Neuroscience

# Atypical Biological Motion Perception in Children with Attention Deficit Hyperactivity Disorder: Local Motion and Global Configuration Processing

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## Abstract

Perceiving biological motion (BM) is crucial for human survival and social interaction. Many studies have reported impaired BM perception in autism spectrum disorder, which is characterised by deficits in social interaction. Children with attention deficit hyperactivity disorder (ADHD) often exhibit similar difficulties in social interaction. However, few studies have investigated BM perception in children with ADHD. Here, we compared differences in the ability to process local kinematic and global configurational cues, two fundamental abilities of BM perception, between typically developing and ADHD children. We further investigated the relationship between BM perception and social interaction skills measured using the Social Responsiveness Scale and examined the contributions of latent factors (e.g., sex, age, attention, and intelligence) to BM perception. The results revealed that children with ADHD exhibited atypical BM perception. Local and global BM processing showed distinct features. Local BM processing ability was related to social interaction skills, whereas global BM processing ability significantly improved with age. Critically, general BM perception (i.e., both local and global BM processing) may be affected by sustained attentional ability in children with ADHD. This relationship was primarily mediated by reasoning intelligence. These findings elucidate atypical BM perception in ADHD and the latent factors related to BM perception. Moreover, this study provides new evidence that BM perception is a hallmark of social cognition and advances our understanding of the potential roles of local and global processing in BM perception and social cognitive disorders.

## eLife assessment

The authors use point light displays to measure biological motion (BM) perception in children (mean = 9 years) with and without ADHD, and relate it to IQ, social responsiveness scale (SRS) scores and age. They report that children with ADHD were worse at all three BM tasks, but that those tasks loading more heavily on local processing relate to social interaction skills and those loading on global processing relate to age. There are still some elements of the results that are unclear, but nevertheless, the **important** and **solid** findings extend our limited knowledge of BM perception in ADHD, as well as biological motion processing mechanisms in general.

# Introduction

Attention deficit hyperactivity disorder (ADHD) is a common developmental disorder with a prevalence ranging from 2% to 7% in children and adolescents, averaging approximately 5%[1]. In addition to the well-established core symptoms of ADHD (including inability to sustained attention, hyperactivity, and impulsivity), some characteristics of autism spectrum disorder (ASD), such as dysfunctions in social communication and social interaction, have also been frequently observed in children with ADHD[2–4]. Nevertheless, experimental studies focusing on social cognition in children with ADHD are limited. Some studies have reported poor performance on social cognition tasks. Among these, impaired theory of mind (ToM) and emotion recognition are the most frequently reported[5–7]. It is difficult for children with ADHD to recognise others' emotions and intentions of others. However, our understanding of other social cognitive processes in ADHD remains limited. Further exploration of a diverse range of social cognitions (e.g., biological motion perception) can provide a fresh perspective on the impaired social function observed in ADHD. Moreover, recent studies have 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], symptoms severity[8], or age[5]. Nevertheless, understanding how these factors relate to social cognitive dysfunction of in ADHD is still in its infancy. Bridging this gap is crucial 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 movement of a living creature, conveys a wealth of information beyond bodily movements[9], such as intention[10], emotion[11], sex[12], and identity[13,14]. The advent of point-light displays (PLD) technology, which is used to depict human motions,[15] allows researchers to separate biological motion from other characteristics such as shape and colour. Considering its seminal impact on cognitive, developmental, and clinical neuroscience, BM perception has drawn significant attention from scientists. Some researchers have 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 revealed differences between local and global BM perception. Separate neural signals for these abilities imply two independent BM processing stages[16–18]. Local BM cues not only help identify locomotive direction[19] but also contribute to the detecting of life in the visual environment[20] without the observers' explicit recognition or attention[21–24]. 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[24,25]. In contrast, global BM processing involves top-down modulation, with attention playing a critical role in its perception[25,26]. Dispersed attention adversely affects performance. Compared with local BM processing, global BM processing is susceptible to learning and is heavily hindered by increased mask densities[25]. These findings suggest that local and global mechanisms play different roles in BM perception, although the exact mechanisms underlying this distinction remains unclear. Exploring these two components of BM perception will enhance our understanding of the differences between local and global BM processing and shed light on the psychological processes involved in atypical BM perception.

In recent years, BM perception has received significant attention in studies on mental disorders (e.g., schizophrenia[27]) and developmental disabilities, particularly in ASD, which is characterised by deficits in social communication and social interaction[28,29]. This is because BM perception is considered a hallmark of social cognition. Individuals with deficits in BM processing exhibit worse social perception in daily life[10]. Another study found that participants' ability to process BM cues correlated with their autistic traits, particularly in the subdimension of social communication[30]. Therefore, examining BM perception could enhance our understanding of social dysfunction in children with ADHD. Compared with the numerous studies examining impaired BM perception in ASD, few studies have focused on BM perception in children with ADHD. An EEG study found neuroelectrophysiological changes in the processing of BM stimuli in children with ADHD[31]. Specifically, compared with the typically developing (TD) group, children with ADHD showed reduced activity of motion-sensitive components (N200) while watching biological and scrambled motions, although no behavioural differences were observed. Another study found that children with ADHD performed worse in BM detection with moderate noise ratios than the TD group[32]. This finding may be due to the fact that BM stimuli with noise dots will increase the difficulty of identification[33], which highlights the difference in BM processing between TD and ADHD groups[31].

Despite initial findings about atypical BM perception in ADHD, previous studies on ADHD treated BM perception as a single entity, which may have led to misleading or inconsistent findings[28]. Hence, it is essential to deconstruct BM processing into multiple components and motion features. To enhance our understanding of the ability to process distinct BM cues in ADHD, we employed a carefully designed behavioural paradigm, as used in our previous study[30], with slight adjustments made to adapt it for children. This paradigm comprised three tasks: Task 1 (BM-local), Task 2 (BM-global), and Task 3 (BM-general). Task 1 (BM-local) assessed the ability to process local BM cues. Scrambled BM sequences were displayed and the participants used 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 the participants used global BM cues to determine the presence of an intact walker. Task 3 (BM-general) tested participants' ability to process general BM cues (local and global cues). The stimulus sequences consisted of an intact walker and a mask containing similar target local cues so that the participants could use general BM cues (local + global cues) to judge the direction the walker was facing.

Experiment 1 examined three specific BM perception abilities in children with ADHD. Children with ADHD show impaired social interaction[2–4], which implies atypical social cognition. Therefore, we speculated that children with ADHD would performed worse on the three tasks than TD children. In Experiment 2, we further explored the relationship between BM perception and social interaction ability in children with ADHD and identified potential factors (e.g., intelligence quotient [IQ], age, and attention) that may affect BM perception in this population. We speculated that if the mechanisms of processing local and global BM cues are indeed distinct, as suggested by previous studies, then impairments in the ADHD population and the influential factors behind the impairment may be different.

