Journal of Autism and Developmental Disorders (2023) 53:2998–3011
https://doi.org/10.1007/s10803-022-05572-5

ORIGINAL PAPER

Impaired Biological Motion Processing and Motor Skills in Adults with Autistic Traits

Priscilla Jacob[1] · **Gerianne Alexander**[1]

Accepted: 11 April 2022 / Published online: 7 May 2022

Abstract

The present study explored the relationship between biological motion (BioM) processing, motor skills, and autistic traits within a non-clinical sample of 621 adults (18–73 years, 51.8% female). Results indicated that adults with greater autistic traits also endorsed difficulties associated with developmental coordination disorder (DCD) in childhood and adulthood. Traits associated with autism spectrum disorder and DCD were predictive of BioM processing abilities. The results also revealed sex differences in DCD, autistic traits, and BioM processing. Overall, these findings suggest that adults with greater autistic traits experience both deficits in motor activities as well as underlying motor perceptual abilities.

Keywords Motor skills · Autistic adults · Biological motion · Visuomotor integration

Introduction

Motor impairment is a prominent feature of autism spectrum disorder (ASD) in children, with a comorbidity rate comparable to that of intellectual impairment (Bhat, 2021; Lee & Bo, 2015; Licari et al., 2020; Ming et al., 2007; Odeh et al., 2020; Piven & Rabins, 2011). Accordingly, approximately 87% of children with ASD are at risk for developmental coordination disorder (DCD), a neurodevelopmental condition marked by gross and fine motor skill delays and/or impairment (Bhat, 2020). However, much less is known about the prevalence and pervasiveness of motor impairment in autistic adults given that systematic studies of motor functioning within ASD have historically focused on the trajectory within early development. Further, more research is needed to understand if motor impairments are bound to a clinical diagnosis of ASD or exist across a spectrum of autistic traits.

A Continuum of Motor Impairment and Autistic Traits

In adults, autistic traits as measured by dimensional screening instruments, have been found to be correlated with DCD, delayed motor inhibition, poor interpersonal motor coordination, poor motor synchrony, and reduced cortico-motor facilitation (Amoruso et al., 2018; Cassidy et al., 2016; Cheng et al., 2017; Curioni et al., 2017; Granner-Shuman et al., 2021; Puzzo et al., 2009). These studies have contributed to our understanding of how continuously distributed autistic traits, in terms of range of deficits, are related to motor impairment (Constantino et al., 2004). It is unclear if motor impairment exists on a similar continuum as other core autistic traits.

Support for quantitative research is also reflected by the severity gradient model of ASD, which posits that the clinical manifestation of the disorder is on the extreme end of a continuous distribution of autistic traits (Baron-Cohen et al., 2001; Cholemkery et al., 2016; Constantino & Todd, 2003; Ring et al., 2008; Spiker et al., 2002; Syriopoulou-Delli & Papaefstathiou, 2020). In addition to severity, Ring et al. (2008) discuss how a greater number of autistic traits may be significantly related to ASD. This is based on genetic research that provides evidence for a relationship between a greater number of pathogenic genes and an increase in severity of the clinical phenotype. Further, evidence that first-degree relatives of autistic individuals demonstrate a

✉ Priscilla Jacob
priscillajacob@tamu.edu

[1] Department of Psychological and Brain Sciences, Texas A&M University, College Station, TX 77843, USA

greater number of dimensional (subclinical) variants of ASD may also provide support for understanding genetic susceptibilities of ASD (Dawson et al., 2002; Ring et al., 2008). A dimensional conceptualization of ASD is therefore served by quantitative approaches, as it is able to reflect the existing heterogeneity of individuals who present with varying degrees of autistic traits.

Although there are varying levels of support for studying distinct subtypes of ASD and the severity gradient model, Syriopoulou-Delli and Papaefstathiou's (2020) review suggests that both approaches are likely not mutually exclusively and uniquely contribute to our understanding of the disorder. The present study aims to add to the literature proposing that categorical and dimensional approaches to ASD may be complementary in nature (Abu-Akel et al., 2019). A review of motor impairment in autistic adults is provided below while acknowledging that there are important implications for understanding motor impairment across the spectrum of autistic traits.

Expressive Motor Impairments in ASD

For the purposes of the present study, we refer to motor functioning as it relates to gross, fine, and complex coordinated body movements as expressive motor skills. Extant literature suggests that autistic adults experience impairments in expressive motor skills including, but not limited to, poor upper- and lower-limb coordination, deficit postural control, slowed gait, weak grip strength and slower finger tapping speed (Armitano et al., 2020; Bhat et al., 2011; Hillus et al., 2019; Travers et al., 2017). Autistic adults are also likely to present with motor stereotypies (e.g., rocking) and impairments in performance of complex movement sequences (e.g., oral imitation) (Bhat et al., 2011). According to a recent study, older autistic adults (aged 40–65 years) also demonstrate reduced functional connectivity of the sensorimotor systems in addition to impaired motor skills (Linke et al., 2020). Although no research has mapped the trajectory of ASD-related motor functioning across the lifespan, there is evidence that children with DCD continue to experience motor impairments into, at least, young adulthood (Cousins & Smyth, 2003; Kirby et al., 2008).

Expressive motor difficulties associated with DCD can significantly interfere with activities of daily living in adulthood (Travers et al., 2017). In a longitudinal study examining the development of motor abilities from childhood to mid-adulthood, manual motor performance (i.e., grip strength, finger tapping speed) was predictive of future adaptive living skills in autistic adults (Travers et al., 2017). Importantly, there is also some evidence that the compounding of poor manual motor skills can lead to increased disability over time (Travers et al., 2017). These findings suggest that difficulties with even subtle motor skills, such as moving fingers, can significantly impact daily living beyond the developmental period (Travers et al., 2017). For adults, poor grip strength can make daily tasks such as opening jars, carrying grocery bags, and pouring liquids, more difficult (Travers et al., 2017). In another study, adults with DCD also reported less participation in activities that require coordination (e.g., avoid clubs or dancing) in addition to expressive motor difficulties (e.g., trouble writing neatly) (Kirby et al., 2010). Accordingly, the presence of expressive motor impairment can have reaching implications for social participation, quality of life, and life satisfaction in adulthood (Tal-Saban et al., 2014).

Perceptual Motor Impairments in ASD

In addition to expressive motor impairments, researchers have also studied potentially underlying perceptual processes related to regulating and organizing sensory input. Perceptual motor impairments may include difficulties in visual-spatial awareness and organization (Tseng & Chow, 2000). While typically-developing individuals are capable of drawing on perceptual information in order to develop competence in motor behaviors, those with and at-risk for ASD demonstrate a weaker ability to integrate auditory, visual and motor stimuli (Adolph & Joh, 2007; Dawson & Watling, 2000). Further, there is evidence to indicate that impaired perceptual mechanisms within the motor system may also underlie receptive and expressive social deficits (Fabbri-Destro et al., 2013).

Tasks of biological motion (BioM) perception, or the ability to perceive human movement with minimal visual cues, have been utilized to assess for perceptual motor skills (Johansson, 1973). BioM is characteristically depicted by point-light displays (PLDs) of dots attached to the joints of an organic figure. Individuals are typically able to perceive the spatial organization of these dots as a biological figure producing movement. It has been suggested that the ability to interpret BioM is related to proficiency in motor movement (Federici et al., 2020). Of relevance to an understanding of ASD is the theory that perceptual systems involved in interpreting BioM are also tied to social abilities (Pavlova, 2011). A preference for BioM and upright figures compared to non-BioM and upside-down figures has been found in as early as two-day-old newborns, and this preference extends into adulthood for typically-developing individuals (Simion et al., 2008). Furthermore, one study demonstrated that infants aged 9-months with a preference for viewing BioM also had higher scores on the developmental index (e.g. physical motor, receptive language, social relationships) (Kutsuki et al., 2009).

