interaction partners during real-time communication. Existing research has shown that interpersonal synchrony plays a vital role in parent-child interactions and socio-emotional development in typically developing children (Davis et al., 2018; DePasquale, 2020). In contrast, children with autism often show synchrony difficulties at multiple levels—including emotion, motor, physiological, and neural activity—which may be a key mechanism underlying their social communication impairments (Kruppa et al., 2021; Valentovich et al., 2018; Wang et al., 2021).

Based on this, this study proposes that social communication impairments in children with autism are essentially a form of "synchrony impairment," meaning that synchrony deficits may lead to interaction failures in social contexts, thereby affecting the establishment of social relationships and the development of social adaptive abilities. Therefore, re-examining autism social communication impairments from the perspective of interpersonal synchrony will help reveal their underlying mechanisms and provide a new theoretical framework for early screening and intervention.

Among various social contexts, this study focuses on parent-child interaction contexts. Parent-child interaction is the primary form of social interaction in early childhood, and parent-child synchrony plays a central role in children' s socio-emotional development (Pacia et al., 2022). This study also proposes using multiple indicators of physiological and behavioral synchrony to deeply understand social communication impairments in children with autism. According to bio-behavioral synchrony theory (Feldman, 2007, 2012), successful parent-child interactions require synchronized coordination at three levels: behavioral (e.g., facial expressions, body movements), physiological (e.g., RSA), and neural (e.g., prefrontal cortex activation patterns). The dynamic synchrony across these three levels collectively forms the coordination foundation of parent-child interactions.

However, children with autism often show synchrony deficits during parent-child interactions. For example, their behavioral synchrony is lower, with facial expressions being asynchronous with parents, leading to reduced emotional resonance in social interactions (Valentovich et al., 2018). Autonomic nervous system synchrony is reduced, with children with autism showing lower RSA levels in social contexts and significantly lower RSA synchrony in parent-child interactions compared to typically developing children (Wang et al., 2021). Additionally, neural synchrony is abnormal, with lower neural synchrony in the prefrontal cortex between children with autism and their parents, which may affect joint attention and emotion regulation during social interactions (Kruppa et al., 2021). These findings suggest that social communication impairments in children with autism may result from impaired dynamic matching abilities across multiple dimensions (facial expression, motor, physiological, and neural activity), representing a multi-level synchrony deficit.

The theoretical framework constructed in this study is based on bio-behavioral synchrony theory (Feldman, 2007, 2012), proposing that social communication impairments in children with autism can be understood by analyzing their parent-child synchrony (behavioral, physiological, and neural synchrony). This theory not only helps explain the social difficulties of children with autism but also provides new measurement indicators for early screening.

In the field of early autism screening, the long-standing challenge is that traditional screening tools (such as M-CHAT, ADOS-2) primarily rely on subjective evaluation, suffering from time-consuming processes and high professional requirements for evaluators (Cai et al., 2022; Zhao et al., 2023). Interpersonal synchrony, especially parent-child synchrony, can serve as a more objective and automated auxiliary screening indicator. In recent years, with the development of artificial intelligence technology, researchers have begun to explore objective assessment methods based on multi-dimensional synchrony. For example, motor synchrony measurement can be achieved through AlphaPose-based multi-person pose estimation models to automatically quantify the degree of limb movement synchrony between parents and children during free interactions (Fang et al., 2017; Li et al., 2019). Facial expression synchrony analysis can use the facial action coding system (FaceReader) to objectively assess emotional synchrony between parents and children, thereby avoiding subjective biases in traditional behavioral coding (Stöckli et al., 2018). Physiological and neural synchrony measurements can combine fNIRS hyperscanning technology to monitor inter-brain synchrony between parents and children in real time, providing neurobiological evidence for early autism screening (Wang et al., 2020; Nguyen et al., 2021).

This study innovatively proposes using parent-child synchrony as an objective indicator combined with artificial intelligence technology to construct an early screening model for autism. By comprehensively analyzing synchrony characteristics between parents and children at behavioral (motor, facial expression), autonomic nervous system (RSA), and neural activity (inter-brain synchrony) levels, this study will develop a machine learning-based predictive model to achieve automated, objective, and precise screening for autism.

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Note: Figure translations are in progress. See original paper for figures.