Atypical Biological Motion Perception in Children with Attention Deficit Hyperactivity Disorder: Dissociating the Roles of Local Motion and Global Configuration Processing

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Abstract

The ability to perceive biological motion (BM) is crucial for human survival and social interaction. Plentiful studies have found impaired BM perception in autism spectrum disorder characterized by deficits in social interaction. Children with attention deficit hyperactivity disorder (ADHD) often exhibit similar deficits in social interaction, but few studies have investigated BM perception in ADHD. Here, we compared the differences in abilities to process local kinematic and global configurational cues, two fundamental abilities of BM perception, between typically developing (TD) and ADHD children. Then, we further investigated the relationship between BM perception and social interaction skills measured by the Social Responsiveness Scale (SRS) and examined the contributions of latent factors (e.g., gender, age, attention and intelligence) to BM perception. Results revealed that children with ADHD exhibited atypical BM perception with a potential dissociation between local and global BM information processing. Local BM processing ability was largely related to social interaction skills, whereas global BM processing ability would significantly improve with age. Critically, general BM perception (i.e., both local and global BM cues) could be affected by sustained attention ability in children with ADHD. This relationship was mainly mediated by Reasoning Intelligence. These findings elucidate the atypical biological motion perception in ADHD and the latent factors related to BM perception. Moreover, this study provides new evidence for local BM perception as a hallmark of social cognition and advances the comprehensive understanding of the distinct roles of local and global processing in BM perception and social cognitive disorders.

Introduction

Attention deficit/hyperactivity disorder (ADHD) is a common developmental disorder, with a prevalence ranging from 2% to 7% in children and adolescents, averaging around 5%[1]. Besides the well-established core symptoms of ADHD (including a deficit of sustained attention, hyperactivity, and impulsivity), some autism spectrum disorder (ASD) characteristics, such as dysfunctions in social communication and social interaction, have also been frequently reported in ADHD children[2-4]. However, experimental studies of social cognition in ADHD are still

scarce. Some studies described worse performance in tasks of social cognition. Among them, impaired theory of mind (ToM) and emotion recognition are most frequently reported[5-7]. It is difficult for children with ADHD to recognize others' emotions and intentions. However, the understanding of other social cognition processes in ADHD remains limited. Further exploring a diverse range of social cognition (e.g., biological motion perception) can provide a fresh perspective on the impaired social function observed in ADHD. Moreover, recent studies indicated that the social cognition in ADHD may vary depending on different factors at the cognitive, pathological, or developmental levels, such as general cognitive impairment[5], the severity of symptoms[8], or age[5]. Yet, how these factors relate to the dysfunctions of social cognition in ADHD is still in its infancy. Bridging the gap is important as it can help depict the developmental trajectory of social cognition and identify effective interventions for impaired social interaction in individuals with ADHD.

Biological motion (BM), which refers to the movements of a living creature, conveys a wealth of information beyond bodily movements[9], such as intention[10], emotion[11], gender[12], and identity[13,14]. The advent of point-light displays (PLD) technology used to depict human motions[15] allowed researchers to separate biological motion from other characteristics like shape and color. Considering the seminal impact on cognitive science, developmental and clinical neuroscience, BM perception has drawn significant attention from scientists. Some researchers attempted to deconstruct BM processing into more specific components. Our study concentrated on two fundamental abilities involved in processing BM cues (Figure 1): the ability to process local BM cues derived from major joint motion tracks and the ability to process global BM cues of human configuration. Previous studies provided some findings about the difference between local and global BM perception. Separable neural signals for these abilities implied two independent BM processing stages[16-18]. The ability to process local BM cues appears to be genetically highly preserved[19]. For example, newly hatched chicks without visual experience exhibit a spontaneous preference for BM[20]. A similar finding is also reported in 2-day-old babies[21]. Local BM cues not only carry locomotive direction[22] but also contribute to detecting life in the visual environment[23] without observers' explicit recognition or attention[24-27]. As a

result, the processing of local BM cues is unaffected by attention, relatively robust to masking noise and does not show a learning trend[27,28]. In contrast, global BM processing involves top-down modulation, with attention playing a critical role in its perception[28,29]. Dispersed attention adversely affects its performance. Compared with local BM processing, global BM processing is susceptible to learning and is heavily hindered by increasing mask densities[28]. These findings suggest that local and global mechanisms might play different roles in BM perception, though the exact mechanisms underlying the distinction remain unclear. Exploring the two components of BM perception will enhance our understanding of the difference between local and global BM processing, shedding light on the psychological processes involved in atypical BM perception.

In recent years, BM perception has received significant attention in studies of mental disorders (e.g., schizophrenia[30]) and developmental disabilities, particularly in ASD, characterized by deficits in social communication and social interaction[31,32]. An important reason is that BM perception is considered a hallmark of social cognition. Individuals with deficits in BM processing exhibit worse social perception in daily life[10]. The other study found that participants' ability to process BM cues was correlated with their autistic traits, especially in the subdimension of social communication[19]. Notably, the contributing factors of impaired BM perception in children with ASD is unclear. Previous meta-analysis studies of BM perception in ASD found mixed results about the effects of age and IQ on processing BM[31,32]. Therefore, it is essential to focus on revealing differences in BM processing between typical and atypical development and identified potential factors that may influence BM perception, which will enhance our comprehension of social dysfunction in atypical development. Compared with numerous studies examining impaired BM perception in ASD, few studies focused on BM perception in children with ADHD. An EEG study found neuro-electrophysiological changes in processing BM stimuli in ADHD[33]. Specifically, children with ADHD showed reduced activity in motion-sensitive components (N200) while watching biological and scrambled motion, although no behavioral difference was observed. Another study found that children with ADHD performed worse in BM detection with moderate ratios of noise[34]. This may be due to the fact that BM stimuli with noise dots will increase the difficulty of

identification, which highlights the difference in processing BM between the two groups[33,35].