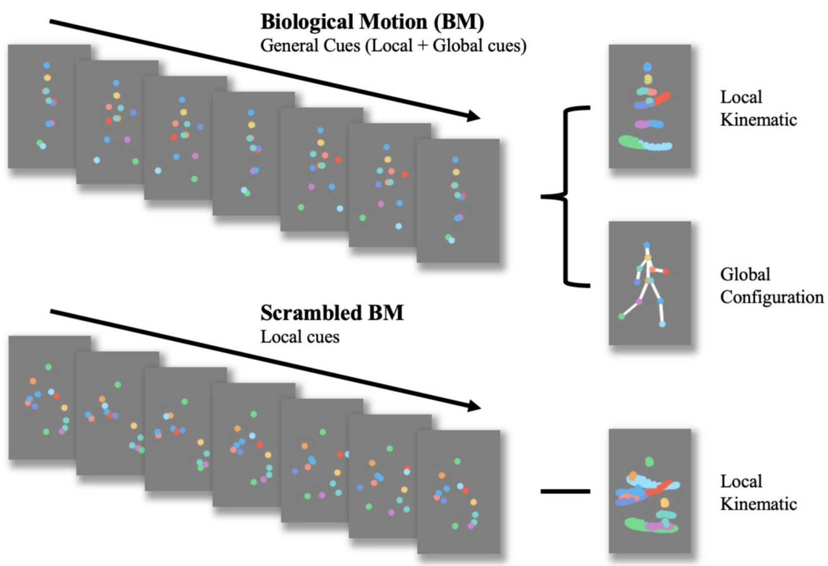


**Figure 1.**

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 the scrambled BM sequence, global configuration cues have been removed, but local kinematics have been retained. (Figure reconstructed from Wang et al., 2018[30])

# Materials and methods

## Participants

One hundred and seventeen children with and without ADHD were recruited for this study. Eighty-one children met the ADHD diagnostic criteria of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5)[34]. The clinical diagnosis was first made by an experienced child and adolescent psychiatrist in the Child and Adolescent Psychiatric Outpatient Department of 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)[35,36], a semi-structured interview instrument, was then implemented to confirm the diagnosis. Thirty-six TD children were from ordinary primary schools in Beijing were screened for the presence of ADHD, ASD, affective disorders, and behavioural disorders by a trained psychiatrist. All participants in the ADHD groups had a full-scale IQ > 75 (5th upper percentile) on the Wechsler Intelligence Scale for Children-Fourth Edition, and all TD children had a full-scale IQ above the 5th percentile on the Raven's Standard Progressive Matrices[37], which is used to measure reasoning ability and is regarded as a non-verbal estimate of intelligence. The exclusion criteria for both groups were as follows: (a) neurological diseases; (b) other neurodevelopmental disorders (e.g., ASD, mental retardation, and tic disorders), affective disorders, and schizophrenia; (c) disorders that would impact the completion of the experiment; (d) taking psychotropic drugs or stimulants within the past 30 days; and (e) previous head trauma or neurosurgery.

Thirty-six TD children (age = 9.09 ± 2.18, 14 male) and 39 children with ADHD (age = 9.88 ± 2.23, 28 male) participated in Experiment 1. The groups did not differ by age ($t = -1.550$, $p = 0.126$) but differed in sex ($\chi^2 = 8.964$, $p = 0.004$). Forty-two ADHD children (age = 9.34 ± 1.89, 27 male) participated in Experiment 2. The participants were naïve to the task and did not participate in Experiment 1. The participants' demographic characteristics are presented in **Table 1**. Currently, there is no comparable study on ADHD that indicates the effect size as a reference. Studies investigating BM perception in children with ASD typically have sample sizes ranging from 15 to 35 participants per group[29]. Considering the mild impairment of social functions in children with ADHD, we determined that a sample size of 35 to 40 participants per group was reasonable for this study. All individuals in each group had normal or corrected-to-normal vision and were naïve to the experiments objectives. Written informed consent was obtained from the parents of all the children before testing. This study was approved by the Institutional Review Boards of the Peking University Sixth Hospital and the Institute of Psychology, Chinese Academy of Sciences.

## Assessment

### K sads pl c dsm 5

The K-SADS-PL-C DSM-5 is a semi-structured interview instrument used to evaluate mental disorders in children and adolescents aged 6–18 years[35]. It involves 35 diagnoses based on the diagnostic criteria of the DSM-5. A trained psychiatrist confirmed the diagnosis by interviewing the parents and children. The Chinese version has demonstrated great psychometric properties[36].

| | 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 |
| Sex ratio (% male) | 38.89% | 71.79% | 0.004 | 42.42% | 64.28% | 0.059 |

**Table 1.**

**Demographic characteristics of TD and ADHD groups**

### ADHD Rating Scale

The ADHD Rating Scale was adapted from the ADHD diagnostic criteria of the DSM[38], which requires parents or teachers to complete the scale independently. Its Chinese version has excellent psychometric properties and consists of 2 subscales[39]: 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 appears “never or rarely”) to 4 (the symptom appears “very often”). The final results 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

The Social Responsiveness Scale (SRS) is a widely used quantitative measure with 65 items used to assess the severity of social impairment in many mental disorders[40], and the psychometric properties of the Chinese version are reliable[41]. It includes five sub-dimensions: 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

The Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV) is widely used to test comprehensive intelligence in individuals aged 6–18 years. It contains 15 subtests comprising four broad areas of intellectual functioning: Verbal Comprehension, Perceptual Reasoning, Working Memory, and Processing Speed. The scores in the four broad areas constitute the full-scale intellectual quotient (FIQ).

### QB Test

The QB Test is a 15-minute Continuous Performance Test (CPT) for assessing inattention and impulsivity, with a high-resolution infrared camera monitoring participant’s activity[42]. Previous psychometric studies have validated its good measurement properties[43]. After the test is completed, several Q scores are calculated to summarise the participants’ performances. The Q scores are standardised based on normative data matched for sex and age. A higher Q score implies more abnormal performance. In this study, we focused on QbInattention, the Q score indicating sustained attention, particularly when children are focused on tasks.

### Stimuli and Procedure

Point-light BM stimuli sequences adopted in this study have been used in previous studies[44], which were derived from the configurations of individual walking motions 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 randomised. The entire point-lighted BM walker was presented at approximately a 5.7° vertical visual angle. Stimuli were presented on a 14-inch monitor, and responses were evaluated using MATLAB together with the PsychToolbox extensions. All subjects completed the experiments in a dimly lit room with their heads on a chinrest to ensure that their eyes were 50 cm away from the monitor.

In Experiment 1, the children were required to complete three tasks that were similar to but slightly modified from the versions implemented in our previous study[30] (**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 lasting for 2 s (60 frames).

