



RESEARCH ARTICLE

Motor performance, praxis, and social skills in autism spectrum disorder and developmental coordination disorder

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Abstract

Previous research has shown that individuals with autism spectrum disorder (ASD) and developmental coordination disorder (DCD) may have overlapping social and motor skill impairments. This study compares ASD, DCD, and typically developing (TD) youth on a range of social, praxis and motor skills, and investigates the relationship between these skills in each group. Data were collected on participants aged 8–17 ($n = 33$ ASD, $n = 28$ DCD, $n = 35$ TD). Overall, the clinical groups showed some similar patterns of social and motor impairments but diverged in praxis impairments, cognitive empathy, and Theory of Mind ability. When controlling for both social and motor performance impairments, the ASD group showed significantly lower accuracy on imitation of meaningful gestures and gesture to command, indicating a prominent deficit in these praxis skills in ASD.

Lay Summary

Individuals with autism spectrum disorder (ASD) and developmental coordination disorder (DCD) have social and motor skill impairments to varying degrees. This study compares ASD, DCD, and typically developing (TD) youth on a range of social, praxis, and motor skills. ASD and DCD shared similar patterns of gross and fine motor skills, but differed in skills related to making gestures. Specifically, our results also suggest that ASD has a prominent deficit in gesture performance and meaningful imitation compared to TD and DCD groups.

KEYWORDS

autism, developmental disorders, dyspraxia, motor skills, social skills

INTRODUCTION

Approximately 80% of children with autism spectrum disorder (ASD) demonstrate deficits in aspects of motor performance and praxis (Bhat, 2020; Green et al., 2009; Hannant et al., 2018; Hilton et al., 2012; Miller et al., 2021; Williams et al., 2004). However, motor impairments are not a diagnostic criteria of ASD (APA,

2013), as they are in developmental coordination disorder (DCD, sometimes referred to as dyspraxia (APA, 2013; Gibbs et al., 2007). Prior to the DSM-5, a dual diagnosis was not possible (DSM-IV-R; APA, 2000). As such, motor skills often were not assessed as part of an ASD diagnostic evaluation and may still be overlooked. While there is more recent attention given to the motor impairments in individuals with ASD, further work is needed to better understand whether motor impairments are comorbid with ASD or a core deficit.

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While social impairments are a core diagnostic component of ASD and not DCD, extensive research in children with DCD has reported social deficits such as lack of friendships, social isolation/loneliness, and decreased participation in social activities (Cairney et al., 2013; Cermak et al., 2015; Cermak & May-Benson, 2020; Cummins et al., 2005; Jarus et al., 2011; Kanioglou et al., 2005; Magalhães et al., 2011; Miller et al., 2021; Poulsen et al., 2007; Tal Saban & Kirby, 2019). It has been suggested that these deficits are secondary to the motor impairments, and may be related to exclusion from opportunities to engage in sports or social activities (Cermak & May-Benson, 2020), developmental delays (Cantell et al., 2003), visual processing impairments (Tal Saban & Kirby, 2019) or other co-occurring disorders such as social anxiety (Pratt & Hill, 2011). However, recent studies have reported that children with DCD have additional social difficulties with emotion recognition (Cummins et al., 2005; Vatandoust & Hasanzadeh, 2018), eye gaze and general socialization (Sumner et al., 2016).

In a direct comparison of social skills between ASD and DCD groups, Sumner et al., 2016 reported that the DCD group performed significantly more poorly than the TD group but similarly to the ASD group on the Benton face processing and Bruce measures of face matching (for expression, sound being made, and eye gaze direction). In contrast, the ASD group scored more poorly than the DCD group on the Socialization Scale of the Vineland Adaptive Behavior Scale (VABS), which measures interpersonal relationships, play and leisure time, and coping skills, as well as the Social Communication Questionnaire (SCQ) which measures communication skills and social functioning. Others have posited that DCD deficits in affect recognition (identifying emotions in others via facial expressions), as well as executive function difficulties may be related to other DCD social impairments, such as empathic skills (Cummins et al., 2005; Gillberg et al., 1992; Tal-Saban et al., 2016; Xavier et al., 2016).

To our knowledge, only two studies have compared empathy and Theory of Mind (ToM; ability to take other people's perspective) between ASD and DCD groups. Wisdom et al. (2007) found that although children with ASD had significantly worse motor, emotional understanding, and ToM skills compared to children with DCD, children in both groups resembled each other across all variables measured (language, intelligence, social cognition, motor coordination, and executive functioning) too closely to be distinguished using a discriminant function analysis that classified participants. Wisdom et al. thus argue that ASD and DCD are distinguished by severity, instead of the type of deficits. Only one study to our knowledge has explored distinctions between affective empathy (emotion sharing), cognitive empathy (perspective taking of other's emotional experiences), and ToM in DCD and ASD and reported only small to medium effect sizes in classifying groups with measures of affect recognition, ToM and emotional and

cognitive empathy (Harrison et al., 2021). Thus, more research is needed to understand the various aspects of social and motor relationships in DCD.