Despite initial indications, a comprehensive investigation into BM perception in ADHD is warranted. We proposed that it is essential to deconstruct BM processing into its multiple components and motion features, since treating them as a single entity may lead to misleading or inconsistent findings[31]. To address this issue, we employed a carefully-designed behavioral paradigm used in our previous study[19], making slight adjustments to adapt for children. This paradigm comprises three tasks. Task 1 (BM-local) aimed to assess the ability to process local BM cues. Scrambled BM sequences were displayed and participants could use local BM cues to judge the facing direction of the scrambled walker. Task 2 (BM-global) tested the ability to process the global configuration cues of the BM walker. Local cues were uninformative, and participants used global BM cues to determine the presence of an intact walker. Task 3 (BM-general) tested the ability to process general BM cues (local + global cues). The stimulus sequences consisted of an intact walker and a mask containing similar target local cues, so participants could use general BM cues (local + global cues) to judge the facing direction of the walker.

In Experiment 1, we examined three specific BM perception abilities in children with ADHD. As mentioned earlier, children with ADHD also show impaired social interaction[2-4], which implies atypical social cognition. Therefore, we speculated that children with ADHD performed worse in the three tasks compared to TD children. In Experiment 2, we further explored the relationship between BM perception and social interaction ability in ADHD, as well as identified potential factors (e.g., IQ, age and attention) that may affect BM perception in this population. We speculate that if local motion and global configuration of BM are indeed contributed by distinct mechanisms as suggested by previous studies, then their impairments in the ADHD population and the influential factors behind the impairments may be different.

Materials and methods

Participants

We recruited a total of one hundred and seventeen children with and without ADHD to enter this study. Eighty-one children met the ADHD diagnostic criteria of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5)[36]. The clinical diagnosis was first made by an experienced child and adolescent psychiatrist in the Child and Adolescent Psychiatric Outpatient Department of the Peking University Sixth Hospital, based on the ADHD Rating Scale. The Chinese version of the kiddie-schedule for affective disorders and schizophrenia-present and lifetime version DSM-5 (K-SADS-PL-C DSM-5)[37,38], a semi-structured interview instrument, was then implemented to confirm the diagnosis. Thirty-six typically developing (TD) children were from ordinary primary schools in Beijing and screened out the presence of ADHD, ASD, affective disorders and behavioral disorders by a trained psychiatrist. All subjects of ADHD groups have full-scale IQ above 75 (5th upper percentile) on Wechsler Intelligence Scale for Children-Fourth Edition, and all TD children had a full-scale IQ that fell above the 5th percentile on the Raven's Standard Progressive Matrices[39] which is used in measuring reasoning ability and regarded as a non-verbal estimate of intelligence. Exclusion criteria for both groups were: (a) neurological diseases; (b) other neurodevelopmental disorders (e.g., ASD, Mental retardation, and tic disorders), affective disorders and schizophrenia; (c) that would impact experiments completion; (d) taking psychotropic drugs or stimulants in 30 days. (e) previous head trauma or neurosurgery.

Thirty-six TD children (age = 9.09 ± 2.18, 14 male) and thirty-nine children with ADHD (age = 9.88 ± 2.23, 28 male) participated in Experiment 1. Groups did not differ by age (t = -1.550, p = 0.126) but differed in sex ($\chi 2$ = 8.964, p = 0.004). 42 ADHD children (age = 9.34 ± 1.89, 27 male) participated in Experiment 2. They were naïve to the task and did not participate in Experiment 1. Participant demographic characteristics are shown in Table 1. There is currently no comparable study in ADHD that indicates the effect size for reference. Studies investigating BM perception in ASD typically have sample sizes ranged from 15 to 35 participants per group[32]. Considering the mild impairment of social functions in children with ADHD, we determined that a sample size of 35 - 40 participants per group would be reasonable for this study. All individuals of each group had a normal or corrected-to-normal vision and were naïve to the objectives of experiments. Written informed

consent was obtained from the parents of all children before testing. The institutional review boards of the Peking University Sixth Hospital and the Institute of Psychology, Chinese Academy of Sciences have approved this study.

Assessment

K-SADS-PL-C DSM-5

K-SADS-PL-C DSM-5 is a semi-structured interview instrument for evaluating mental disorders in children and adolescents aged 6–18 years[37]. It involved thirty-five diagnoses based on the diagnostic criteria of DSM-5. A trained psychiatrist concluded the diagnosis by interviewing the parents and child. Chinese version showed great psychometric criterion[38].