BioM studies utilizing behavioral measures such as, reaction time and accuracy, reveal mixed findings regarding lower-order abilities of autistic adults to discriminate

BioM from non-BioM. That is, two studies using comparable stimuli found that an ASD-group performed comparably to a non-ASD group while the other study revealed a deficit to discriminate BioM in the ASD-group (Blake et al., 2003; Hubert et al., 2007). More consistent evidence exists related to autistic adults' ability to extract higher-order information (e.g., emotion) from PLDs. Some studies have demonstrated that autistic adults demonstrate weakened abilities to extract information from PLDs regarding subjective and emotional states (e.g., tired, hurt, cold, angry, happy) (Atkinson, 2009; Hubert et al., 2007; Nackaerts et al., 2012). In addition to less accuracy in extracting emotional information, autistic adults have been found to produce more saccades and shorter fixation durations for BioM stimuli (Nackaerts et al., 2012). In sum, there is evidence that autistic adults demonstrate greater difficulty at extracting higher-order information of moving figures, suggesting a possible deficit in motor-related perceptual skills.

Present Study

The present study is the first to examine the co-occurrence of expressive and perceptual motor impairments as it relates to autistic traits in adulthood. Based on previous research, we hypothesized that adults with greater ASD traits would endorse greater symptoms associated with DCD and perform worse on tasks of BioM processing. There is also evidence for motor-related sex differences in autistic children (Carter et al., 2007; Gabis et al., 2020; Matheis et al., 2018). Therefore, we hypothesized that compared to females, DCD would be more prevalent in males compared to females and that males would demonstrate more impairment across tasks of BioM.

Methods

Participants

The initial sample included 943 participants who volunteered to participate through one of two recruitment pools. Seven hundred and forty-three participants were recruited through Amazon Mechanical Turk (mTurk) and 200 participants were recruited through an undergraduate psychology pool at Texas A&M University (SONA). Inclusion criteria for SONA included an age of 18 years or older, and mTurk participation was restricted to profile ratings of at least 95%. Exclusion criteria included failing one or more attention-check items (e.g., item prompts participant to select "definitely agree"), inputting an incorrect survey code, or clear evidence of low effort (i.e., selecting all 1's). These data exclusion practices as well as our overall rate of exclusion are consistent with published recommendations for assuring mTurk data quality (Ahler et al., 2020). The final sample consisted of 621 participants (see Table 1).

Participants (320 males, 295 females) ranged from 18 to 73 years of age (M = 36.66, SD = 12.33) and were primarily (65.8%) White/Caucasian (15.4% Black/African-American, 5.8% Asian, 7.0% Hispanic, 5.3% Mixed Race, 0.5% American Indian/Alaskan Native, 0.2% Other Race). Participants also reported on handedness (83.9% usually to always right-handed), preterm status (33.2% Preterm), paternal education (51.2% College Graduate), maternal education (41.8% College Graduate), personal history of serious illness/injury (70.3% none), and personal/sibling history of developmental delays or disorders (86.4% personal none, 89.2% sibling none). Participants also filled out general information related to preterm status, personal report of medical illness/injury, personal and sibling report of medical illness/injury and developmental delays, parental education, parental age, as well as handedness as measured by the Edinburgh Handedness Inventory (Short Form) (Veale, 2013) (See Table 1).

Measures

Autism Spectrum Quotient—Short (AQ-28)

The original Autism Spectrum Quotient (AQ-50) is a 50-item self-report questionnaire that measures autistic traits in adults (Baron-Cohen et al., 2001). The AQ-50 comprises five domains of ASD-related deficits: social skills, attention switching, attention to detail, communication, and imagination. Since the development of the AQ-50, several studies have empirically tested alternative models with the purpose of enhancing psychometric properties. A recent comprehensive analysis of various proposed factor structures found the most support for the three-factor structure proposed by Russell-Smith et al. (2011) (English et al., 2019). Based on findings from this analysis, the present study utilized this model which consists of a 28-item version of the AQ comprising three domains of ASD-related deficits: social skills, details/patterns, and communication/mindreading (Russell-Smith et al., 2011).

Adult Repetitive Behaviors Questionnaire-2 (RBQ-2A)

The Adult Repetitive Behaviors Questionnaire-2 (RBQ-2A) is a 20-item self-report questionnaire that measures restricted and repetitive behaviors and interests (RRBIs). The RBQ-2A was developed to address the gap in the literature examining RRBIs in adults and is based on the RBQ-2, a parent-report of RRBIs in children. The RBQ-2A has been shown to be a reliable and valid self-report measure of RRBIs in adults (Barrett et al., 2018; Jia et al., 2019). For the purposes of the present study, the RBQ-2A served as a measure of expressive motor functioning.

Table 1 Descriptive statistics of demographic variables

Demographic variable	N	% of mTurk n = 452	% of SONA n = 169	M (SD)
Age	–	–	–	*mTurk* 36.72 years (11.00) *SONA* 18.51 years (1.34)
Handedness	–	–	–	*mTurk*
More left	100	18.1	10.7	63.89
More right	523	81.9	89.3	(61.61) *SONA* 79.81 (52.94)
Sex				
Female	320	43.8	71.6	–
Male	295	55.3	26.9	–
Prefer not to answer	4	.7	.6	–
Ethnicity				
American Indian/Alaskan native	3	.7	0	–
Asian	36	3.5	11.8	–
Black/African-American	96	20.9	.6	–
Hispanic	44	3.5	16.6	–
White/Caucasian	410	68.7	58	–
Mixed	33	2.4	13	–
Other	1	.2	0	–
Preterm status				
Pre-term	179	32.6	18.3	–
Full-term	360	56.6	60.9	–
Maternal education				
Some high school	39	5.7	7.7	–
High school graduate	145	30	5.3	–
Some college	178	35	11.2	–
College graduate	260	29.3	75.1	–
Paternal education				
Some high school	45	7	7.7	–
High school graduate	103	20.3	6.5	–
Some college	156	30	11.8	–
College graduate	319	42.7	74	–
Serious illnesses/injuries				
Yes	184	33.7	18.3	–
No	438	66.1	81.7	–
Developmental delays/disorders				
Yes	77	16.1	2.4	–
No	538	83	95.3	–
Siblings yes	64	12.1	5.3	–

The Adult DCD/Dyspraxia Checklist (ADC)

The Adult DCD/Dyspraxia Checklist (ADC) is a 30-item self-report questionnaire that assesses movement difficulties in adulthood. DCD is a developmental disorder that was considered a childhood disorder until more recent evidence suggesting that persistent difficulties extend into adulthood (Kirby et al., 2010). The subscales of the ADC assess both

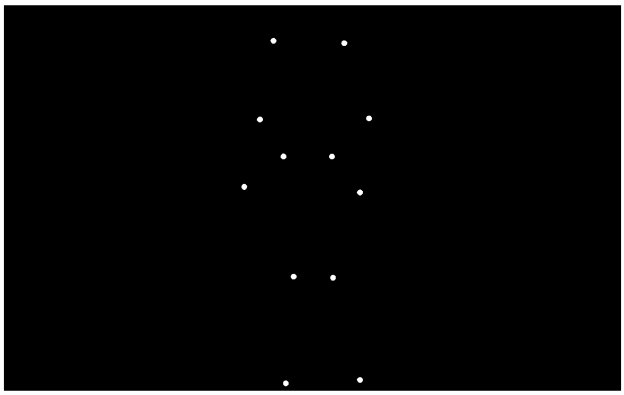

Fig. 1 Example of BioM PLD—neutral male walk

Fig. 2 Example of non-BioM PLD—scrambled neutral male walk

childhood history and current report of motor-related daily difficulties. The ADC has been shown to have high levels of internal validity, construct and concurrent validity, and discriminant validity (Kirby et al., 2010). For the purposes of the present study, the ADC served as a measure of expressive motor functioning along with the RBQ-2A.