Motor performance and praxis skills: Terminology in ASD and DCD literature

Imitation, praxis, or coordination problems have been used to describe motor impairments in both ASD and DCD (Dewey et al., 2007; Edwards, 2014; Gibbs et al., 2007; Gizzonio et al., 2015; Mostofsky et al., 2006; Paquet et al., 2019; Roley et al., 2014; Sumner et al., 2016). Here, we refer to motor performance skills as controlled and goal-directed actions measuring skills such as fine motor, ball, and balancing using quantitative metrics of frequency, speed, and so forth (Harris et al., 2015; Henderson et al., 2007). By contrast, we refer to praxis as representational or non-representational imitation and gesture production, with or without the use of tools (Ayres, 1989; Dziuk et al., 2007; Mostofsky et al., 2006). Praxis measures may also be regarded as having more socio-communicative value. For example, the praxis assessments used in the current study (Florida Apraxia Battery, Modified; FAB), involves scoring based on one's accuracy of imitation of another person's actions, an innately social task, and gesture to verbal command (e.g., show me how you brush your teeth) or with tools (e.g., scooping ice-cream) which have communicative components. Further, performing the praxis tasks correctly is less rule based than other motor tasks like the Movement Assessment Battery for Children second revision (MABC-2; e.g., turning pegs, catching and aiming, etc.). Instead, the praxis requires an implicit understanding of the experimenter's intent to perform it correctly, which may be related to ToM ability. The inclusion of symbolic gestures in the praxis examination especially makes this assessment more social/communicative in nature, which speaks to the inherent social nature of praxis skills. Given that social deficits are core to ASD, we expect greater praxis deficits in ASD compared to both TD and DCD groups.

Motor performance and praxis deficits in ASD compared to DCD

To the best of our knowledge, only six other prior studies (Dewey et al., 2007; Green et al., 2002; Miller et al., 2021; Paquet et al., 2019; Sumner et al., 2016; Wisdom et al., 2007) and a systematic review (Caçola et al., 2017) have directly compared motor and/or praxis skills between individuals with ASD and DCD. Taken together, these studies indicate that in praxis skills, children with ASD perform worse than children with DCD (Dewey et al.; Green et al.; Paquet et al.), however none of these studies have controlled for social skills in their comparisons. The findings for motor performance skills are less conclusive with some studies showing poorer motor performance skills in

the ASD group (Dewey et al.; Miller et al.; Wisdom et al.), other studies showing the opposite (Paquet et al.), or mixed results, depending on the motor assessment utilized (Green et al.; Sumner et al.). For example, the ASD and DCD groups did not differ significantly from each other on the Fine Motor and Gross Motor measures of the VABS whereas the DCD group significantly scored lower than the ASD group on the MABC-2 (Sumner et al.). However, this finding must be interpreted cautiously since a low score on the MABC-2 was an inclusion criteria for the DCD group (Sumner et al.).

Interaction of social and motor performance skills in ASD and DCD

Relationships between social and motor skills have been found for both ASD (Sumner et al., 2016) and DCD groups (Cummins et al., 2005; Sumner et al.; Vatandoust & Hasanzadeh, 2018), although specific patterns of social and motor ability between these groups is unclear. Vatandoust and Hasanzadeh (2018) reported a positive correlation between motor skill performance (MABC-2) and emotion recognition (facial and voice emotion recognition; $r = 0.490$) and understanding the mental states of others ($r = -0.465$) in children with DCD. To date, Sumner et al. (2016) is the only study that directly compared relationships between motor and social skills in ASD, DCD, and TD children. They found that ASD and DCD had a few significant differences in various motor and social skills, as discussed previously. Further, they reported a significant relationship between motor (Vineland Adaptive Behavior Questionnaire-II Gross and Fine Motor Scales) and social skills (VABS Socialization Scale) for children with ASD ($r = 0.36$) and children with DCD ($r = 0.41$). However, motor skills only accounted for 13%–17% of the variance in socialization scores, suggesting that motor performance constitutes a small portion of the factors influencing social skills. As children with ASD also have deficits in emotion recognition, these data may signify that the relationship between social and motor skills in ASD and DCD may be more similar than previously recognized. Indeed, previous research has shown that imitation skills are associated with social engagement (Masur, 2006; Young et al., 2011) and predictively associated to nonverbal communication (Heimann et al., 2006), language development (Bates et al., 1988; Rose et al., 2009; see also McEwen et al., 2007), social understanding (Olineck & Poulin-Dubois, 2009), and cognitive skills (Strid et al., 2006). Thus, a better understanding of praxis skills in other motor impaired clinical groups may have implications for related social skills as well.