ADHD Rating Scale

ADHD Rating Scale is adapted from the ADHD diagnostic criteria of DSM[40], which requires parents or teachers to complete the scale independently. Its Chinese version has an excellent psychometric criterion and consists of 2 subscales[41]: inattention (IA, nine items) and hyperactivity-impulsivity (HI, nine items). Each item is rated on a four-point Likert scale ranging from 1 (the symptom is “never or rarely”) to 4 (the symptom is “very often”). The final results will create three scores: (1) IA dimension score, (2) HI dimension score, and (3) Total score. Higher scores indicate more severe ADHD symptoms.

Social Responsiveness Scale

Social Responsiveness Scale (SRS) is a widely used quantitative measure with 65 items to assess the severity of social impairment in many mental disorders[42], and the psychometric properties of the Chinese version are desirable[43]. It includes five subdimensions: social awareness, social cognition, social communication, social motivation, and autistic mannerisms. Each item is rated on a scale from 0 (never true) to 3 (almost always true), with higher scores indicating worse social ability.

Wechsler Intelligence Scale for Children-Fourth Edition

Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV) is widely used to test comprehensive intelligence in individuals aged 6–18. It contains fifteen subtests which comprise four broad areas of intellectual functioning: Verbal Comprehension, Perceptual Reasoning, Working Memory, and Processing Speed. Scores of the four broad areas constitute the full-scale intellectual quotient (FIQ).

QB Test

QB Test is a 15-min Continuous Performance Test (CPT) for assessing inattention and impulsivity with a high-resolution infrared camera monitoring participant's activity[44]. Previous psychometric studies have validated its good measurement properties[45]. After the test was completed, several Q scores were calculated to summarize participant performance. The Q scores were standardized based on normative data matching gender and age. The higher Q score implies more abnormal performance. In this study, we focused on the QbInattention, the Q score responsible for sustained attention, particularly when children focused on tasks.

Stimuli and Procedure

Point-light BM stimuli sequences adopted in this study have been used in previous studies[46], which were derived from configurations of individual walking motion on a treadmill and did not contain an overall translation. Each frame of BM sequences consisted of 13 white dots representing the human head and major joints and was displayed on a grey background (see video 1). Each walking cycle lasted 1s with 30 frames. For each trial, the initial frame of BM sequences was randomized. The whole point-lighted BM walker presented about 5.7 ° visual angle vertically. Stimuli were presented on a 14-inch monitor using MATLAB together with the PsychToolbox extensions. All subjects completed experiments in a dim-lit room with heads on the chinrest to ensure their eyes were 50 cm away from the monitor.

In Experiment 1, children were required to complete three tasks that were similar to but slightly modified from the versions implemented in our previous study[19] (Figure 2). Each trial began with a fixation cross (0.6° * 0.6°). Following a random interval of 1200-1500 ms, the monitor displayed a task-specific BM sequence that lasted 2 seconds (60 frames).

Task 1 (BM-Local) aimed to assess the participants' ability to process local BM cues. During the task, the monitor only displayed a scrambled walker facing either left or right (see video 2). Specifically, 13 dots constituting the intact walker were randomly relocated within the original range of the BM walker (presented randomly within the 2D region). This manipulation disrupted the global configuration of the intact walker while retaining the local kinematics. After the display, we required children to press a left or right button to indicate the motion direction of the unidentified creature (i.e., scrambled BM walker) as accurately as possible. Children did not receive feedback regarding the accuracy of each response. A total of 30 trials were conducted, with 15 trials for each condition (left and right).

Task 2 (BM-Global) tested the ability to process the global configuration cues of the BM walker. A target walker (either scrambled or intact) was displayed within a mask (see video 3) during this task. The mask consisted of two scrambled target walkers (26 dots) with the same locomotion direction as the target walker, displayed within the boundary about 1.44 times larger than the intact walker. The scrambled or intact version of the target walker was randomly embedded into the mask and entirely overlaid by the mask. By this means, the global BM component could be isolated as two conditions (i.e., scrambled and intact walker) contained the same information of local kinematics, rendering the local motion cues uninformative. Children were required to judge whether there was an intact walker in the mask. The correct response relied on extracting global cues from the intact walker. To prevent children from learning the shape of the walker[24], we set target walkers possibly facing one of five equally spaced directions from left to right. Out of the five walkers we used, two faced straight left or right, orthogonal to the viewing directions. Two walked with their bodies oriented at a 45-degree angle to the left or right of the observer. The last one walked towards the observer. Video 4 demonstrated the five facing directions. A total of 30 trials were conducted, consisting of two conditions (intact or scrambled target).

Task 3 (BM-General) tested the ability to process general BM cues (local + global cues). In Task 3, the monitor displayed an intact walker (facing either left or right) embedded within a mask (see video 5). The mask used in this task was similar to that in Task 2. Children were required to judge the facing direction of the target walker (left or right). Since the mask and the target walker contained the same local BM cues

and the target walker is presented with additional global configuration cues, children could rely on the general BM information (i.e., a combination of local and global cues) BM information to perform the task. Task 3 consisted of 30 trials, with 15 trials for each facing directions. Other parameters of Task 2 and 3 were similar to Task 1. Before each task, children practiced five trials to make sure good understanding. We performed three tasks in a fixed order so that participants were naïve to the nature of local BM cues in Task 1.

In Experiment 2, 42 children with ADHD completed the same procedures as in Experiment 1. Beyond that, their parents should fill in the Social Responsiveness Scale (SRS) to assess social interaction.

