Atypical Interpersonal Synchrony in Children with Autism: Manifestations and Neural Mechanisms

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Abstract

Interpersonal synchrony plays a crucial role in the process of individuals constructing social communication systems. Systematic literature reviews have found that children with Autism Spectrum Disorder (ASD) exhibit reduced or disrupted interpersonal synchrony across behavioral, cognitive, and emotional dimensions during social interactions. Further neuroimaging evidence reveals that coordinated brain synchrony responses between children with ASD and their peers are reduced or disrupted, making it difficult to achieve sharing of implicit mental states and synchronization of explicit interactive behaviors. Future research may need to construct an atypical interpersonal synchrony model for children with ASD from three aspects: cognitive rigidity, behavioral discoordination, and imbalanced emotional expression, and explore whether atypical interpersonal synchrony in children with ASD is a product of impaired ontogenetic development or an underlying mechanism of such impairment.

Full Text

Atypical Interpersonal Synchronization in Children with Autism Spectrum Disorder and Its Neural Mechanisms

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Abstract

Interpersonal synchrony plays a critical role in the construction of social communication systems. A systematic review of the literature reveals that children with Autism Spectrum Disorder (ASD) exhibit reduced or disrupted interpersonal synchrony across multiple domains during social interaction, including behavioral, cognitive, and emotional dimensions. Further neuroimaging evidence demonstrates diminished or interrupted brain-to-brain synchronous coordination between children with ASD and their interaction partners, making it difficult for them to achieve shared implicit mental states and explicit behavioral synchronization. Future research should aim to construct a model of atypical interpersonal synchrony in ASD children from three perspectives: cognitive rigidity, behavioral incoordination, and emotional expression imbalance. Additionally, it remains to be investigated whether atypical interpersonal synchrony in ASD children is a product of impaired individual development or a potential mechanism underlying such impairment.

Keywords: Interpersonal synchrony, autism spectrum disorder, inter-brain synchrony, atypical, children

Interpersonal synchrony refers to the phenomenon where individuals engaged in social interaction within the same space perform identical actions or enter identical states at a given moment. It constitutes a dynamic, complex social communication system constructed through the mutual coordination of behaviors, cognitions, and emotions between two or more individuals. Interpersonal synchrony plays a vital role in early human development and is closely associated with social competencies such as prosocial behavior, positive affect, and cognitive empathy [1-4]. Recent research suggests that interpersonal synchrony may serve as a potential biomarker for clinical diagnosis and assessment in populations with social dysfunction, such as Autism Spectrum Disorder (ASD) [5,6].

Autism Spectrum Disorder is a pervasive neurodevelopmental condition that emerges early in development, persists throughout life, and impacts individual social functioning. Recent studies have found that children and adolescents with ASD exhibit disrupted or reduced coordination across cognitive, emotional, and behavioral domains, which may lead to interrupted or diminished interpersonal synchrony and potentially underlie their social difficulties [5-8].

1.1 Behavioral Synchronization

Behavioral synchronization refers to the temporal and formal alignment of behaviors between two or more interacting individuals, encompassing motor synchrony [1], vocal synchrony [3], and sensory stimulation synchrony [7]. Bloch et al. quantified intrapersonal connectivity in individuals with ASD using interpersonal coordination dynamics and found that reduced intrapersonal connectivity and coordination may lead to decreased motor synchrony and coordination [7]. Consequently, some researchers have proposed using children' s motor coordi-

nation as a diagnostic marker for ASD [8] and suggest that diminished motor synchrony constitutes a mechanism underlying social communication deficits in children with ASD [6].

During social interaction, individuals continuously rotate their heads and eyes to observe and gather information, which they integrate with prior experience to determine whether their behaviors align with those of their interaction partners. This selection process relates not only to intrapersonal coordination but also to individuals' ability to acquire and process information [9]. However, when children with ASD engage in real-time dynamic social interactions, they exhibit reduced eye contact and decreased capacity to process social information compared to when acting alone or in simple interactions [10]. A recent study using head-mounted eye-tracking devices to collect data on gaze patterns in face-to-face structured conversations confirmed that gaze aversion behaviors in children with ASD may be context-specific. When required to attend to increasing amounts of interactive information, children with ASD spend less time looking at their partners and are more likely to focus on irrelevant information, demonstrating reduced sensitivity to critical social cues [11]. This may prevent them from maintaining behavioral alignment with partners, resulting in disrupted or diminished behavioral synchrony during social interaction.

1.2 Cognitive Empathy

Cognitive empathy involves understanding others' cognitive states, thoughts, beliefs, and intentions, adopting others' perspectives, and using experience to infer others' viewpoints and their potential behavioral and emotional consequences. It forms the foundation of interpersonal synchrony [2]. However, children with ASD experience difficulties in understanding others' thoughts, inferring motivations and intentions, identifying key social cues, and interpreting ambiguous statements. They tend to focus on specific points in their partners' communications, exhibit discrepancies between language expression and comprehension, and fail to establish common communication strategies with interaction partners, thereby reducing interpersonal coordination [5,12-14].