Perceptual-Motor Assessment: BioM Processing

BioM perception was assessed utilizing two computer-based tasks. The BioM stimuli were acquired from Alaerts et al. (2011), who created PLDs utilizing motion capturing of actors. For a detailed description of these stimuli and validation of action and emotion recognition, see Alaerts et al. (2011). The present stimuli consist of 12 moving PLDs of a male actor walking (Fig. 1) and 12 scrambled/non-BioM versions of these stimuli (Fig. 2). The presented PLDs contained three exemplars of a male walking in one of four emotional states: neutral, happy, sad, angry. Within each emotion category, three perspectives of PLDs were included: front, medium, side. In a follow-up study to Alaerts et al. (2011), ASD-subjects were found to be less accurate in recognizing BioM and emotions utilizing these stimuli (Nackaerts et al., 2012).

Perceptual Task 1: BioM Recognition

The first paradigm assessed for recognition of BioM and is modeled after Nackaerts et al. (2012). Nine randomized PLD's, looped to 10-s each, were presented to all participants. Characteristics of the PLDs included a male actor, neutral emotion, three perspectives (front, medium, side), and three actions (walk, jump, kick). Standardized instructions were provided on the monitor at the start of each test before subjects were presented with a series of PLDs that either depicted a person's movements ('biological motion') or did not depict a person's movements ('scrambled'). Participants were asked to categorize each clip as "person" or "not a person."

Perceptual Task 2: BioM Emotion Categorization

The third paradigm assessed for categorization of emotion PLDs using a forced-choice response task. Similar to the first paradigm, the task included 12 PLD's looped to 10-s each. Characteristics of the non-scrambled PLDs included a male actor, four emotions (neutral, happy, mad, sad), one perspective (front), and three actions (walk, jump, kick). Participants categorized each clip as one of four emotions: neutral, happy, mad, sad. The purpose of the categorization task was to see how participants extracted higher-order information from PLDs when they were presented with given emotion words.

Procedure

Participants signed up for the online-based study through mTurk or the TAMU Psychology SONA system. Each participant tested remotely in one session lasting a maximum of 60 min. Participants provided informed signed consent before completing the five questionnaires and the two computer-based tasks. Individuals recruited through mTurk received $2.00, and students recruited through SONA received credit to apply towards undergraduate course requirements.

Results

Predicting BioM Processing

Four sets of three-Step hierarchical multiple regressions were run to predict BioM processing. BioM scores were calculated as a proportion of correct items over completed

items: [(items correct/items completed) × 100]. BioM Recognition (Task 1 performance) was entered as the dependent variable for the first two regressions, and BioM Emotion Categorization (Task 2 performance) was entered as the dependent variable for the third and fourth regressions. Several demographic variables were entered at Step one of all four regressions including Sex (male, female), PSAI, Age, Preterm Status, Sibling with Developmental Disorder/Delay, Parental Education, and Handedness to control for the proportion of variance accounted for by factors relevant to a diagnosis of ASD as indicated by previous research. Recruitment Pool (mTurk, SONA) was also entered in Step one to control for other extraneous differences between the two samples. Step two of all four regressions included Autistic traits as measured by the AQ-28 (AQ-SS, AQ-DP, AQ-CM). Step three of all four regressions included expressive motor behaviors as measured by the ADC and RBQ-2. However, given that expressive motor functioning in childhood and adulthood as measured by the ADC were highly correlated ($r(622) = 0.908$, $p < 0.001$), Step three included either ADC-Childhood or ADC-Adulthood for both BioM Recognition and BioM Emotion Categorization regressions. For ease of reference, regressions are labeled 1–4 on Tables 2 and 3. Intercorrelations between the variables were reported in Table 4 and the summary of hierarchical regression statistics are reported in Tables 2 and 3. Means and standard deviations for all demographic and study variables can be found in Tables 1 and 4.

Predicting BioM Recognition (Task 1)

For Task 1, both hierarchical multiple regressions revealed that at Step one, demographic factors significantly contributed to the model, $F(8, 492) = 4.704$, $p < .001$ and accounted for 7.1% of the variance in the ability of individuals to discriminate between BioM and non-BioM. Two significant predictors emerged within step 1. Individuals who reported having at least one sibling with a developmental disorder/delay scored poorer on Task 1 ($\beta = -.126$, $p < .01$). Individuals who reported a greater preference to use the left-hand more than the right-hand also scored poorer on BioM Recognition ($\beta = .091$, $p < .05$).

In Step two, it was revealed that adding autistic traits to the model did not account for a significant proportion of the variance above and beyond demographic variables. Only report of siblings with developmental disorder/delay maintained as a significant predictor ($\beta = -.123$, $p < .01$).

In Step three of Regression #1, the inclusion of repetitive behaviors and movements (RBQ-2A) and motor dysfunction in childhood (ADC-Childhood) to the model explained an additional 4% of the variance and was statistically significant, $F(13, 487) = 4.886$, $p < .001$. Unlike RBQ-2A, ADC-Childhood emerged as an individual significant

Table 2 Hierarchical regression analysis for variables predicting BioM recognition (Task 1)

Variable	β	*t*	*R*	R^2	ΔR^2
Step 1			.267	.071	.071***
Sex	− .024	− .437			
PSAI	.088	1.633			
Age	− .095	− 1.756			
Preterm status	− .058	− 1.218			
Sibling with DD	− .126	− 2.739**			
Parental education	.019	.428			
Handedness	.091	2.049*			
Recruitment pool	.074	1.301			
Step 2			.273	.075	.004
Sex	.− .022	− .404			
PSAI	.093	1.695			
Age	− .097	− 1.761			
Preterm status	− .047	− .958			
Sibling with DD	− .123	− 2.646**			
Parental education	.030	.641			
Handedness	.094	2.120*			
Recruitment pool	.081	1.390			
AQ-SS	.041	.838			
AQ-DP	− .045	− .981			
AQ-CM	− .011	− .208			
Step 3 (Regression #1)			.340	.115	.041***
Sex	− .007	− .129			
PSAI	.080	1.495			
Age	− .109	− 2.002			
Preterm status	.042	.812			
Sibling with DD	− .098	− 2.138*			
Parental education	.039	.866			
Handedness	.067	1.526			
Recruitment pool	.043	.751			
AQ-SS	.034	.710			
AQ-DP	.010	.218			
AQ-CM	.081	1.498			
RBQ-2A	− .071	− .917			
ADC-childhood	− .222	− 2.978**			
Step 3 (Regression #2)			.324	.105	.030***
Sex	− .010	− .175			
PSAI	.077	1.425			
Age	− .114	− 2.070*			
Preterm status	.028	.537			
Sibling with DD	− .104	− 2.266*			
Parental education	.038	.835			
Handedness	.071	1.609			
Recruitment pool	.050	.867			
AQ-SS	.044	.902			
AQ-DP	.008	.174			
AQ-CM	.072	1.315			
RBQ-2A	− .123	− 1.542			
ADC-adulthood	− .127	− 1.793			

$N = 501$

*$p < .05$, **$p < .01$, ***$p < .001$

Table 3 Hierarchical regression analysis for variables predicting BioM emotion categorization (Task 2)