Statistics

We carried out a two-sample t-test to examine the difference in BM perception abilities between TD and ADHD children[47,48] and the Pearson correlation analysis was used to assess the relationship between the accuracy of each task and the SRS score. Additionally, general linear models and path analysis were used to explore the potential factors influencing BM perception. A p-value < 0.05 was considered statistically significant. Path analysis was conducted using AMOS and other analyses were conducted using SPSS.

Results

Children with ADHD exhibit atypical BM perception

Figure 3 displays the mean accuracies (ACC) for both the TD and ADHD groups across the three tasks in Experiment 1. We examined the difference in ACC between the TD and ADHD groups for each task using the two-sample t-test. The results of Task 1 showed a significant difference (TD: 0.52 ± 0.13, ADHD: 0.44 ± 0.09, t_{73} = 3.059, p = 0.003, Cohen's d = 0.716), indicating that children with ADHD exhibited impaired local BM processing ability. For Task 2 and 3, where children were asked to detect the presence or discriminate the facing direction of the target walker (Task 2 - TD: 0.70 ± 0.12, ADHD: 0.59 ± 0.12, t_{73} = 3.677, p < 0.001, Cohen's d = 0.861; Task 3 - TD: 0.79 ± 0.12, ADHD: 0.63 ± 0.17, t_{73} = 4.702, p < 0.001, Cohen's d = 1.100). These findings suggest impaired global and general BM perception in children with

ADHD. To further ensure that gender did not influence the results, we conducted a subsampling analysis with balanced data, and the results remained consistent (see Supplementary Information).

Atypical perception of local BM information predicted impaired social interaction in ADHD

Experiment 1 provided evidence of atypical BM perception in children with ADHD. Previous study revealed that local BM processing ability is heritable and negatively correlated with autistic traits, especially in the subdimension of communication[19]. In addition, substantial evidence indicates that children with ADHD often have problems in social interaction. We expected that compromised social interaction in ADHD might be associated with atypical local BM processing. To confirm this assumption, we recruited 42 naïve children with ADHD to participate in Experiment 2 and examined the relationship between their social interaction abilities and BM perception. Their parents or caregivers who took care of the children completed SRS. The SRS total score of the ADHD group was higher than that of the TD group (SRS total score - ADHD: 54.64 ± 18.42, TD: 38.64 ± 12.47, $t = -4.277$, $p < 0.001$). We found that children with higher total score of SRS performed worse in Task 1, i.e., the ability of local BM processing was negatively correlated to SRS total scores ($r = -0.264$, FDR-corrected $p = 0.033$). We also found significant correlations between SRS total score and global BM processing as well as general BM processing (global BM perception: $r = -0.238$, FDR-corrected $p = 0.039$; general BM perception: $r = -0.359$, FDR-corrected $p = 0.006$).

In further subgroup analysis, as depicted in Figure 4, the correlation between the SRS total score and the ability to process local cues was only found in the ADHD group (ADHD: $r = -0.461$, FDR-corrected $p = 0.004$; TD: $r = 0.109$, FDR-corrected $p = 0.547$), particularly on subscales of social awareness, social cognition, social communication, social motivation (see Table 2 for detailed information). However, we did not find significant correlation between SRS total score and global or general BM processing in either the ADHD or TD groups separately (global BM perception - TD: $r = -0.020$, FDR-corrected $p = 0.910$, ADHD: $r = -0.207$, FDR-corrected $p = 0.374$; general BM perception - TD: $r = -0.118$, FDR-corrected $p = 0.514$, ADHD: $r = -0.286$, FDR-corrected $p = 0.134$).

For an exploration of the distinct relationship between local BM processing and SRS total scores in the ADHD group, we further examined the differences among these correlations (see Supplementary Information). In Task 1, we observed a significantly stronger correlation between SRS total score and the response accuracy of the ADHD group compared to the TD group ($p = 0.003$). However, this distinction was not identified in Tasks 2 ($p = 0.381$) or Task 3 ($p = 0.455$). Additionally, we found that the correlation between SRS total score and the response accuracy of the ADHD group in Task 1 was slightly stronger than in Task 2 ($p = 0.066$) and Task 3 ($p = 0.181$). These findings suggested that atypical local BM processing may specifically reflect the impaired social interaction in the ADHD group.

Global BM processing develops with age and is regulated by reasoning intelligence and attention function

Experiment 2 indicated that local BM processing, as opposed to global BM processing, was more closely associated with social interaction in the ADHD group. To investigate the specificity of this association, we examined the relationship between impairments in different biological processing abilities and factors such as age, IQ, and attention function in the ADHD group. Data from the ADHD group in both Experiment 1 and Experiment 2 were integrated, resulting in a total of 80 ADHD participants (with one child not completing the QB test). Three linear models were built to investigate contributing factors: (a) BM-local = $\beta_0 + \beta_1$ * age + β_2 * gender + β_3 * FIQ + β_4 * QbInattention; (b) BM-global = $\beta_0 + \beta_1$ * age + β_2 * gender + β_3 * FIQ + β_4 * QbInattention; (c) BM-general = $\beta_0 + \beta_1$ * age + β_2 * gender + β_3 * FIQ + β_4 * QbInattention + β_5 * BM-local + β_6 * BM-global. We screened factors with the largest contribution to the models using step-wise regression. In model (a), no regressor has remained after step-wise regression, suggesting that the local BM processing remained stable with age and was not affected by attention and IQ. In model (b), the ability to process global BM cues was enhanced with age (standardized $\beta_1 = 0.251$, $p = 0.025$). In model (c), higher FIQ, particularly on subdimension of Perceptual Reasoning (standardized $\beta_3 = 0.271$, $p = 0.005$), and better performance in global BM processing (standardized $\beta_6 = 0.290$, $p = 0.004$) predicted better performance in general BM processing. Furthermore, as children grew up, the ability to probe general BM information improved (standardized $\beta_1 = 0.365$, $p < 0.001$). It is