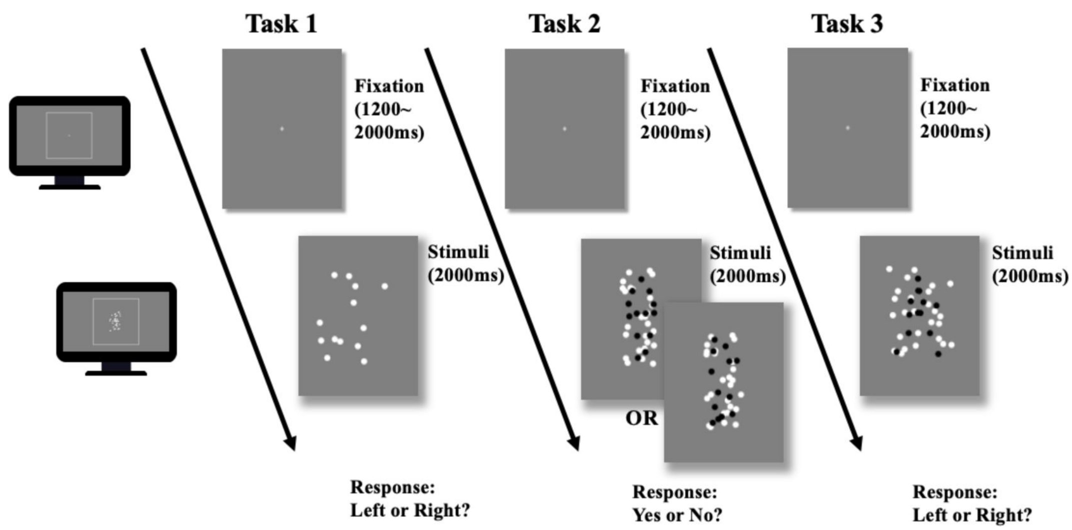


**Figure 2.**

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, the participant must rely on global BM cues to determine whether an intact walker was present in the mask. The figure shows one of five possible directions the intact walker could face (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 direction the walker was facing using general BM cues (local + global). Dots in the figure were rendered in black for better illustration but were displayed in white in the actual experiments.

Task 1 (BM-Local) assessed participants' ability to process local BM cues. During the task, the monitor displayed only a scrambled walker facing either the left or right (see Video 2). Specifically, the 13 dots constituting the intact walker were randomly relocated within the original range of the BM walker (randomly presented in 2D). This manipulation disrupted the global configuration of the intact walker while retaining local kinematics. After the display, we required the children to press a left or right button to indicate the direction of motion of the unidentified creature (i.e., the scrambled BM walker) as accurately as possible. Children did not receive feedback on the accuracy of each response. Thirty 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 (scrambled or intact) was displayed within the 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 a boundary approximately 1.44 times larger than the intact walker. A scrambled or intact version of the target walker was randomly embedded into the mask and entirely overlaid. Thus, the global BM component could be isolated as two conditions (i.e., scrambled and intact walkers) containing the same local kinematics information, rendering the local motion cues uninformative. The children were required to judge whether there was an intact walker on the mask. A correct response relied on the extraction of global cues from an intact walker. To prevent children from learning the shape of the walker[21], we set target walkers that possibly faced one of five equally spaced directions from left to right. Of the five walkers used, two faced straight to the left or right, orthogonal to the viewing direction. 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 shows the five facing directions of the walker. Thirty trials were conducted consisting of two conditions (intact or scrambled target).

Task 3 (BM-General) tested participants' ability to process general BM cues (local and global). In Task 3, the monitor displayed an intact walker (facing either the left or right) embedded within a mask (see Video 5). The mask used in this task was similar to that used in Task 2. The children were required to judge the direction the target walker was facing (left or right). Because the mask and target walker contained the same local BM cues and the target walker was presented with additional global configuration cues, children could rely on general BM information (i.e., a combination of local and global cues) to perform the task. Task 3 consisted of 30 trials, with 15 trials in each facing direction. The other parameters of Tasks 2 and 3 were similar to those of Task 1. Before each task, the children practiced for five trials to ensure a good understanding. We performed the three tasks in a fixed order so that the participants were naïve to the nature of the local BM cues in Task 1.

In Experiment 2, 42 children with ADHD completed the same procedures as in Experiment 1. In addtion, the parents completed the SRS to assess social interaction.

## Statistics

Two-sample t-tests were used to examine the difference in BM perception abilities between TD and ADHD children[45,46], and the Pearson's correlation analysis was used to assess the relationship between the accuracy of each task and the SRS score. Additionally, general linear models and path analyses were used to explore potential factors influencing BM perception. A $p$-value < 0.05 was considered statistically significant. Path analysis was conducted using AMOS, whereas 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 the ACC between the TD and ADHD groups for each task using a 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 Tasks 2 and 3, where children were asked to detect the presence or discriminate the direction the target walker was facing, the TD group had higher accuracies than the ADHD group (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 the presence of impaired global and general BM perception in children with ADHD. To ensure that sex 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 predicts impaired social interaction in ADHD

Experiment 1 provides evidence of atypical BM perception in children with ADHD. Previous studies have revealed that BM processing ability is a hallmark of social cognition[10] and is negatively correlated with social ability[30]. Substantial evidence indicates that children with ADHD often experience problems with social interaction. We hypothesised that compromised social interaction in children with ADHD would be associated with BM processing. To confirm this hypothesis, we recruited 42 naïve children with ADHD to participate in Experiment 2 and examined the relationship between their social interaction abilities and BM perception. Parents or caregivers completed the 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 SRS scores performed worse on the three tasks; that is, the abilities of BM processing were negatively correlated with SRS total scores (Task 1: $r$ = −0.264, false discovery rate [FDR]-corrected $p$ = 0.033; Task 2: $r$ = −0.238, FDR-corrected $p$ = 0.039; Task 3: $r$ = −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 statistically significant correlation between the SRS total score and global or general BM processing in either the ADHD or TD groups (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).

To explore whether the significant correlation between local BM processing and SRS total scores in the ADHD group was greater than other correlations, we constructed a general linear model to compare these correlations further (see Supplementary Information). In Task 1, we observed a significantly stronger correlation between SRS total score and response accuracy in the ADHD group than in the TD group ($p$ = 0.003). However, this distinction was not observed for Task 2 ($p$ = 0.381) or Task 3 ($p$ = 0.455). Additionally, we found that the correlation between the SRS total score and response accuracy of the ADHD group in Task 1 was slightly greater than in Task 2 ($p$ = 0.066) and Task 3 ($p$ = 0.181). For complete information, see Supplementary Information.