Variable	β	*t*	*R*	R^2	ΔR^2
Step 1			.487	.237	.237***
Sex	− .058	− 1.153			
PSAI	.120	2.465*			
Age	.154	3.131*			
Preterm status	− .234	− 5.434***			
Sibling with DD	− .051	− 1.214			
Parental education	.052	1.271			
Handedness	.057	1.429			
Recruitment pool	.406	7.882***			
Step 2			.538	.289	.052***
Sex	− .036	− .749			
PSAI	.097	2.019*			
Age	.118	2.446*			
Preterm status	− .161	− 3.700***			
Sibling with DD	− .026	− .627			
Parental education	.070	1.728			
Handedness	.060	1.544			
Recruitment pool	.395	7.758***			
AQ-SS	.130	3.049**			
AQ-DP	− .057	− 1.435			
AQ-CM	− .234	− 5.204***			
Step 3 (Regression #3)			.554	.308	.019**
Sex	− .024	− .503			
PSAI	.086	1.813			
Age	.105	2.164*			
Preterm status	− .100	− 2.164*			
Sibling with DD	− .009	− .211			
Parental education	.076	1.894			
Handedness	.041	1.063			
Recruitment pool	.368	7.252***			
AQ-SS	.123	2.914**			
AQ-DP	− .014	− .321			
AQ-CM	− .169	− 3.517***			
RBQ-2A	− .087	− 1.280			
ADC-childhood	− .119	− 1.808			
Step 3 (Regression #4)			.558	.311	.022***
Sex	− .028	− .587			
PSAI	.085	1.801			
Age	.109	2.251*			
Preterm status	− .096	− 2.086*			
Sibling with DD	− .010	− .254			
Parental education	.078	1.956			
Handedness	.041	1.053			
Recruitment pool	.370	7.305***			
AQ-SS	.139	3.228**			
AQ-DP	− .020	− .476			
AQ-CM	− .167	− 3.485**			
RBQ-2A	− .059	− .844			
ADC-adulthood	− .155	− 2.309*			

$N = 501$

*$p < .05$, **$p < .01$, ***$p < .001$

predictor, such that individuals who reported greater expressive motor difficulties performed poorer on BioM Recognition (β = − .222, $p < .01$). Report of siblings with a developmental disorder/delay once again maintained as a significant predictor (β = − .098, $p < .01$). In Step three of Regression #2, the inclusion of repetitive behaviors and movements (RBQ-2A) and motor dysfunction in adulthood (ADC-Adulthood) to the model explained an additional 3% of the variance and was statistically significant, F (13, 487) = 4.404, $p < .001$. However, neither RBQ-2A nor ADC-Adulthood emerged as individual significant predictors. Report of siblings with a developmental disorder/delay maintained as a significant predictor (β = − .104, $p < .05$). Age emerged as a significant predictor, such that older individuals performed poorer on BioM Recognition (β = − .114, $p < .05$).

Predicting BioM Emotion Categorization (Task 2)

For Task 2, both hierarchical multiple regressions revealed that at Step one, demographic factors significantly contributed to the model, F (8, 492) = 19.105, $p < .001$ and accounted for 23.7% of the variance in the ability of individuals to categorize BioM displays of emotion. Four significant predictors accounted for the variance above and beyond other variables. Gender-stereotyped play behavior as indicated by the PSAI emerged as significant predictor, such that individuals who reported more feminine behavior in childhood performed poorer on BioM Emotion Categorization (β = .120, $p < .05$). Another significant predictor was age, such that younger individuals performed poorer on Task 2 (β = .154, $p < .01$). Preterm status was also a significant predictor, such that individuals born pre-term performed poorer on BioM Emotion Categorization (β = − .234, $p < .001$). Recruitment pool was also a significant predictor, such that individuals recruited from the mTurk pool performed poorer on BioM Emotion Categorization (β = .406, $p < .001$).

Unlike the BioM Recognition task, the inclusion of autistic traits in Step two significantly predicted an additional proportion of the variance (5.2%) in the BioM Emotion Categorization task above and beyond demographic variables, F (11, 489) = 19.098, $p < .001$. Scores on the PSAI, Age, Preterm Status, and Recruitment Pool maintained as significant predictors and matched directionality of previous Steps (β = .097, $p < .05$; β = .118, $p < .05$; β = − .161, $p < .001$; β = .395, $p < .001$). Two subscales of the AQ emerged as significant predictors: AQ-CM, AQ-SS. Individuals who reported more communication/mindreading difficulties performed poorer on BioM Emotion Categorization (β = − .234, $p < .001$). Contrary to our hypothesis, individuals who reported less social skill difficulties performed poorer on BioM Emotion Categorization, (β = .130, $p < .01$).

In Step three of Regression #3, the inclusion of RBQ-2A and ADC-Childhood scores further accounted for an

Table 4 Descriptive statistics and correlations of study variables

Variable ($N=623$)	M (SD)	1	2	3	4	5	6	7	8	9	10
1. AQ-28 Total	65.15 (10.68)	–									
2. AQ-SS	30.26 (7.53)	.787 **	–								
3. AQ-DP	17.67 (4.61)	.447*	− .084*	–							
4. AQ-CM	17.23 (3.96)	.682**	.318**	.201**	–						
5. RBQ-2A	1.86 (.56)	.404**	.055	.421**	.497**	–					
6. ADC Childhood	8.08 (7.68)	.383**	.121**	.279**	.478**	.760**	–				
7. ADC Adulthood	27.10 (21.57)	.439**	.212*	.245**	.495**	.771**	.908**	–			
8. PSAI	47.85 (15.81)	− .007	− .007	.079*	− .097*	− .036	.005	− .034	–		
9. Task 1 (BioM vs Non-BioM)	73.74 (17.43)	− .015	0.36	− .059	− .040	− .168**	− .239**	− .198**	.071	–	
10. Task 2 (Emotion)	48.76 (16.64)	− .198**	− .037	− .129**	− .313**	− .371**	− .393**	− .394**	.010	.229**	–

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

additional statistically significant proportion of the variance (1.9%) above and beyond demographic variables and autistic traits, F (13, 487) = 16.694, $p < .001$. However, neither RBQ-2A nor ADC-Childhood emerged as individual significant predictors. Age, preterm status, recruitment pool, AQ-CM, and AQ-SS maintained as significant predictors and matched directionality of previous Steps (β = .105, $p < .05$; β = − .100, $p < .05$; β = .368, $p < .001$; β = − .169, $p < .001$; β = .123, $p < .01$). In Step three of Regression #4, the inclusion of RBQ-2A and ADC-Adulthood scores was statistically significant, explaining an additional 2.2% of the proportion of variance, F (13, 487) = 4.404, $p < .001$. Unlike RBQ-2A, ADC-Adulthood emerged as a significant predictor such that individuals who reported more expressive motor difficulties in adulthood performed poorer on BioM Emotion Categorization (β = − .155, $p < .05$). Age, Preterm status, Recruitment Pool, AQ-CM, and AQ-SS maintained as significant predictors and matched directionality of previous Steps (β = .109, $p < .05$; β = − .096, $p < .05$; β = .370, $p < .001$; β = − .167, $p < .01$; β = .139, $p < .01$).

Motor Functioning Within Individuals

A repeated-measures analysis of variance was conducted to examine the individual trajectories of motor functioning within participants. Utilizing scoring guidelines of the ADC, a binary variable was created to indicate if individuals endorsed significant past motor difficulties in childhood (i.e. score of at least 17). A within-subjects variable included both scores of BioM Recognition and BioM Emotion Categorization. The analysis revealed an interaction between BioM Task and Childhood Motor Problems, F (1, 621) = 6.845, $p < .01$, $\eta_p^2 = .011$. Individuals with significant childhood motor difficulties performed poorer ($M = 66.61$, $SD = 20.17$) on BioM Recognition than individuals who did not report significant past motor difficulties ($M = 75.75$, $SD = 16.04$). Individuals with significant childhood motor difficulties also performed worse on BioM Emotion Categorization ($M = 37.47$, $SD = 14.80$) than counterparts ($M = 51.95$, $SD = 15.73$).

Following scoring guidelines of the ADC, adulthood motor difficulties were considered only as a scaled score. A bivariate correlation revealed significant negative relationships between ADC-Adulthood and BioM Recognition ($r(623) = - .198$, $p < .001$) as well as BioM Emotion Categorization ($r(623) = - .394$, $p < .001$). Overall, individuals who reported more adult motor difficulties performed poorer on both perceptual tasks.