worth noting that QbInattention showed a strong negative correlation with Perceptual Reasoning (r = -0.355, p = 0.001) and general BM perception (r = -0.246, p = 0.028). Due to the potential issue of collinearity, we employed path analysis post hoc to visualize these relationships (Figure 5). The result indicated sustained attention (i.e., QbInattention) did not directly predict performance in BM-General (i.e., Task 3). However, a significant indirect path via the ability of Perceptual Reasoning was identified. Furthermore, as children with ADHD grew older, their performance in BM-General (i.e., Task 3) improved, both directly and through enhanced processing of global BM cues.

We also built three models to further explore the effects of Reasoning IQ and age on BM perception in TD children: (a) BM-local = $\beta_0 + \beta_1$ * age + β_2 * gender + β_3 * FIQ. (b) BM-global = $\beta_0 + \beta_1$ * age + β_2 * gender + β_3 * FIQ; (c) BM-general = $\beta_0 + \beta_1$ * age + β_2 * gender + β_3 * FIQ + β_4 * BM-local + β_5 * BM-global. In model (a), no regressor remained significant after the step-wise regression. However, in models (b) and (c), we observed positive relationships between age and performance (BM-global: standardized β = 0.396, p = 0.017; BM-general: standardized β = 0.330, p = 0.049).

To sum up, our findings suggest that the abilities to perceive global and general BM cues, rather than local BM cues, would improve with age. Age might play different roles in the processing of different BM cues. To further verify this speculation, we examine the differences between the improvements in processing local cues and that in processing global and general cues with age (see Supplementary Information). In the ADHD group, we observed that the abilities to process general BM cues significantly improved with age compared to local cues (p < 0.001). Additionally, there was a trend indicating that the improvement in processing global BM cues with age was greater than that in processing local BM cues (p = 0. 073). However, these patterns were not observed in the TD group (BM-Local vs BM-Global: p = 0. 575; BM-Local vs BM-General: p = 0. 739).

Discussion

Our study contributes several promising findings concerning atypical biological motion perception in ADHD. Specifically, we observe the atypical local and global BM perception in children with ADHD. Notably, a potential dissociation between the

processing of local and global BM information is identified. The ability to process local BM cues appears to be linked to the traits of social interaction among children with ADHD. In contrast, global BM processing exhibits an age-related development. Additionally, general BM perception may be affected by factors including attention.

BM perception is a widely studied topic in the field of visual cognition, due to its inherent biological and social properties. BM processing has significant value in successful daily life, particularly in nonverbal communication[11,49] and adaptive behavior[29,50]. As an early emerging ability, BM can be discriminated in the newborn baby[21]. In typical development children, there is a clear association between BM perception and social cognitive abilities[51]. For example, 12-month-old infants exhibit social behaviors (i.e., following gaze) elicited by BM displays[52]. It is, therefore, of supreme importance of BM to children's development of social cognition. This 'social interpretation' of BM proposed that the difficulties in processing BM may serve as an indicator of impaired social interaction[19] This is evident in children with ASD, where impaired BM perception is a characteristic feature linked to impaired social function[10,53] .

ADHD, a neurodevelopmental disorder, is typically identified in early childhood. Children with ADHD often show impaired social function. We observed atypical BM perception in children with ADHD, potentially contributing to social disfunctions. The proposition that BM perception serves as a prerequisite for attributing intentions to others, facilitating adaptive interaction with other individuals[23,54,55], aligns with our discovery of a significant relationship between BM perception performance and the SRS total score. Further subgroup analysis revealed a significant negative correlation between the SRS total score and the accuracy of processing local BM specifically in the ADHD group. Notably, this correlation was stronger in the ADHD group compared to the TD group. This may be due to the narrow range of SRS scores in TD group. Future study should increase sample size to explore the correlation in diverse individuals. To sum up, these findings suggest that local BM processing could be regarded as a distinct hallmark of social cognition in ADHD children[10,19].

BM perception is considered a multi-level phenomenon[56-58]. At least in part, processing information of local BM and global BM appears to involve different

genetic and neural mechanisms[16,19]. Using the classical twin method, Wang et al. found that the distinction between local and global BM processing may stem from the dissociated genetic bases. The former, to a great degree, seems to be acquired phylogenetically[20,21,59,60], while the latter is primarily obtained through individual development[19]. The sensitivity to local rather than global BM cues seems to emerge early in life. Visually inexperienced chicks exhibit a spontaneous preference for the BM stimuli of hen, even when the configuration was scrambled[20]. The same finding was reported in newborns. On the contrary, the ability to process global BM cues rather than local BM cues may be influenced by attention[28,29] and shaped by experience[24,56]. There is evidence of an age-related improvement in global BM, as a previous study indicated that global BM perception was enhanced with age in TD children[61,62]. This developmental trend also seems to exist in individuals with ASD. The studies in children consistently showed the impairment of global BM processing in children with ASD[63,64], whereas no impairment was found in studies with regard to adults with ASD[65-67]. The performance of BM processing in children with ASD becomes more aligned with TD children as they get older[32].