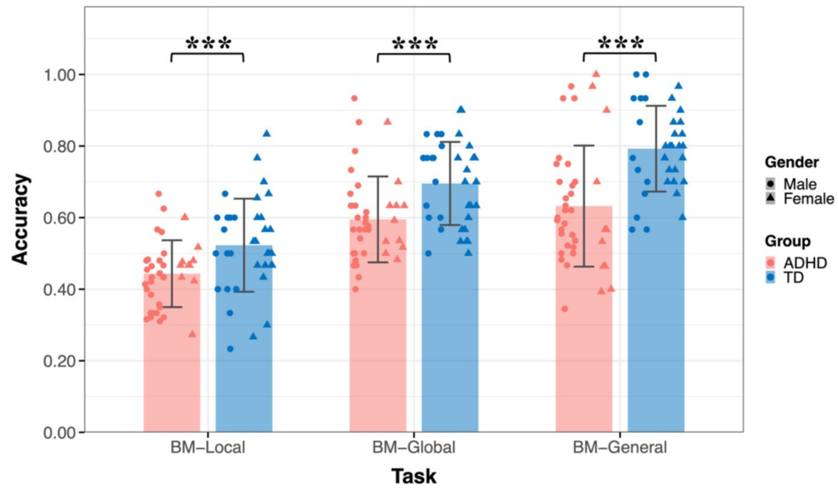


**Figure 3.**

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

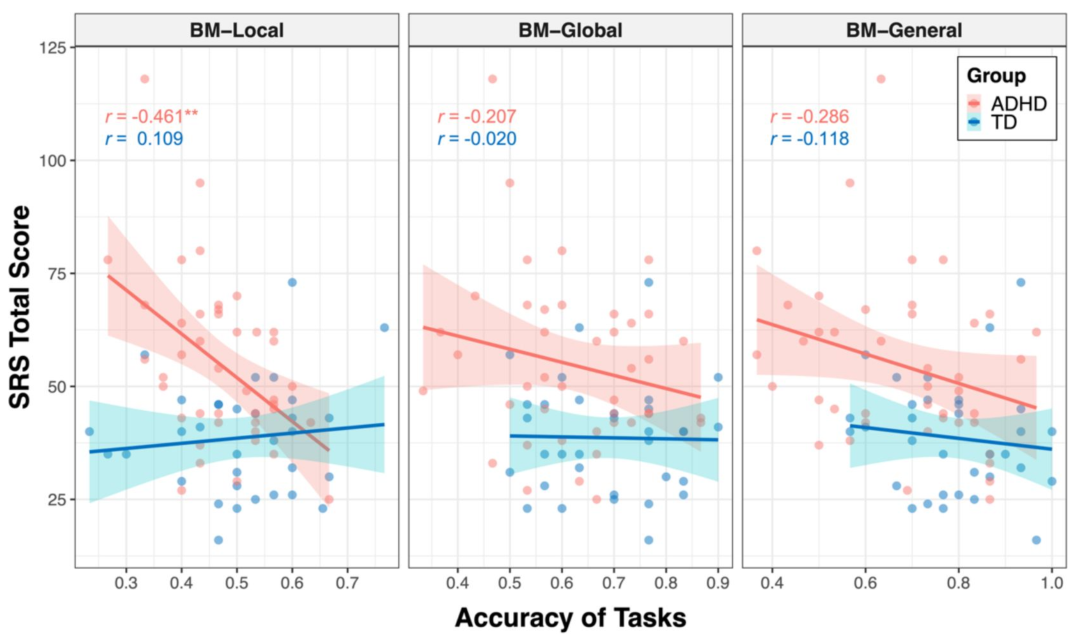


**Figure 4.**

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

| | 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 |

**Table 2.**

**The correlation between the ability of local BM processing and subdimensions of SRS in ADHD children**

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

Many factors can affect social cognition in ADHD, such as general cognitive impairment[5], symptom severity[8], or age[5]. Therefore, we examined the relationship between impairments in different BM processing abilities and factors such as age, IQ, and attention function in the ADHD group. Data from the ADHD group in both Experiments 1 and 2 were integrated, resulting in 80 ADHD participants (one child did not complete the QB test). Three linear models were built to investigate the contributing factors: (a) $ACC_{local} = \beta_0 + \beta_1 * age + \beta_2 * gender + \beta_3 * FIQ + \beta_4 * QbInattention$, (b) $ACC_{global} = \beta_0 + \beta_1 * age + \beta_2 * gender + \beta_3 * FIQ + \beta_4 * QbInattention$, and (c) $ACC_{general} = \beta_0 + \beta_1 * age + \beta_2 * gender + \beta_3 * FIQ + \beta_4 * QbInattention + \beta_5 * ACC_{local} + \beta_6 * ACC_{global}$. $ACC_{local}$, $ACC_{global}$ and $ACC_{general}$ refer to the response accuracies of the three tasks in the ADHD group, and QbInattention is the standardised score for sustained attention function. We screened the factors with the largest contribution to the models using step-wise regression. In model (a), no variable remained after stepwise regression, suggesting that local BM processing remained stable with age and was not affected by attention or IQ. In model (b), the ability to process global BM cues was enhanced with age (standardised $\beta_1 = 0.251$, $p = 0.025$). In model (c), higher FIQ, particularly on the subdimension of Perceptual Reasoning (standardised $\beta_3 = 0.271$, $p = 0.005$), and better performance in global BM processing (standardised $\beta_6 = 0.290$, $p = 0.004$) predicted better performance in general BM processing. Furthermore, as children aged, the ability to probe general BM information improved (standardised $\beta_1 = 0.365$, $p < 0.001$). It is worth noting that QbInattention showed a strong negative correlation with Perceptual Reasoning ($r = -0.355$, $p = 0.001$) and general BM perception ($r = -0.246$, $p = 0.028$). Owing to the potential collinearity issue, we employed a post hoc path analysis to visualise these relationships (**Figure 5**). The results indicated that sustained attention (i.e., QbInattention) did not directly predict performance on BM-General (i.e., Task 3) but was significantly indirectly predicted by Perceptual Reasoning ability. Furthermore, as children with ADHD aged, their performance in BM-General (i.e., Task 3) improved, both directly and through the enhanced processing of global BM cues.

We also built three models to explore further the effects of Reasoning IQ and age on BM perception in TD children: (a) $ACC_{local} = \beta_0 + \beta_1 * age + \beta_2 * gender + \beta_3 * FIQ$. (b) $ACC_{global} = \beta_0 + \beta_1 * age + \beta_2 * gender + \beta_3 * FIQ$; (c) $ACC_{general} = \beta_0 + \beta_1 * age + \beta_2 * gender + \beta_3 * FIQ + \beta_4 * ACC_{local} + \beta_5 * ACC_{global}$. In model (a), no regressor remained significant after stepwise regression. However, in models (b) and (c), we observed positive relationships between age and performance ($ACC_{global}$: standardised $\beta = 0.396$, $p = 0.017$; $ACC_{general}$: standardised $\beta = 0.330$, $p = 0.049$). We also a conducted a path analysis similar to that in the ADHD group and found no statistically significant mediator effect (Figure S3).

In summary, our findings suggest that the ability to perceive global and general BM cues, rather than local BM cues, improves with age in both groups. We speculated that age-related improvement was different when processing different BM cues and in different groups. Therefore, we examined the differences between the age-related improvement in processing local cues and that in processing global and general cues (see Supplementary Information for detail methods). In the ADHD group, we observed that the ability to process general BM cues significantly improved with age compared to local cues ($p < 0.001$) and a trend 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 (see Supplementary Information). In addition, we examined the differences in the improvements in processing of BM cues with age between the two groups for each task. There was no difference in the effect of age on the response accuracy between the TD and ADHD groups for the three tasks (see Supplementary Information).

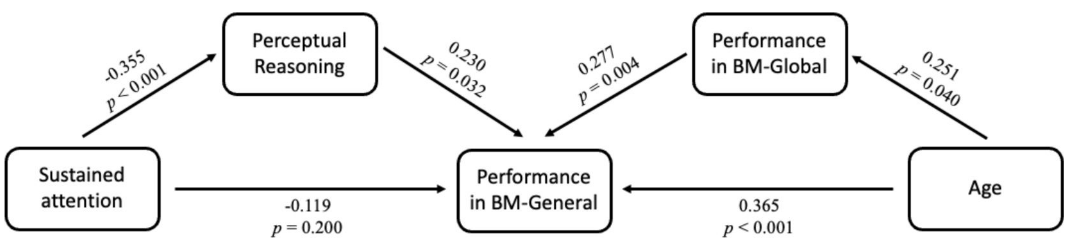


**Figure 5.**

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.