Sex Differences in Autistic Traits and Motor Functioning

A multivariate analysis of covariance (MANCOVA) was conducted to examine if autistic traits and motor functioning varied as a function of sex when controlling for age. The means and standard deviations for the analysis are presented in Table 5. The MANCOVA revealed significant main effects of Sex for RBQ-2A [F(1, 571) 10.853, $p = .001$ $\eta_p^2 = .019$], ADC-Childhood [F(1, 571) 8.471, $p = .004$, $\eta_p^2 = .015$], ADC-Adulthood [F(1, 571) 5.822, $p = .016$, $\eta_p^2 = .010$], AQ-DP [F(1, 571) 6.664, $p = .010$, $\eta_p^2 = .012$], and BioM Emotion Categorization [F(1, 571) 6.104, $p = .014$, $\eta_p^2 = .011$]. Males reported greater deficits in autistic traits and expressive motor functioning across the RBQ-2A, ADC-Childhood, ADC-Adulthood, and AQ-DP. Females performed better than males on categorizing emotion displays of BioM as measured by Task 2. Main effects of Sex for AQ-SS, AQ-CM, and BioM Recognition were not significant. Age was a significant covariate in the model for all variables.

Table 5 Means and standard deviations for variables across sex

	Males N = 284 M (SD)	Females N = 290 M (SD)
Autistic traits		
AQ-SS	30.57 (6.73)	30.03 (7.92)
AQ-DP*	18.26 (4.80)	17.33 (4.42)
AQ-CM	17.49 (3.91)	17.10 (3.90)
Motor functioning		
RBQ-2A**	1.94 (.58)	1.80 (.55)
ADC-childhood**	9.32 (8.06)	7.38 (7.44)
ADC-adulthood*	30.06 (22.78)	25.48 (20.81)
Task 1 (BioM recognition)	73.77 (17.50)	73.21 (17.70)
Task 2 (BioM emotion)*	46.11 (16.24)	49.85 (16.77)
Other		
PSAI***	57.20 (12.46)	39.31 (12.97)
Handedness	64.81 (61.55)	69.06 (58.48)

MANCOVA (see 3.3)

*$p < .05$, **$p < .01$, ***$p < .001$

Discussion

The present study explored the relationship between autistic traits and motor functioning. The results supported our hypothesis that individuals with greater autistic traits also report greater expressive motor deficits. Expressive motor dysfunction in childhood was predictive of individuals' abilities in recognizing BioM from scrambled motion, but not in categorizing emotion PLDs. Expressive motor dysfunction in adulthood was only predictive of individuals' abilities in categorizing emotion PLDs. Regarding autistics traits, not all domains of the AQ-28 were predictive of BioM performance deficits. Neither deficits in social skills, details/patterns, nor communication/mindreading were predictive of BioM recognition. However, impairment in communication/mindreading predicted poorer performance on BioM emotion categorization. The results also supported our hypothesis that there are sex differences across expressive/perceptual motor variables. Notably, males were more likely to endorse expressive motor difficulties associated with DCD and performed poorer on BioM tasks of emotion categorization.

Autistic Traits and Perceptual Motor Dysfunction

The finding that autistic traits were not predictive of BioM recognition is consistent with studies suggesting a distinction between higher- and lower-order BioM abilities. Unlike Task 2, the stimuli used in Task 1 consisted only of neutral walkers. The absence of information pertaining to emotional state and action characterize Task 1 stimuli as less socially complex (Todorova et al., 2019). The finding that individuals' performance on BioM recognition did not vary as a function of autistic traits is consistent with evidence that autistic individuals may be more successful in lower-order BioM processing (Hubert et al., 2007; Murphy et al., 2009; Parron et al., 2008). Other studies have found that group differences in BioM performance exist when individuals are required to extract higher order information, such as emotional content, from BioM stimuli (Nackaerts et al., 2012; Parron et al., 2008). A recent meta-analysis of BioM processing abilities in autistic individuals revealed the strongest processing impairment for simple and complex emotional recognition tasks, while only small effects were found for simple BioM detection (Todorova et al., 2019). Our finding that no group differences were found in BioM recognition suggests that autistic traits in adulthood are not associated with impairment in extracting simple social information from BioM stimuli.

Our finding that individuals with greater autistic traits (social skills, details/patterns) showed decreased performance in categorizing emotion point-light displays (PLD) is consistent with previous studies (Todorova et al., 2019). BioM can convey various types of social information even in the absence of recognizable features of human faces and bodies (Johansson, 1973). If dynamic elements of BioM are responsible for conveying critical social information, it is conceivable that individuals with ASD, who experience deficits in social interactions, may also experience deficit in underlying motor processing abilities. This finding within a general population sample suggests that autistic traits on a continuum are associated with deficits in higher-order BioM processing. The ability to extract social information from PLDs may require an underlying proficiency to process motion, which may not be developed in individuals with greater autistic traits.

Results also revealed that ASD-related deficits in social skills and communication/mindreading predicted decreased performance on emotion categorization. Performance on BioM tasks depended on the domain of ASD deficit. These results suggest that social competence as it relates to interaction, communication, and interpretation of others' thoughts and feelings is related to the ability to successfully extract social information from BioM. This interpretation is consistent with other studies that have examined the relationship between social cognitive autistic traits and BioM perception (Pavlova, 2011). Interestingly, ASD traits related to attention to details and patterns did not predict decreased performance in BioM processing. A possible interpretation is that hyper-attention to details and patterns, which may have real-world negative social implications, may be considered an adaptive skill when it comes to processing BioM stimuli. This finding warrants further exploration into the re-conceptualization of autistic traits as impairment or expertise.

More research is needed to provide a distinction between the weight of social and motor proficiency in BioM processing abilities.

Whether or not the ability to extract social information from BioM influences how individuals develop social competence has not yet been studied. Existing and future literature on BioM processing in early infancy may serve to answer this question. There is evidence that preferential attention to BioM changes during the first months of life, however the extent to which the development of motor competence coincides with that of social competence is understudied (Sifre et al., 2018). In order to better understand if underlying motor processing abilities are necessary for the development of social competence, future research should expand study of expressive motor deficits in infancy to include how motor perceptual processes develop and interact with social development.

Expressive and Perceptual Motor Deficits

Within the ASD literature, no studies have examined the co-occurrence of expressive and perceptual motor deficits at any age. While there is research to indicate a general ASD-related impairment in both domains of motor deficit, the present study is the first to indicate that individuals with greater expressive motor impairments also demonstrate greater perceptual motor impairments. Our study revealed significant relationships between all expressive motor measures and all perceptual motor measures, but performance on BioM tasks significantly differed depending on if motor difficulties occurred in childhood or adulthood. That is, DCD in childhood was only predictive of lower-order BioM detection, and DCD in adulthood was only predictive of higher-order BioM emotion categorization. Our hypothesis that childhood motor difficulties would be predictive of both BioM tasks was based on evidence that motor difficulties in childhood have pervasive implications for later motor competence (Travers et al., 2017). However, the finding that childhood motor difficulties were only predictive of simple BioM detection may reflect a discrepancy between the difficulty between the tasks, as participants scored higher on simple detection overall. The finding that adult motor difficulties only predicted emotion categorization is consistent with our hypothesis that the co-occurrence of expressive and perceptual deficits exists in adulthood. More research is needed to determine if a diagnosis of ASD moderates the relationship between motor difficulties and complex BioM processing. It will also be important for future studies to examine the co-occurrence of expressive and perceptual deficits within a clinical sample as well as within an at-risk sample.

Sex Differences in Motor Functioning

As diagnostic criteria currently stand, males are four times more likely than females to receive a diagnosis of ASD (Duvekot et al., 2017). Early ASD research traditionally included predominantly male samples, which has raised concerns that females with ASD may be under-identified and miss opportunities for early diagnosis and intervention (Duvekot et al., 2017). Recently, more efforts have been made to recruit females in equal proportion to males. The present study included a comparable sample of males and females in order to identify if true group differences exist in motor functioning abilities.