Our study contributes new evidence to the understanding of the development of global BM processing. We found that the ability to process global and general BM cues improved significantly with age in both TD and ADHD groups, which imply the processing module for global BM cues tends to be mature with development. In the ADHD group, the improvement in processing general and global BM cues is greater than that in processing local BM cues, while no difference was found in TD group. This may be due to the relatively higher baseline abilities of BM perception in TD children, resulting in a relatively milder improvement. These findings also suggest a dissociation between the development of local and global BM processing. There seems to be an acquisition of ability to process global BM cues, akin to the potential age-related improvements observed in certain aspects of social cognition deficits among individuals with ADHD[5], whereas local BM may be considered an intrinsic trait[19]. It is worth noting that the ability to process global BM cues is positively correlated with the performance of processing general BM cues in ADHD group, while no such correlation was not found in TD group. This suggests that TD children are able to extract and integrate both local and global cues, whereas children with

ADHD may rely more on global BM cues to judge the facing direction of the walker when presented with both local and global BM cues, which correspond to a hierarchical model[56]. Once a living creature is detected, an agent (i.e., is it a human?) can be recognized by a coherent, articulated body structure perceptually organized from its motions (i.e., local BM cues)[68]. This process involves a top-down processing and probably requires attention[28,69], especially in the presence of competing information[29]. Our findings are consistent with previous research on the cortical processing of BM[70], as we found the severity of inattention in the children with ADHD was negatively correlated to their performance of BM processing. More future works are required to verify these conjectures.

Interestingly, children with impaired BM perception may employ a compensation strategy[71]. Previous study found no impairment in BM recognition in autistic individuals with high IQ[71], but children with ASD exhibited weaker adaptation effects for biological motion compared to TD children[72]. One possibility is that individuals with high IQ and impaired BM perception are able to develop or employ reliable strategies used for BM recognition, compensating for the lack of intuitive social perceptual processing[73,74]. The current study supports this assumption, as children with higher IQ, particularly in Perceptual Reasoning, demonstrated better performance. Due to the impact of attention deficits on Perceptual Reasoning, the performance of children with ADHD did not align with that of TD children.

Overall, our study first revealed two distinct and atypical fundamental abilities underlying BM perception in children with ADHD, indicating a potential dissociation of local and global BM processing. Notably, anomalous local BM processing could predict impaired social interaction in ADHD. Moreover, these results unraveled the potential contributions of age, IQ and attention to the process of BM information. These findings also shed new light on the direction of future studies. Firstly, more studies are required to confirm the dissociation between the two fundamental BM processing abilities, which will contribute to understanding the respective neural mechanisms underlying the two BM processing. Secondly, exploring the performance of more advanced BM processing in children with ADHD, such as emotion and identity recognition in BM tasks, is necessary to delineate the neural profiles for the processing of biological motion in ADHD. Finally, a comparative study between

ADHD and ASD is warranted to identify common neuropsychological traits and biomarkers of social cognition impairments.

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Author contributions

Junbin Tian: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Project administration, Writing – original draft. Fang Yang: Formal analysis, Methodology, Investigation. Ying Wang: Methodology, Software, Writing – review & editing. Li Wang: Methodology, Software, Writing – review & editing. Ning Wang: Investigation. Yi Jiang: Conceptualization, Methodology, Supervision, Writing – review & editing. Li Yang: Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of interests

The authors declare no competing interest.

Ethics

All procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. The institutional review boards of the Peking University Sixth Hospital and the Institute of Psychology, Chinese Academy of Sciences have approved this study (reference number for approval: (2020) Ethics Review No.9 and H23030).

Date availability

The data analyzed during the study is available at https://osf.io/37p5s/

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Figures

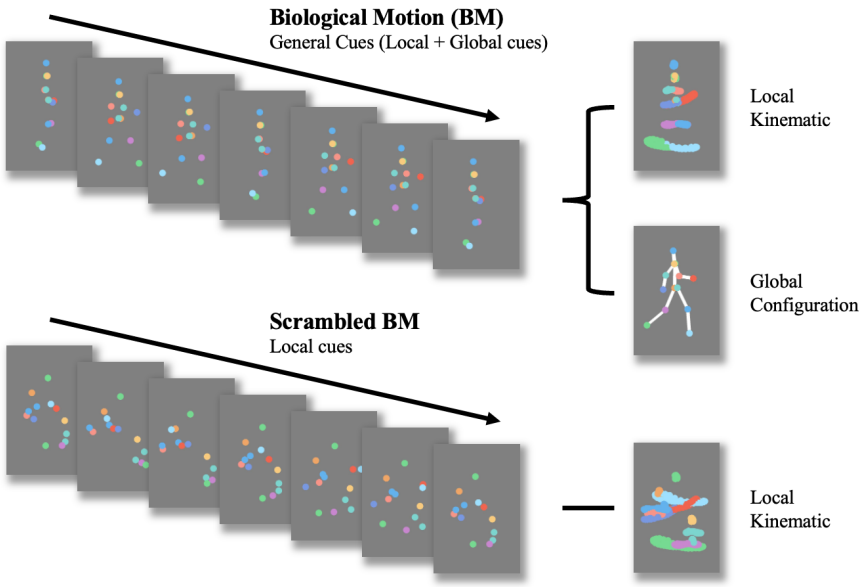

Figure 1. Schematic representation of Biological Motion (BM) and scrambled BM sequence. Intact walker contains information of local kinematics and global configuration. Local kinematics refers to the motion tracks of each critical joint illustrated by the chromatic dot. Global configuration is composed of the relative locations of each joint. In scrambled BM sequence, global configuration cues have been deprived, but local kinematics have been retained. (Figure reconstructed from Wang et al., 2018[19])