# Discussion

Our study contributes several promising findings concerning atypical BM perception in children with ADHD. Specifically, we observed the atypical local and global BM perception in children with ADHD. Notably, local and global BM processing exhibited distinct features. The ability to process local BM cues appears to be associated with social interaction traits in children with ADHD. In contrast, global BM processing was associated with age-related development. In addition, general BM perception may be affected by factors such as attention.

BM perception is a widely studied topic in visual cognition owing to its inherent biological and social properties. BM processing has significant value in successfully navigating daily life, particularly in non-verbal communication[11,47] and adaptive behavior[26,48]. In TD children, there is a clear association between BM perception and social cognitive abilities[49]. For example, 12-month-old infants exhibit social behaviours (i.e., following gaze) elicited by BM displays[50]. Therefore, BM perception plays a crucial role in the development of children's social cognition. This 'social interpretation' of BM suggests that the difficulties in processing BM may serve as an indicator of impaired social interaction[30]. Our results are consistent with these findings. We observed atypical BM perception in children with ADHD and a significant relationship between BM perception performance and the SRS total score. Further subgroup analysis revealed a significant negative correlation between SRS total score and the accuracy of local BM processing in the ADHD group. This correlation was stronger in the ADHD group then in the TD group. The lack of a significant correlation may be due to the narrow range of SRS scores in the TD group. Future studies should increase the sample size to explore the correlation among diverse individuals. These findings suggest that BM processing is regarded as a distinct hallmark of social cognition in ADHD children[10,30].

BM perception is a multi-level phenomenon[51–53]. At least in part, the processing of of local and global BM information appears to involve different neural mechanisms[16]. Sensitivity to local BM cues emerges early in life[54,55] and involves rapid processing in the subcortical regions[16,56–58]. As a basic pre-attentive feature[23], local BM cues can guide visual attention spontaneously[59,60]. In contrary, the ability to process global BM cues is related to slow cortical BM processing and is influenced by many factors such as attention[25,26] and visual experience[21,51]. As mentioned above, we found a significant negative correlation between the SRS total score and the accuracy of local BM processing, specifically in the ADHD group. This could be due to decreased visual input related to atypical local BM processing, which further impairs global BM processing. According to the two-process theory of biological motion processing[61], local BM cues guide visual attention towards BM stimuli[55,62]. Consequently, the visual input of BM stimuli increases, facilitating the development of the ability to process global BM cues through learning[21,63]. The latter is a prerequisite for attributing intentions to others and facilitating social interactions with other individuals[20,64,65]. Thus, atypical local BM processing may contribute to impaired social interaction through altered visual inputs. Further empirical studies are required to confirm these hypotheses.

The ability to process global BM cues develops with age. Previous studies indicated that global BM perception is enhanced with age in TD children[66,67]. This developmental trend in global BM processing is also evident in individuals with impaired BM perception (e.g., children with ASD). BM processing performance in children with ASD becomes more aligned with that of TD children as they age[29,68–70]. 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 the TD and ADHD groups, impling that the processing module for global BM cues tends to mature with development. This finding is akin to the potential age-related improvements observed in certain aspects of social cognitive deficits in individuals with ADHD[5]. Interestingly, in the ADHD group, the improvement in processing general and global BM cues was greater than in processing local BM cues. Few developmental studies have been conducted on local BM processing. The ability to process local BM cues remained stable and did not exhibit a learning trend[21,25]. A reasonable interpretation may be that local BM processing is a low-level mechanism, probably performed by the primary visual cortex and subcortical regions such as the superior colliculus, pulvinar, and ventral lateral nucleus[14,56,61]. Although there was no statistical difference between the improvements in processing local and global BM cues in the TD group, this may be due to the relatively small sample size or the relatively higher baseline abilities of BM perception in TD children, resulting in a relatively milder improvement. It is worth noting that the ability to process global BM cues was positively correlated with the performance in processing general BM cues in the ADHD group, whereas no such correlation was found in the 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 direction the walker is facing when presented with both local and global BM cues, which correspond to a hierarchical model[51]. Once a living creature is detected, an agent (i.e., is it a human?) can be recognised by a coherent, articulated body structure that is perceptually organised based on its motions (i.e., local BM cues)[71]. This involves top-down processing and probably requires attention[25,72], particularly in the presence of competing information[26]. Our findings are consistent with those of previous studies on the cortical processing of BM[73], as we found that the severity of inattention in children with ADHD was negatively correlated with their performance in BM processing. However, further studies are needed to verify this hypothesis.

Interestingly, children with impaired BM perception may employ a compensatory strategy[74]. Previous studies found no impairment in BM recognition in individuals with autism with high IQ[74], but children with ASD exhibited weaker adaptation effects for biological motion than TD children[75]. One possibility is that individuals with a high IQ and impaired BM perception can develop or employ reliable strategies for BM recognition, compensating for the lack of intuitive social perceptual processing[76,77]. The current study supports this assumption, as children with a higher IQ, particularly in Perceptual Reasoning, demonstrated better performance. Owing 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 reveals two distinct and atypical fundamental abilities underlying BM perception in children with ADHD. Notably, anomalous local BM processing may predict impaired social interactions in children with ADHD. Moreover, these results revealed the potential contributions of age, IQ, and attention to BM information processing. These findings also shed new light for future studies. First, different developmental trends appear in local and global BM processing. Further studies are required to explore the relationship between the two fundamental BM processing abilities, which will contribute to understanding the respective and mutual neural mechanisms underlying the two types of BM processing. Second, 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 involved in processing BM in ADHD. Finally, a comparative study between ADHD and ASD is warranted to identify common neuropsychological traits and biomarkers of social cognition impairment.

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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).

# Data availability

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

# 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.

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**Reviewer #2 (Public Review):**

Summary:

Tian et al. aimed to assess differences in biological motion (BM) perception between children with and without ADHD, as well as relationships to indices of social functioning and possible predictors of BM perception (including demographics, reasoning ability and inattention). In their study, children with ADHD showed poorer performance relative to typically developing children in three tasks measuring local, global, and general BM perception. The authors further observed that across the whole sample, performance in all three BM tasks was negatively correlated with scores on the social responsiveness scale (SRS), whereas within groups a significant relationship to SRS scores was only observed in the ADHD group and for the local BM task. Local and global BM perception showed a dissociation in that global BM processing was predicted by age, while local BM perception was not. Finally, general (local & global combined) BM processing was predicted by age and global BM processing, while reasoning ability mediated the effect of inattention on BM processing.

Strengths:

Overall, the manuscript is presented in a clear fashion and methods and materials are presented with sufficient detail so the study could be reproduced by independent researchers. The study uses an innovative, albeit not novel, paradigm to investigate two independent processes underlying BM perception. The results are novel and have the potential to have wide-reaching impact on multiple fields.

Weaknesses:

The manuscript has improved in clarity and conceptual and methodological considerations in response to the last review. However, the reported results still provide incomplete support for the claims the authors make in the paper.

In relation to other reviewers' earlier comments, the model notation used is still not consistent and model results are reported incompletely, which make it difficult to gain a full picture of the data and how they support the authors' secondary claims. For instance, across the models in the supplementary materials, ß coefficients are only reported selectively which makes it difficult to assess the model as a whole. Furthermore, different terms (task 1, task 2 vs. BM-Local, BM-global) are used to refer to the same levels of a variable, and it is unclear which levels of a dummy variable correspond to which task, making it overall very difficult to comprehend the modelling procedure.