The finding that females performed better than males on categorizing emotion displays of BioM is consistent with the systemizing-empathizing theory originally proposed by Baron-Cohen (2006). Autistic males are more likely to be experts at systemizing, or recognizing repeating patterns in stimuli (Escovar et al., 2016). It has been suggested that excellent attention to detail is related to sensory hypersensitivity in autism (Baron-Cohen et al., 2009). Adult females tend to score higher on empathizing, which is the related to abilities to perceive the emotional states of others (Escovar et al., 2016). Our finding is contrary to a recent meta-analysis that found no effects of sex on BioM paradigms in ASD individuals (Todorova et al., 2019) However, it should be noted that the meta-analysis focused on a clinical sample while ours assessed for autistic traits across a continuum. It is possible that there is more variability in BioM performance across males and females when utilizing a quantitative approach, which may have implications for improving the under-identification of individuals.

The present study also found that males reported greater deficits in all measures of expressive motor functioning. Our finding that males reported greater deficits on the RBQ-2A is consistent with previous research indicating that restricted and repetitive behaviors and interests (RRBIs), which are most related to motor stereotypies, occur more frequently in males (Knutsen et al., 2018). The ADC, which measures the presence of motor difficulties associated with a diagnosis of adult DCD, yielded greater scores for males than females in our sample. The ADC is the first screening tool designed to specifically identify motor difficulties experienced by adults (Kirby et al., 2010). Although DCD has historically been considered a childhood disorder, there is recent evidence to suggest that expressive motor difficulties persist into adulthood (Scott-Roberts & Purcell, 2018). Further, there is evidence that motor difficulties in adulthood predict quality of life (Engel-Yeger, 2020). More research is needed to examine the extent to which motor difficulties present in adulthood for males and females.

These combined findings suggest that an exploration beyond core social domains may reveal gender differences

that are not included in the current conceptualization of ASD. There is continued debate as to whether or not males are at a greater susceptibility for the disorder or if the bias in prevalence rate reflects issues with the conceptualization and assessment of the disorder (Lai et al., 2015). Our findings did not reveal motor functioning as an area in which females reported more deficit than males or inform a male-biased phenotype of ASD. However, further exploration into motor functioning and other areas outside core domains will serve to help identify where true group differences exist.

Limitations

The present study faced several limitations. First, the sample was drawn from two recruitment pools which differed significantly across performance on several study variables. It should be noted that a cognitive measure was not included, which may have been a primary significant difference between the college sample (SONA) and the general sample (mTurk). Although a recent meta-analysis suggested no effect of intelligence scores on BioM performance, future research may benefit from investigating how specific cognitive factors apart from general intelligence scores (e.g., processing speed) moderate the relationship between autistic traits and BioM performance (Todorova et al., 2019).

The present study also utilized a general population sample, which limits the generalizability of our findings to an exclusively clinical group. However, the present study aimed to utilize a dimensional approach in order to explore motor functioning in individuals across a severity gradient of autistic traits. In doing so, more emphasis is given to the degree in which various symptoms manifest in severity and frequency across individuals and better represents the existing heterogeneity across individuals. Our findings imply that BioM processing abilities are relevant to autistic traits that exist on a continuum. Furthermore, the identification of deficits outside of core domains may contribute to the evolving conceptualization of the disorder.

Conclusions

Very little is known about the trajectory of motor functioning in adults with autistic traits. The presented data suggest that there may be detectable disruptions to sensory-motor processes that coincide with expressive motor impairments. The presence of expressive and perceptual motor deficits in adulthood suggest that associated difficulties persist and may have the potential to worsen after the developmental period.

The present study is the first to utilize quantitative autistic traits to examine the co-occurrence of expressive and perceptual motor deficits in adults. Our findings provide important implications for understanding motor impairment, along with other autistic traits, on a continuum. That is, individuals across a spectrum of autistic traits may experience disruptions in both expressive and perceptual motor functioning to similar or differing degrees. Future research should examine the extent to which the relationship between continuous motor deficits and autistic traits is linear.

The present findings may also have implications for the development of evidence-based motor interventions in adults with ASD, a group that is often understudied in regards to intervention. Although there has been some review of intervention programs targeting expressive motor skills in autistic adults, our findings also suggest a potential utility for interventions focused on perceptual skills (Azar et al., 2016; Virues-Ortega et al., 2013). Further, adults who endorse autistic traits on moderate to lower ends of the severity gradient may also benefit from such interventions. Considering the positive relationship between motor and social impairments, this may be especially relevant for adults who report social difficulties in daily life.

Acknowledgment The authors would like to thank Alaerts et al. (2011) for sharing stimuli with our team.

Author Contributions PJ and GA contributed to the study conception and design. Material preparation, data collection and analysis were performed by PJ. The first draft of the manuscript was written by PJ. PJ and GA commented on previous versions of the manuscript. PJ and GA read and approved the final manuscript.

Funding No external funding was received for this research.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Abu-Akel, A., Allison, C., Baron-Cohen, S., & Heinke, D. (2019). The distribution of autistic traits across the autism spectrum: Evidence for discontinuous dimensional subpopulations underlying the autism continuum. *Molecular Autism, 10*, 24. https://doi.org/10.1186/s13229-019-0275-3

Adolph, K., & Joh, A. S. (2007). Motor development: How infants get into the act. In A. Slater & M. Lewis (Eds.), *Introduction to infant development* (2nd ed., pp. 63–80). Oxford University Press.

Ahler, D. J., Roush, C. E., & Sood, G. (2020). The micro-task market for lemons: Data quality on Amazon's mechanical turk. *Political Science Research and Methods*. https://doi.org/10.1017/psrm.2021.57

Alaerts, K., Nackaerts, E., Meyns, P., Swinnen, S. P., & Wenderoth, N. (2011). Action and emotion recognition from point light displays: An investigation of gender differences. *PLoS ONE*, *6*(6). https://doi.org/10.1371/journal.pone.0020989

Amoruso, L., Finisguerra, A., & Urgesi, C. (2018). Autistic traits predict poor integration between top-down contextual expectations and movement kinematics during action observation. *Scientific Reports, 8*, 16208. https://doi.org/10.1038/s41598-018-33827-8

Armitano, C. N., Bennett, H. J., & Morrison, H. S. (2020). Assessment of the gait-related acceleration patterns in adults with autism spectrum disorder. *Gait & Posture, 75*, 155–162. https://doi.org/10.1016/j.gaitpost.2019.09.002

Atkinson, D. P. (2009). Impaired recognition of emotions from body movements is associated with elevated motion coherence thresholds in autism spectrum disorders. *Neuropsychologia, 47*(3), 3023–3029. https://doi.org/10.1016/j.neuropsychologia.2009.05.019

Azar, N. R., McKeen, P., Carr, K., Sutherland, C. A., & Horton, S. (2016). Impact of motor skills training in adults with autism spectrum disorder and an intellectual disability. *Journal of Developmental Disabilities, 22*(1), 28–38.