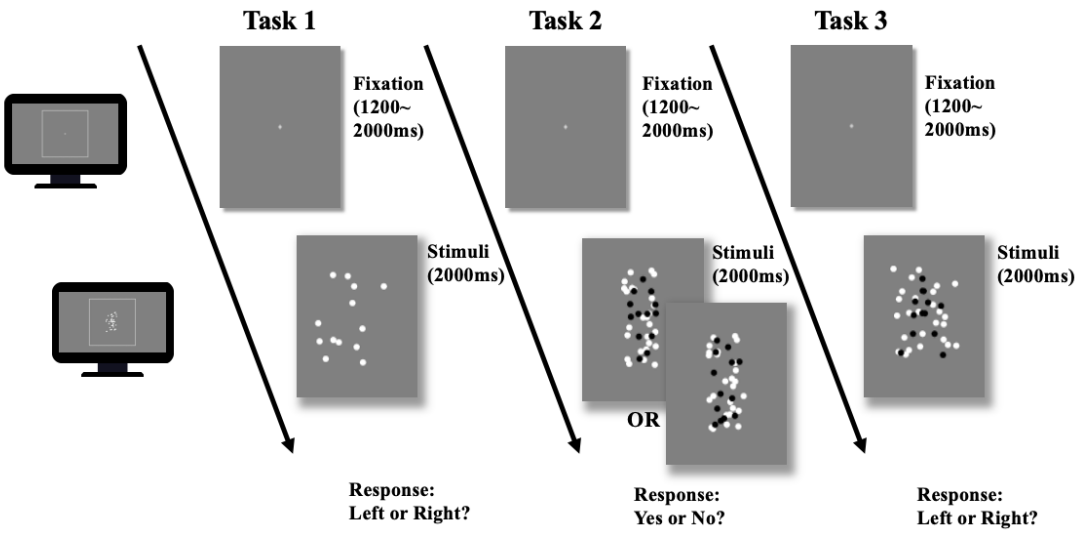

Figure 2. Illustration of the trial sequence. In Task 1 (BM-local), a monitor displayed scrambled BM sequences. Participants only judged the facing direction of

the scrambled walker using local BM cues. In Task 2 (BM-global), each trial only showed an intact or scrambled walker (black dots in the figure) embedded within a mask containing local BM cues. Because the two conditions contained the same local cues that were also present in the mask, a participant must rely on global BM cues to determine whether an intact walker was present in the mask. The figure showed one of five possible facing directions of an intact walker (i.e., facing participants). In Task 3 (BM-general), the stimuli sequence consisted of an intact walker (black dots) and a mask containing similar target local cues, and children judged the facing direction of the walker using general BM cues (local + global). Dots in the figure were rendered in black for better illustration and displayed in white in the actual experiments.

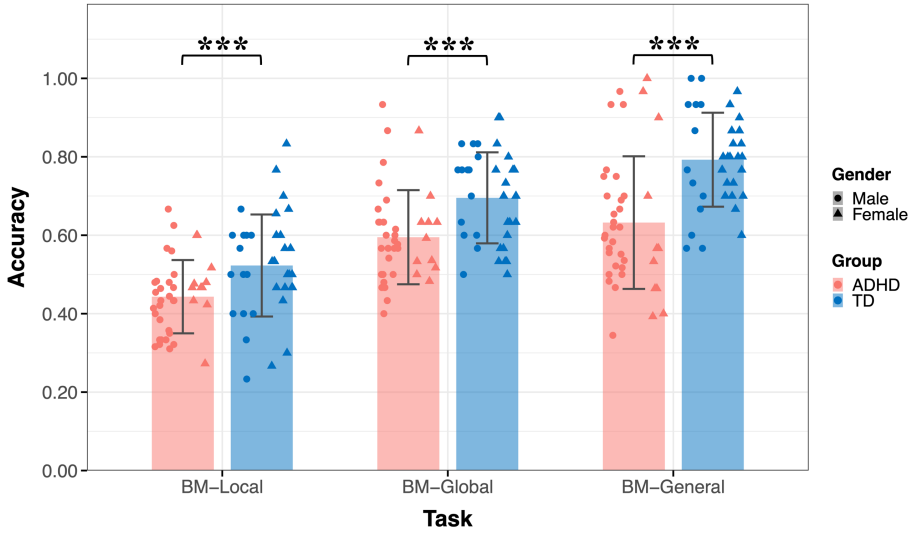

Figure 3. The mean accuracy of the three tasks. Typically developing (TD) children had higher accuracies than children with attention deficit hyperactivity disorder (ADHD) in three tasks in Experiment 1. Error bars show standard deviations. ***$p < 0.001$