Aims

The current study aims to better understand social and motor impairments in ASD and DCD youth and

investigate how these impairments relate to each other on different social and motor measures.

1. Aim 1: To compare groups on social measures including autism symptomatology, affective and cognitive empathy, and ToM. Based on previous literature, we hypothesize that the DCD group will have elevated scores on normed measures of ASD symptomatology (SRS-2 Total; Sumner et al., 2016), and greater cognitive empathy skills compared to the ASD group, but no difference in empathy (Tal Saban & Kirby, 2019) or ToM skills (Wisdom et al., 2007) compared to the TD group.
2. Aim 2: To compare motor performance and praxis skills between groups as well as patterns of correlations between the different motor skill measures. We hypothesize that the ASD group will have greater praxis impairment compared to the TD and DCD groups given the inherently social nature of praxis and that social deficits are core to an ASD diagnosis.
3. Aim 3: To examine the relationships between motor and social skills within each group. Based on previous findings (Gizzonio et al., 2015; Sumner et al., 2016), we hypothesize that social skills, as measured by SRS Total Score and NEPSY ToM, will be significantly related to praxis skills in the ASD group, due to the social/communicative nature of praxis and the deficit in social skills in ASD.

METHODS

Participants

This study was approved by the Institutional Review Board at the University of Southern California. Children and adolescents ages 8–17, participated in the study. Participant inclusion and exclusion criteria including measures of Attention Deficit Hyperactivity Disorder (ADHD; Conners 3AI, 2009) and IQ (WASI-II; Wechsler, 2011) criteria are described in Kilroy et al., 2021. Inclusion/exclusion criteria related to social and motor skills for each group are described below. Age, gender, and medication use details for each group are reported here with greater details in Table 1. There was no community involvement in the reported study.

1. TD participants ($n = 35$; males = 24) had absence of any psychological diagnosis or neurological disorder, a score above the 25th percentile on the MABC-2, and a score of $T > 60$ on the Social Responsiveness Scale, Second Edition (SRS-2; Constantino & Gruber, 2012).
2. ASD participants ($n = 33$; males = 26) had a formal diagnosis of ASD and a qualifying score on either the Autism Diagnostic Observation Schedule (ADOS-2; Lord et al., 2012) or Autism Diagnostic Interview-

TABLE 1 Demographic information and group comparisons of assessments.

Variable	TD (N = 35)		ASD (N = 33)		DCD (N = 28)		TD:ASD	TD:DCD	ASD:DCD
Sex (M, F)	M = 24, F = 11		M = 26, F = 7		M = 17, F = 11				
Ethnicity									
American Indian	0		0		0				
Asian	4		1		2				
African American	2		3		0				
Native Hawaiian/Pacific islander	0		0		0				
White	17		17		19				
Mixed	8		8		4				
Other	0		3		0				
Decline to answer	4		1		3				
Parental education (highest)									
Highschool	1		2		0				
College	16		14		9				
Graduate degree	15		15		16				
Decline to answer	3		2		3				
	M	SD	M	SD	M	SD	Cohen's d, p*	Cohen's d, p*	Cohen's d, p*
Age	11.90	2.22	11.88	2.24	11.96	2.35	0.01	-0.03	-0.04
FS-IQ	114.94	12.64	107.97	19.63	110.68	17.04	0.42	0.26	-0.16
VCI-IQ	115.91	12.44	105.3	20.14	114.0	15.05	0.64	0.11	-0.52
PRI-IQ	110.69	14.70	109.7	20.38	105.21	21.58	0.05	0.29	0.24
Conners A3	46.71	6.21	83.45	9.86	72.68	17.36	-1.87***	-1.32***	0.55**
SRS-2 total	45.43	5.24	75.67	9.25	57.14	9.39	-2.00***	-0.77***	1.22***
SRS-2 SCI	45.29	4.97	74.52	9.61	56.54	9.57	-0.97***	-0.38***	0.60***
NEPSY-II ToM total	24.97	1.99	23.0	3.179	25.04	2.49	0.73*	-0.03**	-0.76**
IRI total	63.06	13.75	60.88	12.94	64.54	13.35	0.16	-0.11	-0.28
IRI empathic concern	18.06	5.19	16.67	5.29	18.43	4.48	0.28	-0.07	-0.35
IRI personal distress	12.29	4.82	13.97	5.38	13.18	5.33	-0.33	-0.17	0.15
IRI perspective taking	15.51	4.91	12.91	5.38	14.89	4.35	0.52*	0.12	-0.40
MABC-2 total	10.46	1.65	5.09	2.49	4.61	1.79	1.59***	1.74***	0.14
MABC-2 manual dexterity	9.83	2.09	5.56	2.79	5.14	2.41	1.32***	1.44***	0.13
MABC-2 balance	10.89	2.48	6.36	3.05	5.57	2.68	1.25***	1.47***	0.22
MABC-2 aiming and catching	10.66	3.34	6.33	3.37	6.64	2.86	1.15***	1.06***	-0.08
FAB GTC	0.70	0.12	0.54	0.16	0.62	0.14	1.03***	0.52***	-0.52*
FAB GTU	0.82	0.08	0.567	0.17	0.65	0.17	1.40***	0.94***	-0.46*
FAB GTI meaningful	0.73	0.11	0.45	0.18	0.56	0.16	1.46**	0.89**	-0.57
FAB GTI meaningless	0.59	0.19	0.42	0.22	0.44	0.18	0.82***	0.72***	-0.10*
SIPT PPr total raw	29.94	12.72	25.06	6.07	26.42	4.38	0.98*	0.70*	-0.27