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**Reviewer #3 (Public Review):**

The authors presented point light displays of human walkers to children (mean = 9 years) with and without ADHD to compare their biological motion perception abilities, and relate them to IQ, social responsiveness scale (SRS) scores and age. They report that children with ADHD were worse at all three biological motion tasks, but that those loading more heavily on local processing related to social interaction skills and global processing to age. The valuable and solid findings are informative for understanding this complex condition, as well as biological motion processing mechanisms in general. However, the correlations present a pattern that needs further examination in future studies because many of the differences between correlations are not significant.

Strengths:

The authors present differences between ADHD and TD children in biological motion processing, and this question has not received as much attention as equivalent processing capabilities in autism. They use a task that appears well controlled. They raise some interesting mechanistic possibilities for differences in local and global motion processing, which are distinctions worth exploring. The group differences will therefore be of interest to those studying ADHD, as well as other developmental conditions, and those examining biological motion processing mechanisms in general.

Weaknesses:

The data are not strong enough to support claims about differences between global and lobal processing wrt social communication skills and age. The mechanistic possibilities for why these abilities may dissociate in such a way are interesting, but the crucial tests of differences between correlations do not present a clear picture. Further empirical work would be needed to test this further. Specifics:

The authors state frequently that it was the local BM task that related to social communication skills (SRS) and not the global tasks. However, the results section shows a correlation between SRS and all three tasks. The only difference is that when looking specifically within the ADHD group, the correlation is only significant for the local task. The supplementary materials demonstrate that tests of differences between correlations present an incomplete picture. Currently they have small samples for correlations, so this is unsurprising.

Theoretical assumptions. The authors make some statements about local vs global biological motion processing that may have been made in previous studies, but would appear controversial and not definitive. E.g., that local BM processing does not improve with age and is uninfluenced by attention.

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**Author response:**

The following is the authors' response to the previous reviews.

> ***eLife assessment***
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> *This manuscript represents a cleanly designed experiment for assessing biological motion processing in children (mean age = 9) with and without ADHD. The group differences concerning accuracy in global and local motion processing abilities are solid, but the analyses suggesting dissociable relationships between global and local processing and social skills, age, and IQ are inconclusive. The results are useful in terms of understanding ADHD and the ontogenesis of different components of the processing of biological motion.*

We thank the editors and reviewers for their valuable feedback and constructive comments. We have carefully considered each point raised by the reviewers and made the necessary revisions to the manuscript. Regarding the relationships between global and local BM processing, the accumulated evidence from previous studies has converged on the dissociation of the two BM components, e.g., while global BM processing is susceptible to learning and practice, local BM processing does not show a learning trend (Chang and Troje, 2009; Grossman et al., 2004), and the brain activations in response to local and global BM cues are different (Chang et al., 2018; Duarte et al., 2022). Nevertheless, we concurred with reviewers that the evidence for such dissociation from the current study by itself is not strong enough. Therefore, we have toned down on this point and no longer claimed the dissociation (including the title). Based on the current results, we focused our discussion on the different aspects of BM processing in children with and without ADHD.

> ***Public Reviews:***
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> ***Reviewer #1 (Public Review):***
>
> *Summary:*
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> *The paper presents a nice study investigating the impairments of biological motion perception in individuals with ADHD in comparison with neurotypical controls. Motivated by the idea that there is a relationship between biological motion perception and social capabilities, the authors investigated the impairments of local and global (holistic) biological motion perception, the diagnosis status, and several additional behavioral variables that are affected in ADHS (IQ, social responsiveness, and attention / impulsivity). As well local as global biological motion perception is impaired in ADHD individuals. In addition, the study demonstrates a significant correlation between local biological motion perception skills and the social responsiveness score in the ADHD group, but not in controls. A path analysis in the ADHD group suggests that general performance in biological motion perception is influenced mainly by global biological motion perception performance and attentional and perceptual reasoning skills.*
>
> *Strengths:*
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> *It is true that there exists not much work on biological motion perception and ADHD. Therefore, the presented study contributes an interesting new result to the biological motion literature, and adds potentially also new behavioral markers for this clinical group. The design of the study is straightforward and technically sound, and the drawn conclusions are supported by the presented results.*

Thanks for this positive assessment of our work.

> *Weaknesses:*
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> *Some of the claims about the relationship between genetic factors and ADHD and the components of biological motion processing have to remain speculative at this point because genetic influences were not explicitly tested in this paper. Specifically, the hypothesis that the perception of human social interaction is critically based on a local mechanism for the detection of asymmetry in foot trajectories of walkers (this is what 'BL-local' really measures), or on the detection of live agents in cluttered scenes seems not very plausible.*

Thanks for these comments. We agree that the relationship between genetic factors and BM perception remains to be further examined, as we did not test the genetic influences in this study. We have deleted relavant discussion about genetics. Based on our results, we discuss the possible mechanisms behind the relationship between local BM processing and social interaction in the revised manuscript as follows:

"As mentioned above, we found a significant negative correlation between the SRS total score and the accuracy of local BM processing, specifically in the ADHD group. This could be due to decreased visual input related to atypical local BM processing, which further impairs global BM processing. According to the two-process theory of biological motion processing61, local BM cues guide visual attention towards BM stimuli55,62. Consequently, the visual input of BM stimuli increases, facilitating the development of the ability to process global BM cues through learning21,63. The latter is a prerequisite for attributing intentions to others and facilitating social interactions with other individuals20,64,65. Thus, atypical local BM processing may contribute to impaired social interaction through altered visual inputs. Further empirical studies are required to confirm these hypotheses." (lines 417 - 428)

> *Based on my last comments, now the discussion has been changed in a way that tries to justify the speculative claims by citing a lot of other speculative papers, which does not really address the problem. For example, the fact that chicks walk towards biological motion stimuli is interesting. To derive that this verifies a fundamental mechanism in human biological motion processing is extremely questionable, given that birds do not even have a cortex. Taking the argumentation of the authors serious, one would have to assume that the 'Local BM' mechanism is probably located in the mesencephalon in humans, and then would have to interact in some way with social perception differences of ADHD children. To me all this seems to make very strong (over-)claims. I suggest providing a much more modest interpretation of the interesting experimental result, based on what has been really experimentally shown by the authors and closely related other data, rather than providing lots of far-reaching speculations.*
>
> *In the same direction, in my view, go claims like 'local BM is an intrinsic trait' (L. 448) , which is not only imprecise (maybe better 'mechanisms of processing of local BM cues') but also rather questionable. Likely, this' local processing of BM' is a lower level mechanisms, located probably in early and mid-levels of the visual cortex, with a possible influence of lower structures. It seems not really plausible that this is related to a classical trait variables in the sense of psychology, like personality, as seems to be suggested here. Also here I suggest a much more moderate and less speculative interpretation of the results.*

We thank the reviewer for pointing out these issues. According to these comments, we have carefully revised the discussion to avoid strong (over-) claims. We have deleted the example of chicks, but substituted with more empirical studies to explain our results. We agree that the Local BM mechanism is probably located in subcortical regions in humans, which were reported by some MRI studies (Chang et al., 2018; Hirai and Senju, 2020; Loula et al., 2005).