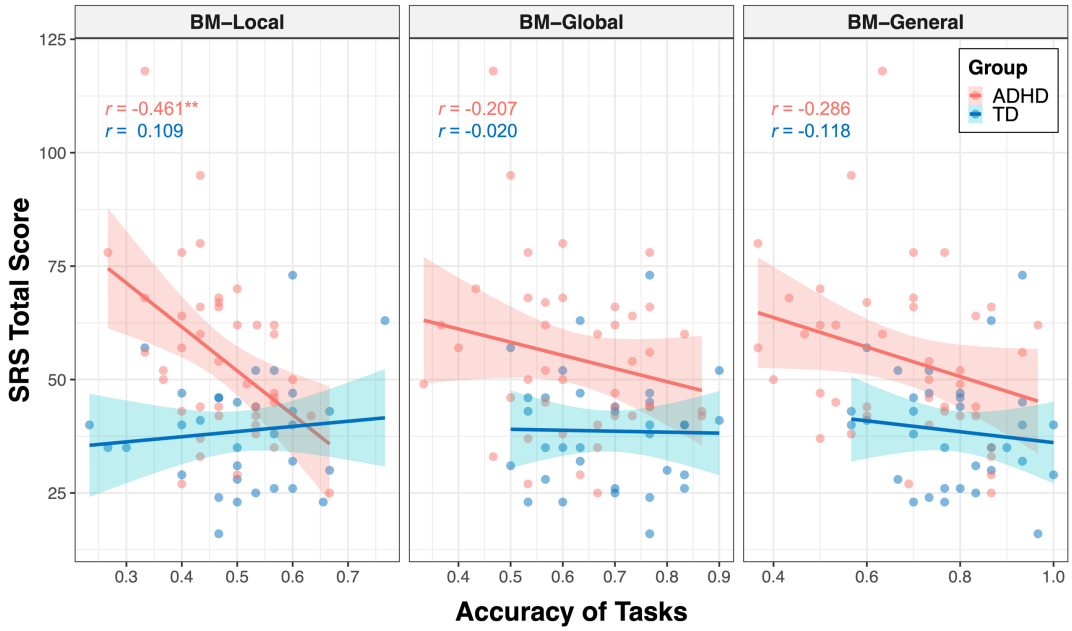

Figure 4. Correlations between response accuracies and SRS total score. The ability to process local cues is significantly correlated with the SRS total score in ADHD group. The grey shading represents a 95% confidence interval. ** FDR-corrected $p < 0.01$.

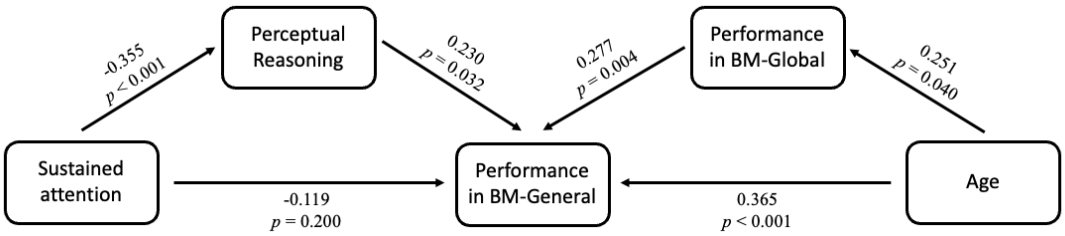

Figure 5. Factors influencing BM perception in ADHD children. Post hoc path analysis confirmed that the effect of sustained attention on performance in BM-General was entirely mediated by Perceptual Reasoning, and the ability of global BM processing partly mediated the effect of age on performance in BM-General.

Tables

Table 1. Demographic characteristics of TD and ADHD groups

	Experiment 1		*p* value	Experiment 2		*p* value
	TD	ADHD		TD	ADHD	

Sample	36	39		33	42	
Age (years)	9.08±2.18	9.88±2.23	0.126	8.75±1.94	9.34±1.89	0.191
Gender ratio (% male)	38.89%	71.79%	0.004	42.42%	64.28%	0.059

Table 2. The correlation between the ability of local BM processing and subdimensions of SRS in ADHD children.

	Correlation coefficient (r)	FDR-corrected *p* value
Social awareness	-0.333	0.039
Social cognition,	-0.416	0.020
Social communication	-0.381	0.022
Social motivation	-0.406	0.020
Autistic mannerisms	-0.245	0.117

Videos

Video 1. An intact walker without a mask. The dots in the video are rendered in chromatic colors for better illustration and displayed in white in the actual experiments.

Video 2. An example of Task 1 (a scrambled walker without a mask). The chromatic dots in this video correspond to the major joints of the intact walker in Video 1 and are displayed in white in the actual experiments.

Video 3. An example of Task 2 (an intact or scrambled walker with a mask). The chromatic dots in this video correspond to the major joints of the intact walker in Video 1 and are displayed in white in the actual experiments.

Video 4. Intact walkers facing five directions in Task 2. The dots in this video are rendered in black for better illustration and displayed in white in the actual experiments.

Video 5. The example of Task 3 (an intact walker with a mask). The chromatic dots in this video correspond to the major joints of the intact walker in Video 1 and are displayed in white in the actual experiments.