Baron-Cohen, S. (2006). The hyper-systemizing, assortative mating theory of autism. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 30*(5), 865–872. https://doi.org/10.1016/j.pnpbp.2006.01.010

Baron-Cohen, S., Ashwin, E., Ashwin, C., Tavassoli, T., & Chakrabarti, B. (2009). Talent in autism: Hyper-systemizing, hyper-attention to detail and sensory hypersensitivity. *Philosophical Transactions of the Royal Society b: Biological Sciences, 364*(1522), 1377–1383. https://doi.org/10.1098/rstb.2008.0337

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): Evidence from asperger syndrome/high-functioning autism, males and females, scientists, and mathematicians. *Journal of Autism and Developmental Disorders, 31*(5), 5–17. https://doi.org/10.1023/A:1005653411471

Barrett, S. L., Uljarevic, M., Jones, C. R. G., & Leekam, S. R. (2018). Assessing subtypes of restricted and repetitive behavior using the adult repetitive behavior questionnaire-2 in autistic adults. *Molecular Autism*. https://doi.org/10.1186/s13229-018-0242-4

Bhat, A. N. (2020). Is motor impairment in autism spectrum disorder distinct from developmental coordination disorder? A report from the SPARK study. *Physical Therapy, 100*(4), 633–644. https://doi.org/10.1093/ptj/pzz190

Bhat, A. N. (2021). Motor impairment increases in children with autism spectrum disorder as a function of social communication, cognitive and functional impairment, repetitive behavior severity, and comorbid diagnoses: A SPARK study report. *Autism Research, 14*, 202–219. https://doi.org/10.1002/aur.2453

Bhat, A. N., Landa, R. J., & Galloway, J. C. (2011). Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. *Physical Therapy, 91*(7), 1116–1129. https://doi.org/10.2522/ptj.20100294

Blake, R., Turner, L. M., Smoski, M. J., Pozdol, S. L., & Stone, W. L. (2003). Visual recognition of biological motion is impaired in children with autism. *Psychological Science*. https://doi.org/10.1111/1467-9280.01434

Carter, A. S., Black, D. O., Tewani, S., Connolly, C. E., Kadlec, M. B., & Tager-Flusberg, H. (2007). Sex differences in toddlers with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 37*(1), 86–97. https://doi.org/10.1007/s10803-006-0331-7

Cassidy, S., Hannant, P., Tavassoli, T., Allison, C., Smith, P., & Baron-Cohen, S. (2016). Dyspraxia and autistic traits in adults with and without autism spectrum conditions. *Molecular Autism, 7*(1), 48. https://doi.org/10.1186/s13229-016-0112-x

Cheng, M., Kato, M., & Tseng, C. (2017). Gender and autistic traits modulate implicit motor synchrony. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0184083

Cholemkery, H., Medda, J., Lempp, T., & Freitag, C. M. (2016). Classifying autism spectrum disorders by ADI-R: Subtypes or severity gradient? *Journal of Autism and Developmental Disorders, 46*(7), 2327–2339. https://doi.org/10.1007/s10803-016-2760-2

Constantino, J. N., Gruber, C. P., Davis, S., Hayes, S., Passanante, N., & Przybeck, T. (2004), The factor structure of autistic traits. *Journal of Child Psychology and Psychiatry*, *45*(4), 719–726. https://doi.org/10.1111/j.1469-7610.2004.00266.x

Constantino, J. N., & Todd, R. D. (2003). Autistic traits in the general population: A twin study. *Archives of General Psychiatry, 60*(5), 524–530. https://doi.org/10.1001/archpsyc.60.5.524

Cousins, M., & Smyth, M. M. (2003). Developmental coordination impairments in adulthood. *Human Movement Science, 22*(4–5), 433–459. https://doi.org/10.1016/j.humov.2003.09.003

Curioni, A., Minio-Paluello, I., Sacheli, L. M., Candidi, M., & Aglioti, S. M. (2017). Autistic traits affect interpersonal motor coordination by modulating strategic use of role-based behavior. *Molecular Autism, 8*(1), 23. https://doi.org/10.1186/s13229-017-0141-0

Dawson, G., & Watling, R. (2000). Interventions to facilitate auditory, visual, and motor integration in autism: A review of the evidence. *Journal of Autism and Developmental Disorders*. https://doi.org/10.1023/A:1005547422749

Dawson, G., Webb, S. J., Schellenberg, G., Dager, S., Friedman, S., Aylward, E., & Richards, T. (2002). Defining the broader phenotype of autism: Genetic, brain, and behavioral perspectives. *Development and Psychopathology, 14*, 581–611. https://doi.org/10.1017/S0954579402003103

Duvekot, J., van der Ende, J., Verhulst, F. C., Slappendel, G., van Daalen, E., Maras, A., & Greaves-Lord, K. (2017). Factors influencing the probability of a diagnosis of autism spectrum disorder in girls versus boys. *Autism, 21*(6), 646–658. https://doi.org/10.1177/1362361316672178

Engel-Yeger, B. (2020). The role of poor motor coordination in predicting adults' health related quality of life. *Research in Developmental Disabilities, 103*, 103686. https://doi.org/10.1016/j.ridd.2020.103686

English, M. C. W., Gignac, G. E., Visser, T. A. W., Whitehouse, A. J. O., & Maybery, M. T. (2019). A comprehensive psychometric analysis of autism-spectrum quotient factor models using two large samples: Model recommendations and the influence of divergent traits on total-scale scores. *Autism Research, 13*(1), 45–60. https://doi.org/10.1002/aur.2198

Escovar, E., Rosenberg-Lee, M., Uddin, L. Q., & Menon, V. (2016). The empathizing-systemizing theory, social abilities, and mathematical achievement in children. *Scientific Reports*. https://doi.org/10.1038/srep23011

Fabbri-Destro, M., Gizzonio, V., & Avanzini, P. (2013). Autism, motor dysfunctions and mirror mechanism. *Clinical Neuropsychiatry, 10*(5), 177–187.

Federici, A., Parma, V., Vicovaro, M., Radassao, L., Casartelli, L., & Ronconi, L. (2020). Anomalous perception of biological motion in autism: A conceptual review and meta-analysis. *Scientific Reports*. https://doi.org/10.1038/s41598-020-61252-3

Gabis, L. V., Attia, O. L., Roth-Hanania, R., & Foss-Feig, J. (2020). Motor delay—An early and more common "red flag" in girls rather than boys with autism spectrum disorder. *Research in Developmental Disabilities, 104*, 103702. https://doi.org/10.1016/j.ridd.2020.103702

Granner-Shuman, M., Dahan, A., Yozevitch, R., & GvirtsProblovski, H. Z. (2021). The association among autistic traits, interactional synchrony and typical pattern of motor planning and execution in neurotypical individuals. *Symmetry, 13*(6), 1034. https://doi.org/10.3390/sym13061034

Hillus, J., Moseley, R., Roepke, S., & Mohr, B. (2019). Action semantic deficits and impaired motor skills in autistic adults without intellectual impairment. *Frontiers in Human Neuroscience, 13*, 256. https://doi.org/10.3389/fnhum.2019.00256

Hubert, B., Wicker, B., Moore, D. G., Monfardini, E., Duverger, H., Fonséca, D. D., & Deruelle, C. (2007). Brief report: Recognition of emotional and non-emotional biological motion in individuals

with autistic spectrum disorders. *Journal of Autism and Developmental Disorders, 37*(7), 1386–1392. https://doi.org/10.1007/s10803-007-0378-0

Jia, R., Steelman, Z. R., & Jia, H. H. (2019). Psychometric assessments of three self-report autism scales (AQ, RBQ-2A, and SQ) for general adult populations. *Journal of Autism and Developmental Disorders, 49*(5), 1949–1965. https://doi.org/10.1007/s10803-019-03880-x

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics, 14*(2), 201–211. https://doi.org/10.3758/bf03212378

Kirby, A., Edwards, L., Sugden, D., & Rosenblum, S. (2010). The development and standardization of the adult developmental co-ordination disorders/dyspraxia checklist (ADC). *Research in Developmental Disabilities, 31*, 131–139. https://doi.org/10.1016/j.ridd.2009.08.010

Kirby, A., Sugden, D., Beveridge, S., & Edwards, L. (2008). Developmental co-ordination disorder (DCD) in adolescents and adults in further and higher education. *Journal of Research in Special Educational Needs, 8*(3), 120–131. https://doi.org/10.1111/j.1471-3802.2008.00111.x