We have added some evidence that atypical local BM processing may decrease visual inputs related to social information as follows:

"According to the two-process theory of biological motion processing61, local BM cues guide visual attention towards BM stimuli55,62. Consequently, the visual input of BM stimuli increases, facilitating the development of the ability to process global BM cues through learning21,63. The latter is a prerequisite for attributing intentions to others and facilitating social interactions with other individuals20,64,65. Thus, atypical local BM processing may contribute to impaired social interaction through altered visual inputs." (lines 421 - 427)

We have also deleted the clarims of 'local BM is an intrinsic trait' (originally L. 448) and related discussion as it was not conclusive based on the current study.

> ***Reviewer #2 (Public Review):***
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> *Summary:*
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> *Tian et al. aimed to assess differences in biological motion (BM) perception between children with and without ADHD, as well as relationships to indices of social functioning and possible predictors of BM perception (including demographics, reasoning ability and inattention). In their study, children with ADHD showed poorer performance relative to typically developing children in three tasks measuring local, global, and general BM perception. The authors further observed that across the whole sample, performance in all three BM tasks was negatively correlated with scores on the social responsiveness scale (SRS), whereas within groups a significant relationship to SRS scores was only observed in the ADHD group and for the local BM task. Local and global BM perception showed a dissociation in that global BM processing was predicted by age, while local BM perception was not. Finally, general (local & global combined) BM processing was predicted by age and global BM processing, while reasoning ability mediated the effect of inattention on BM processing.*
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> *Strengths:*
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> *Overall, the manuscript is presented in a clear fashion and methods and materials are presented with sufficient detail so the study could be reproduced by independent researchers. The study uses an innovative, albeit not novel, paradigm to investigate two independent processes underlying BM perception. The results are novel and have the potential to have wide-reaching impact on multiple fields.*

We appreciate the reviewer's positive feedback very much.

> *Weaknesses:*
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> *The manuscript has greatly improved in clarity and methodological considerations in response to the review. There are only a few minor points which deserve the authors' attention:*
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> *When outlining the moviation for the current study, results from studies in ADHD and ASD are used too interchangeably. The authors use a lack of evidence for contributing (psychological/developmental) factors on BM processing in ASD to motivate the present study and refer to evidence for differences between typical and non-typical BM processing using studies in both ASD and ADHD. While there are certainly overlapping features between the two conditions/neurotypes, they are not to be considered identical and may have distinct etiologies, therefore the distinction between the two should be made clearer.*

We thank the reviewer for pointing out this issue. We have removed some unnecessary citations about ASD and referred to studies about social cognition in ADHD to elaborate the motivation of this study:

"Further exploration of a diverse range of social cognitions (e.g., biological motion perception) can provide a fresh perspective on the impaired social function observed in ADHD. Moreover, recent studies have indicated that the social cognition in ADHD may vary depending on different factors at the cognitive, pathological, or developmental levels, such as general cognitive impairment5, symptoms severity8, or age5. Nevertheless, understanding how these factors relate to social cognitive dysfunction of in ADHD is still in its infancy. Bridging this gap is crucial as it can help depict the developmental trajectory of social cognition and identify effective interventions for impaired social interaction in individuals with ADHD." (lines 53 - 62)

> *In the first/main analysis, is unclear to me why in the revised manuscript the authors changed the statistical method from ANOVA/ANCOVA to independent samples t-tests (unless the latter were only used for post-hoc comparisons, then this needs to be stated). Furthermore, although p-values look robust, for this analysis too it should be indicated whether and how multiple comparison problems were accounted for.*

Thanks for the reviewer's comments. According to the suggestions from reviewer #3, it may be inapposite to regard gender as a covariate in ANOVA, which may violate the assumptions of ANCOVA. To ensure that gender does not influence the results, firstly, we separated boys and girls on the plots with different coloured individual data points, and there are no signs of a gender effect in their TD group. Secondly, we use t-tests to examine the difference between TD and ADHD groups. Finally, we conducted a subsampling analysis with balanced data, and the results remained consistent.

In part 1 of the results, we aimed to compare the task accuracies between the TD and ADHD groups in three independent tasks, which assess the participants' abilities to process three types of BM cues. We assumed that individuals with ADHD show poorer performance in three tasks compared to TD individuals. With regard to that, we consider that multiple comparisons may not be necessary.

> ***Reviewer #3 (Public Review):***
>
> *Strengths:*
>
> *The authors present differences between ADHD and TD children in biological motion processing, and this question has not received as much attention as equivalent processing capabilities in autism. They use a task that appears well controlled. They raise some interesting mechanistic possibilities for differences in local and global motion processing, which are distinctions worth exploring. The group differences will therefore be of interest to those studying ADHD, as well as other developmental conditions, and those examining biological motion processing mechanisms in general.*

We appreciate the reviewer's positive assessment of this work.

> *Weaknesses:*
>
> *The data are not strong enough to support claims about differences between global and lobal processing wrt social communication skills and age. The mechanistic possibilities for why these abilities may dissociate in such a way are interesting, but the crucial tests of differences between correlations do not present a clear picture. Further empirical work would be needed to test the authors' claims. Specifics:*

> *The authors state frequently that it was the local BM task that related to social communication skills (SRS) and not the global tasks. However, the results section shows a correlation between SRS and all three tasks. The only difference is that when looking specifically within the ADHD group, the correlation is only significant for the local task. The supplementary materials demonstrate that tests of differences between correlations present an incomplete picture. Currently they have small samples for correlations, so this is unsurprising.*

Thanks for this comment. We agree with the reviewer that the relationship between local and global processing with social communication and age needs more expirical work. Based on our results, there are only possible dissociable roles of local and global BM processing. The accumulated evidence from previous studies has converged on this dissociation, e.g., whild global BM processing is susceptible to learning and practice, local BM processing does not show a learning trend (Chang and Troje, 2009; Grossman et al., 2004), and the brain activations in response to local and global BM cues are different (Chang et al., 2018; Duarte et al., 2022). We concurred with reviewers that the evidence for such dissociation from the current study by itself is not strong enough. Therefore, we have toned down on this point and no longer emphasized the dissociation. Based on the current results, we focused our discussion on the different aspects of BM processing in children with and without ADHD. Future studies with larger sample sizes are needed to confirm this disociable relationship.