Individuals with ASD display different cognitive performances across contexts, showing a tendency to repeatedly use strategies that peers can understand. This suggests that in dyadic interactions where social information becomes simple and does not require constant attention, perception, and updating, the interpersonal synchrony abilities of children with ASD may remain unimpaired [14]. Some researchers have found that adults with ASD compensate for social deficits through cognitive abilities, with high-functioning individuals particularly employing cognitive compensation strategies. For instance, individuals with ASD may look at their interaction partners during social exchanges but cannot infer others' mental states from eye contact [15,16]. Further investigation is needed to explore how cognitive compensation mechanisms affect interpersonal synchrony in children with ASD and how interpersonal synchrony interventions might influence these compensation mechanisms.

1.3 Emotional Resonance

Emotional resonance refers to the consistency of emotional expression between individuals during social interaction [4]. Children with ASD exhibit delays in spontaneously imitating peers' facial expressions, unconsciously avoid eye contact, and show abnormalities in recognizing others' facial expressions and understanding the meaning of their own facial expressions [17]. These factors may lead them to display strange, rigid facial expressions when communicating with others through facial cues, resulting in mismatched emotional expressions and reduced emotional resonance [18]. Some researchers have suggested that the limited emotional resonance displayed by children with ASD during social interaction may not stem from autism symptoms themselves but from co-occurring alexithymia—a personality trait characterized by difficulty identifying one' s own or others' emotional feelings [19]. Future research should further investigate the underlying mechanisms of reduced emotional resonance in children with ASD.

Human emotional resonance also relates to vocal synchrony. Intentional use of vocal synchrony can enhance emotional resonance between communicators. Nishimura et al. found that when robots synchronize with human voices, they can elicit emotional resonance in humans [3]. Recent research has also identified vocal asynchrony or interruption between children with ASD and their peers, including delayed speech, reduced language-related vocalizations, disrupted feedback loops in vocal interaction, and prosodic asynchrony [20]. Stroganova et al. administered monaural auditory stimulation to school-age children and recorded auditory responses using magnetoencephalography. Compared to typically developing children, children with ASD showed delayed neural responses in the left hemisphere auditory cortex, while right hemisphere responses did not differ from controls [21]. The researchers speculated that selective slowing of neural activity in the left anterior lateral Heschl' s gyrus may hinder pitch processing in children with ASD, leading to difficulties in language perception. This may represent one potential mechanism underlying vocal asynchrony and subsequent reduced emotional resonance in children with ASD. Future research should further examine how facial expression asynchrony and vocal asynchrony affect interpersonal synchrony in children with ASD.

1.4 Summary

During social interaction, children with ASD exhibit reduced or disrupted interpersonal synchrony across three domains—behavioral synchronization, cognitive empathy, and emotional resonance—which interact and collectively form an atypical interpersonal interaction pattern [6]. Children with ASD struggle to attend to, extract, and comprehend socially relevant information, and during information gathering, they tend to focus on details, leading to insufficient social information processing. This ultimately manifests as behavioral heterogeneity, executive dysfunction, inability to respond dynamically to partners, and difficulty establishing emotional bonds with peers [4,6,20]. When observational information is incomplete, children with ASD may require longer time windows to

process information, preventing them from adjusting their behaviors promptly according to their partners' states. This results in connection deficits between perception and behavior, further affecting social cognitive functions and making it difficult to understand others' mental and emotional states, thereby leading to interpersonal synchrony disruption [7,14].

2.1 Neurobiological Basis

Neurotransmitters provide the neurobiological foundation for human social interaction. Recent research has increasingly identified that atypical social interaction patterns in children with ASD may relate to abnormalities in certain neurotransmitter secretions, such as dopamine, melatonin, and oxytocin [22,23].

First, as an important modulatory neurotransmitter, dopamine promotes individuals to utilize prior experience to predict behavioral outcomes and make optimal choices. Based on research from the past five years on the dopamine system in individuals with ASD, Pavăl and Micluția speculated that deficits in the striatal/prefrontal cortical neural circuits lead to midbrain dopamine system dysfunction, resulting in erroneous processing of environmental information and abnormal behaviors [22]. The relationship between interpersonal synchrony deficits and the dopamine system in children with ASD awaits empirical investigation.