Knutsen, J., Crossman, M., Perrin, J., Shui, A., & Kuhlthau, K. (2018). Sex differences in restricted repetitive behaviors and interests in children with autism spectrum disorder: An Autism Treatment Network study. *Autism, 23*(4), 858–868. https://doi.org/10.1177/1362361318786490

Kutsuki, A., Kuroski, M., Sonoko, E., Ogura, T., & Itakura, S. (2009). Individual differences in changes in infants' interest in social signals relation to developmental index. *Infant Behavior and Development, 32*(4), 381–391. https://doi.org/10.1016/j.infbeh.2009.06.004

Lai, M., Lombardo, M. V., Auyeung, B., Chakrabarti, B., & Baron-Cohen, S. (2015). Sex/gender differences and autism: Setting the scene for future research. *Journal of the American Academy of Child & Adolescent Psychiatry, 54*(1), 11–24. https://doi.org/10.1016/j.jaac.2014.10.003

Lee, C. M., & Bo, J. (2015). Motor functioning in children with autism spectrum disorder. *Acta Psychopathologica*. https://doi.org/10.4172/2469-6676.100013

Licari, M. K., Alvares, G. A., Varcin, K., Evans, K. L., Cleary, D., Reid, S. L., Glasson, E. J., Bebbington, K., Reynolds, J. E., Wray, J., & Whitehouse, A. J. O. (2020). Prevalence of motor difficulties in autism spectrum disorder: Analysis of a population-based cohort. *Autism Research, 13*(2), 298–306. https://doi.org/10.1002/aur.2230

Linke, A. C., Kinnear, M. K., Kohli, J. S., Fong, C. H., Lincoln, A. J., Carper, R. A., & Müller, R.-A. (2020). Impaired motor skills and atypical functional connectivity of the sensorimotor system in 40- to 65-year-old adults with autism spectrum disorders. *Neurobiology of Aging, 85*, 104–112. https://doi.org/10.1016/j.neurobiolaging.2019.09.018

Matheis, M., Matson, J. L., Hong, E., & Cervantes, P. E. (2018). Gender differences and similarities: Autism symptomatology and developmental functioning in young children. *Journal of Autism and Developmental Disorders, 49*, 1219–1231. https://doi.org/10.1007/s10803-018-3819-z

Ming, X., Brimacombe, M., & Wagner, G. C. (2007). Prevalence of motor impairment in autism spectrum disorders. *Brain and Development, 29*(9), 565–570. https://doi.org/10.1016/j.braindev.2007.03.002

Murphy, P., Brady, N., Fitzgerald, M., & Troje, N. F. (2009). No evidence for impaired perception of biological motion in adults with autistic spectrum disorders. *Neuropsychologia, 47*(14), 3225–3235. https://doi.org/10.1016/j.neuropsychologia.2009.07.026

Nackaerts, E., Wagemans, J., Helsen, W., Swinnen, S. P., Wenderoth, N., & Alaerts, K. (2012). Recognizing biological motion and emotions from point-light displays in autism spectrum disorders. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0044473

Odeh, C. E., Gladfelter, A. L., Stoesser, C., & Roth, S. (2020). Comprehensive motor skills assessment in children with autism spectrum disorder yields global deficits. *International Journal of Developmental Disabilities*. https://doi.org/10.1080/20473869.2020.1764241

Parron, C., Fonseca, D. D., Santos, A., Moore, D. G., Monfardini, E., & Deruelle, C. (2008). Recognition of biological motion in children with autistic spectrum disorders. *Autism, 12*(3), 261–274. https://doi.org/10.1177/1362361307089520

Pavlova, M. A. (2011). Biological motion processing as a hallmark of social cognition. *Cerebral Cortex, 22*(5), 981–995. https://doi.org/10.1093/cercor/bhr156

Piven, J., & Rabins, P. (2011). Autism spectrum disorders in older adults: Toward defining a research agenda. *Journal of the American Geriatrics Society, 59*(11), 2151–2155. https://doi.org/10.1111/j.1532-5415.2011.03632.x

Puzzo, I., Cooper, N. R., Vetter, P., Russo, R., & Fitzgerald, P. B. (2009). Reduced cortico-motor facilitation in a normal sample with high traits of autism. *Neuroscience Letters, 467*(2), 173–177. https://doi.org/10.1016/j.neulet.2009.10.033

Ring, H., Woodbury-Smith, M., Watson, P., Wheelwright, S., & Baron-Cohen, S. (2008). Clinical heterogeneity among people with high functioning autism spectrum conditions: Evidence favouring a continuous severity gradient. *Behavioral and Brain Functions, 4*, 11. https://doi.org/10.1186/1744-9081-4-11

Russell-Smith, S. N., Maybery, M. T., & Bayliss, D. M. (2011). Relationships between autistic-like and schizotypy traits: An analysis using the autism spectrum quotient and oxford-liverpool inventory of feelings and experiences. *Personality and Individual Differences, 51*(2), 128–132. https://doi.org/10.1016/j.paid.2011.03.027

Scott-Roberts, S., & Purcell, C. (2018). Understanding the functional mobility of adults with developmental coordination disorder (DCD) through the international classification of functioning (ICF). *Current Developmental Disorders Reports, 5*(1), 26–33. https://doi.org/10.1007/s40474-018-0128-3

Sifre, R., Olson, L., Gillespie, S., Klin, A., Jones, W., & Shultz, S. (2018). A longitudinal investigation of preferential attention to biological motion in 2- to 24-month-old infants. *Scientific Reports*. https://doi.org/10.1038/s41598-018-20808-0

Simion, F., Regolin, L., & Bulf, H. (2008). A predisposition for biological motion in the newborn baby. *PNAS, 105*(2), 809–813. https://doi.org/10.1073/pnas.0707021105

Spiker, D., Lotspeich, L. J., Dimiceli, Su., Myers, R. M., & Risch, N. (2002). Behavioral phenotypic variation in autism multiplex families: Evidence for a continuous severity gradient. *American Journal of Medical Genetics, 114*(2), 129–136. https://doi.org/10.1002/ajmg.10188

Syriopoulou-Delli, C. K., & Papaefstathiou, E. (2020). Review of cluster analysis of phenotypic data in autism spectrum disorders: Distinct subtypes or a severity gradient model? *International Journal of Developmental Disabilities, 66*(1), 13–21. https://doi.org/10.1080/20473869.2018.1542561

Tal-Saban, M., Ornoy, A., & Parush, S. (2014). Young adults with developmental coordination disorder: A longitudinal study. *American Journal of Occupational Therapy, 68*, 307–316.

Todorova, G. K., Hatton, R. E. M., & Pollick, F. E. (2019). Biological motion perception in autism spectrum disorder: A meta-analysis. *Molecular Autism*. https://doi.org/10.1186/s13229-019-0299-8

Travers, B. G., Bigler, E. D., Duffield, T. C., Prigge, M. D. B., Froehlich, A. L., Lange, N., Alexander, A. L., & Lainhart, J. E. (2017). Longitudinal development of manual motor ability in autism spectrum disorder from childhood to mid-adulthood relates to adaptive living skills. *Developmental Science*. https://doi.org/10.1111/desc.12401

Tseng, M. H., & Chow, S. M. K. (2000). Perceptual-motor function of school-age children with slow handwriting speed. *American Journal of Occupational Therapy, 54*(1), 83–88. https://doi.org/10.5014/ajot.54.1.83

Veale, J. F. (2013). Edinburgh handedness inventory—short form: A revised version based on confirmatory factor analysis. *Laterality: Asymmetries of Body, Brain and Cognition, 19*(2), 164–177. https://doi.org/10.1080/1357650x.2013.783045

Virues-Ortega, J., Julio, F. M., & Pastor-Barriuso, R. (2013). The TEACCH program for children and adults with autism: A meta-analysis of intervention studies. *Clinical Psychology Review, 33*(8), 940–953. https://doi.org/10.1016/j.cpr.2013.07.005