> *Theoretical assumptions. The authors make some statements about local vs global biological motion processing that should still be made more tentatively. They assume that local processing is specifically genetically whereas global processing is a product of experience. These data in newborn chicks are controversial and confounded - I cannot remember the specifics but I think there an upper vs lower visual field complexity difference here.*

We appreciate the reviewer's suggestion. We agree that the relationship between genetic factors and BM perception remains to be further examined as we didn't perform any genetic analysis in the current study. Some speculative papers have been removed, so do the statement about newborn chicks given the controversial and confounded results. We have toned down our claims and povided a moderate interpretation of the results:

"Sensitivity to local BM cues emerges early in life54,55 and involves rapid processing in the subcortical regions16,56-58. As a basic pre-attentive feature23, local BM cues can guide visual attention spontaneously59,60. In contrary, the ability to process global BM cues is related to slow cortical BM processing and is influenced by many factors such as attention25,26 and visual experience21,51. As mentioned above, we found a significant negative correlation between the SRS total score and the accuracy of local BM processing, specifically in the ADHD group. This could be due to decreased visual input related to atypical local BM processing, which further impairs global BM processing. According to the two-process theory of biological motion processing61, local BM cues guide visual attention towards BM stimuli55,62. Consequently, the visual input of BM stimuli increases, facilitating the development of the ability to process global BM cues through learning21,63. The latter is a prerequisite for attributing intentions to others and facilitating social interactions with other individuals20,64,65. Thus, atypical local BM processing may contribute to impaired social interaction through altered visual inputs." (lines 413 - 427)

"Few developmental studies have been conducted on local BM processing. The ability to process local BM cues remained stable and did not exhibit a learning trend21,25. A reasonable interpretation may be that local BM processing is a low-level mechanism, probably performed by the primary visual cortex and subcortical regions such as the superior colliculus, pulvinar, and ventral lateral nucleus14,56,61." (lines 441- 446)

*Readability. The manuscript needs very careful proofreading and correction for grammar. There are grammatical errors throughout.*

Thank the reviewer for this feedback. We have performed thorough proofreading and corrected grammatical errors throughout the manuscript.

***Recommendations for the authors:***

***Reviewer #1 (Recommendations For The Authors):***

*I thank the authors for their revisions that address several of the minor points that I raised in my last review. A number of requests are still not sufficiently answered:*

*L. 290 ff.: These model 'BM-local = age + gender etc ' is a pretty sloppy notation. I think what is meant that a GLM was used that uses the predictors genderetc. time appropriate beta_i values. This formulas should be corrected or one just says that a GLM was run with the predictors gender*

*The same criticism applies to these other models that follow.*

This was corrected.

*However, the corrected text remains sloppy: example: 'BM-locaL = ...' What exacty is 'BM-Local' the accuracy? etc. Here a precise notation shoudl be given that clearly names which variables are used here as predictors and target variables.*

We appreciate the reviewer's suggestion. We clarified which variables are used in our model and gived them precise notations:

"Three linear models were built to investigate the contributing factors: (a) ACClocal = β0 + β1 * age + β2 * gender + β3 * FIQ + β4 * QbInattention, (b) ACCglobal = β0 + β1 * age + β2 * gender + β3 * FIQ + β4 * QbInattention, and (c) ACCgeneral = β0 + β1 * age + β2 * gender + β3 * FIQ + β4 * QbInattention + β5 * ACClocal + β6 * ACCglobal. ACClocal, ACCglobal and ACCgeneral refer to the response accuracies of the three tasks in the ADHD group, and QbInattention is the standardised score for sustained attention function." (lines 337 - 343)

*All these models assume linearity of the combination of the predictors. was this assumption verified?*

We referred to the previous study of BM perception in children. They found main predictor variables, including IQ (Rutherford et al., 2012; Jones et al., 2011) and age (Annaz et al., 2010; van et al., 2016), have a linear relation with the ability of BM processing.

*This answer is insufficient and not convincing. Because a variable Y depends linearly on predictor A and B in some other study, this does not imply that is is also linear in predictor C, or does not show interactions with such predictors in the present study.*

*What is needed here is the testing of models with interaction terms and verifying that such models are not better predictors. If authors do not want to do this, they need at least to clearly point out that they made the strong assumption of linearity of their model, which might be wrong and thus be a substantial limitation of their analysis.*

Thanks for the suggestion. We tried to compare each possible mode with and without relative interactions. The results showed that the change of Coefficient of Determination (R-squared, R2) between the two models was not statistically significant.

> *L. 296ff.: For model (b) it looks like general BM performance is strongly driven by the predictor global BM performance in the ADHD group. Does the same observation also apply to the controls?*

The same phenomenon was not observed in TD children. We have briefly discussed this point in the Discussion section of the revised manuscript (lines 449 - 459).

> *Was such a path analysis also done for the TD subjects or not? If yes, was then also predicted that the variable BM-Global largely and directedly influences the variable BM-General? (The answer refers to the general discussion section, where no such analysis is presented, as far as I understand.)*

Thank you for your comment. We also conduct a path analysis similar to that in the ADHD group. There is no statistically significant mediator effect in the TD group. Please see Figure S3 for complete statistics.

> ***Reviewer #2 (Recommendations For The Authors):***
>
> *(1) Please add public access to the data repository so data availability can be assessed.*

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

> *(2) Lines 119-115: The differences observed in ADHD participants in the studies referenced here were relative to what group? The last sentence here also refers to two groups, and it is difficult to gather which specific groups are meant, also because the two references relate to both ADHD and ASD samples. Please clarify.*

The suggestion is well taken. We have clarified the expressions accordingly:

"Specifically, compared with the typically developing (TD) group, children with ADHD showed reduced activity of motion-sensitive components (N200) while watching biological and scrambled motions, although no behavioural differences were observed. Another study found that children with ADHD performed worse in BM detection with moderate noise ratios than the TD group32." (lines 100 - 105)

> *(3) Line 116: I'm not sure what is meant by 'despite initial indications' - please briefly specify/summarise here why the investigation into BM processing in ADHD is warranted.*

Thank the reviewer for pointing out this issue. We rephrase this part and briefly specify "why the investigation into BM processing in ADHD is warranted":

"Despite initial findings about atypical BM perception in ADHD, previous studies on ADHD treated BM perception as a single entity, which may have led to misleading or inconsistent findings28. Hence, it is essential to deconstruct BM processing into multiple components and motion features." (lines 108 -111)

> *(4) Lines 290-293: Please complete the sentence.*

Thank the reviewer for pointing out this issue. Th sentence has been completed:

"For Task 2 and 3, where children were asked to detect the presence or discriminate the facing direction of the target walker, TD group have higher accuracies than the ADHD group (Task 2 - TD: $0.70 \pm 0.12$, ADHD: $0.59 \pm 0.12$, $t_{73} = 3.677$, $p < 0.001$, Cohen's $d = 0.861$; Task 3 - TD: $0.79 \pm 0.12$, ADHD: $0.63 \pm 0.17$, $t_{73} = 4.702$, $p < 0.001$, Cohen's $d = 1.100$)." (lines 284 - 288)

> ***Reviewer #3 (Recommendations For The Authors):***
>
> *(1) Conclusions concerning differences between the local and global tasks wrt SRS and age (see above). I believe the authors need to reword throughout to reflect that the tests of differences between these crucial correlations did not present a clear picture.*

We have reworded throughout the paper to reflect the inconclusiveness with regard to the relationship between local and global processing with social communication based on this study only. Future studies with larger sample sizes are needed to confirm this conclusion. The mechanism for this dissociable relationship should be validated by more psychologial tests in the future studies.

> *(2) I would again tone down the discussion of genetic specification of local processing, given it is highly controversial.*

We thank the reviewer for pointing out the issue. We agree the point about the genetic specification of local processing remains controversial. The interpretation of results about local BM processing has been rephrased. Please refer to our response to the point #2 mentioned.

> *(3) The manuscript needs very careful proofreading and grammatical correction throughout.*

Thanks for the suggestion to check the grammar. We have carefully proofread the manuscript to correct grammatical errors