Second, melatonin relates to physiological rhythms in specific brain regions. Children with ASD exhibit melatonin secretion disorders and abnormal cortisol levels, leading to discontinuous physiological rhythms, altered sleep-wake cycles, reduced sleep duration, and circadian rhythm disturbances. These factors not only affect neurodevelopment in individuals with ASD but also make it more difficult for them to adapt to internal and external environmental changes. Clinical evidence has shown that exogenous melatonin intervention in children with ASD increases total sleep duration, improves sleep quality, and consequently alleviates ASD symptoms [23]. Whether bidirectional regulation exists between melatonin and intrapersonal synchrony in children with ASD represents a potential direction for future research.

Third, oxytocin forms the basis of physiological-behavioral synchrony. It promotes enhanced synchronization of alpha-band neural oscillations in the brain, improving individuals' capacity to synchronize with, understand, and adapt to others, thereby facilitating social interaction. A meta-analysis of 28 studies using oxytocin intervention in individuals with ASD found that although oxytocin improved social interaction patterns, it did not significantly improve non-social ASD symptoms [24]. Another study found that after a four-week intranasal oxytocin treatment in children with ASD, the experimental group showed increased plasma oxytocin concentration and enhanced social abilities compared to the placebo control group, though repetitive and stereotyped behaviors did not decrease [25]. Therefore, whether oxytocin directly relates to interpersonal synchrony disruption in children with ASD or promotes interpersonal synchrony

by influencing other neurotransmitter secretions (such as dopamine) requires further mechanistic exploration.

2.2 Single-Brain Neural Basis

The brain is a complex neurophysiological network that dynamically identifies, processes, and receives diverse social information to regulate individuals' internal states. When cognition, behavior, and emotion become coordinated, different brain regions and underlying neuronal networks are activated [2].

Atypical interpersonal synchrony in children with ASD during social interaction may relate to atypical activation and impairment in frontal, temporal, and parietal brain regions [26]. Neuroimaging studies have found that deficits in language comprehension in children with ASD may stem from early distortions in left hemisphere temporal cortex, abnormal callosal fiber structure in the temporal lobe, and genomic variations in cortical regions [27]. Compared to typically developing children, children with ASD perform poorly on multiple tasks related to interpersonal synchrony abilities. For instance, in a block-cleaning task reflecting interpersonal synchrony, children with ASD show atypical lateralization, with reduced activation in the middle-inferior prefrontal gyrus and middle-superior temporal gyrus, and enhanced activation in the inferior parietal lobule/small lobule [28]. These findings suggest that interpersonal synchrony disruption or reduction in children with ASD may relate to atypical activation in specific brain regions, which represent important pathways for understanding social function deficits in ASD.

Children with ASD also exhibit abnormal brain functional connectivity. Nebel et al. used functional magnetic resonance imaging to collect resting-state brain activation data from typically developing children and children with ASD aged 8-12 years. They found intrapersonal visual-motor asynchrony in children with ASD, with atypical functional connectivity or connection disruption between motor and visual regions [29]. This may prevent children with ASD from completing the process from facial recognition to understanding others' intentions and forming coordinated social interaction patterns with others [9].

2.3 Inter-Brain Neural Synchronization

Inter-brain synchronization refers to the phenomenon of neural coupling between two individuals. When external information stimulates the inferior frontal region in typical individuals, spontaneous synchronized body movements occur between them and promote real-time information transmission [30]. However, children with ASD exhibit deficits in joint attention and may fail to activate brain regions related to shared attention, preventing inter-cortical synchronization between individuals. This ultimately makes it difficult for them to understand and share partners' intentions through eye contact and impairs their insight into fundamental social interaction mechanisms [11]. Using functional near-infrared spectroscopy (fNIRS) hyperscanning, researchers have explored

the degree of inter-brain coupling between children with ASD and their parents during interpersonal coordination tasks. Results showed that compared to solitary/non-interactive tasks, coordinated interaction tasks between children with ASD and their parents promoted neural synchronization in the frontal cortex of children with ASD. Moreover, during cooperative task coordination, more pronounced ASD symptom characteristics correlated with poorer task completion and reduced neural synchronization with parents, indicating that inter-individual neural synchrony is influenced by ASD symptoms [31]. However, another study using the same experimental task in parent-child cooperation found that although children with ASD showed reduced motor synchrony with peers, inter-group differences in neural synchrony were not significant [32]. Inter-brain neural synchronization may represent an important avenue for further exploring atypical interpersonal synchrony in children with ASD.

3.1 Potential of Interpersonal Synchronization Interventions to Improve Social Abilities in Autism

Interpersonal synchrony influences the development of social cognition and emotion, promotes prosocial behavior, enhances understanding of others, and improves interaction quality [4]. Trevarthen noted that through continuous face-to-face interaction, 2-3-month-old infants and their mothers initially establish nonverbal communication through visual, auditory, and tactile modalities between right hemispheres, gradually achieving interpersonal synchrony [33]. Existing literature confirms that during social interaction, infants and toddlers with ASD lack spontaneous intersubjective communicative behaviors and cannot engage in nonverbal emotional exchanges with interaction partners, making interpersonal synchrony nearly impossible [34]. A recent longitudinal study tracking infant-mother interaction behaviors (gaze, vocalization, etc.) during play at 6, 9, and 12 months found that lower infant synchrony and responsiveness in dyadic interaction predicted more pronounced ASD characteristics at 36 months [35]. These findings raise the possibility that early interpersonal synchrony-based interventions might promote neurodevelopment and improve social interaction abilities in children with ASD. A recent study using observational coding systems to quantitatively analyze one-year intervention sessions with toddlers with ASD found that enhanced dyadic interactivity enabled them to participate in more complex interactive activities, achieve shared activities with therapists, and display characteristics of interpersonal synchrony [36]. Thus, interpersonal synchrony may serve not only as a biomarker for early clinical assessment [5] but also as an effective early intervention approach. How early interpersonal synchrony interventions improve social abilities in ASD during critical periods of enhanced brain plasticity requires more detailed investigation and thorough exploration of their social validity.

3.2 Similarities Between Music/Dance Interventions and Interpersonal Synchronization Intervention Mechanisms

Synchronous rhythmic behaviors in group settings, such as dance and music, promote group cohesion and cooperative behavior. Music evokes physiological-level synchrony between individuals through emotional arousal, which is then expressed through movements, facial expressions, and vocalizations, creating possibilities for interpersonal synchrony in children with ASD [37]. A study using paired drumming tasks to provide rhythmic intervention for children with ASD found that after eight sessions, their ability to act jointly with others improved and asynchronous drumming behaviors with partners decreased [37]. During music therapy, therapists typically select preferred instruments to play favored songs and communicate with children through improvised lyrics. Research has found that even children with severe physical disabilities who do not speak exhibit inter-brain synchrony with their parents during music therapy [38]. A recent study using computer analysis of videos from music therapy sessions found that when children with ASD displayed repetitive rhythms more than twice per second, synchrony between therapists and children increased. However, at the end of therapy, neither ASD symptom severity nor synchrony ability with therapists showed significant improvement [39]. Schirmer et al. suggested that in dyadic interaction, music promotes interpersonal synchrony possibly because musical rhythm imposes a highly structured temporal framework on interacting individuals, amplifying rhythm frequencies related to music and leaving individuals no time to reflect on their current states, thereby hindering potentially different social processes [40]. This may explain why synchrony between interaction partners increases during music therapy but children' s synchrony abilities do not significantly improve afterward. Therefore, the effectiveness of dance and music interventions may require further investigation into their active therapeutic components and the common neural mechanisms underlying motor imitation and interpersonal synchrony.

4. Conclusions and Future Directions

During interpersonal interaction, children with ASD not only display asynchrony in explicit behaviors but also struggle to develop empathy with others in implicit cognitive and emotional domains [2,33]. This atypical interpersonal synchrony may represent a potential mechanism underlying their social dysfunction [5,6] and could also serve as an early intervention approach to influence neural network development in infants and toddlers with ASD, thereby improving their social functioning [36,37,39]. Future research directions primarily include the following aspects:

First, atypical interpersonal synchrony manifestations in behavioral, cognitive, and emotional domains in children with ASD correlate positively with symptom severity. Children with ASD exhibit deficits in receiving and processing information. Individuals with more pronounced autistic traits may partially receive social information from the environment but tend to rigidly adhere to

their existing beliefs and ideas, failing to adjust their behaviors promptly based on new social information. They experience difficulties predicting others' intentions, display motor incoordination, and show mismatched facial expressions [4,6,7,14,20]. Future work should further construct a model of atypical interpersonal synchrony in children with ASD from three perspectives: cognitive rigidity, behavioral incoordination, and emotional expression imbalance.

Second, atypical interpersonal synchrony interactions and individual development influence each other. Synchrony in parent-child interaction not only plays an important role in children' s emotional development but also promotes social cognitive development and emotion regulation abilities [4]. Previous research found that less spontaneous interactive behavior in infants and toddlers with ASD correlates with less interpersonal synchrony and more pronounced ASD symptoms [34,35]. Other studies suggest that interaction synchrony disruption between children with ASD and peers may also relate to the social abilities of interaction partners [6]. From infancy to pre-adolescence, individuals undergo significant changes in social cognition and neurodevelopment. Future explorations of inter-brain synchrony mechanisms in children with ASD may need to consider how developmental characteristics at different ages and individual characteristics of interaction partners influence changes in brain synchrony.

Additionally, whether research findings on atypical interpersonal synchrony in children with ASD can be directly applied to clinical assessment, diagnosis, and intervention warrants consideration. Future investigations of interpersonal synchrony interventions for children with ASD may need to address differences between simulated and natural environments and examine the effectiveness of interpersonal synchrony interventions when children with ASD are placed in complex, naturalistic social interactions.

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