Note: * $p < 0.05$, ** $p < 0.01$; *** $p < 0.001$.

Abbreviations: ASD, autism spectrum disorder; DCD, developmental coordination disorder; F, female; FAB, Florida Apraxia Battery; FS-IQ, full scale IQ; GTC, gesture to command; GTI, gesture to imitation; GTU, gesture to tool use; IQ, intelligence quotient; IRI, interpersonal reactivity index; M, male; MABC-2, movement battery for children; NEPSY-II, developmental neuropsychological assessment; PRI-IQ, perceptual reasoning IQ; SCI, social communication and interaction; SIPT PPr, the sensory integration and praxis tests, postural praxis; SRS-2, social responsivity scale 2; TD, typically developing; ToM, theory of mind; VCI-IQ, verbal composite index IQ.

Revised (ADI-R; Lord et al., 1994) at the time of data collection administered by research certified study personnel and overseen by certified clinicians. Parent report indicated 31 had ADHD, 6 Anxiety, and 32 qualified for DCD on the MABC-II. A total of 11 ASD participants were taking prescribed

psychotropic medications for ADHD and/or anxiety and 1 individual was on anti-depression medication.

3. DCD participants ($n = 28$; males = 17) had performance at or below the 16th percentile on the MABC-2, no current or previous ASD diagnosis nor any first degree relative with ASD. SRS-2 score

indicating “no to mild risk for ASD.” Five DCD participants had SRS-2 scores indicating “moderate risk for ASD,” however, none met criteria on the ADOS-2 and therefore were included in the sample. Parent report indicated 21 had clinical concerns of ADHD and three of Anxiety. Four DCD participants were taking prescribed psychotropic medications for ADHD and/or anxiety.

Behavioral measures

Each participant completed behavioral measures. For participants over the maximum age of standardization for any given measure, scores were normalized to the oldest age bracket available.

Motor skill measures

Motor performance skills were assessed using the MABC-2 (Henderson et al., 2007) which consists of three subsections: Manual Dexterity, Aiming and Catching (ball skills), and Balance (static and dynamic). Total scaled scores were used for our main analyses. In a recent systematic review of the reliability and validity of assessment tools to measure motor skills in school-age children, Eddy et al. (2019) reported that the MABC/MABC-2 was one of the most widely researched tools with 23 studies. Findings indicated strong evidence for inter-rater reliability but more mixed evidence for intra-rater reliability (ICC) and for test validity.

Praxis skills were assessed using two different assessments stemming from two frameworks: (1) The Florida Apraxia Battery (FAB; Rothi et al., 2003), modified for children (Mostofsky et al., 2006). The FAB is standardized, but not norm-referenced, and comprises three subsections described below. During the assessment, participants were videotaped from two perspectives, frontal and lateral. See supplementary materials for detailed FAB scoring; (2) The postural praxis (PPr) from The sensory integration and praxis tests (SIPT; Ayres, 1989) is a standardized praxis examination with strong reliability (Ayres; Mailloux et al., 2021) involving imitation of 17 nonrepresentational gestures and body positions. Raw scores were used since the majority of data were collected from participants above standardization age (Reynolds et al., 2017). Raw score distributions were checked for skewness in order to ensure scores were not topping out and decreasing the ability to find relationships with the measure.

The two different praxis measures were used to provide a broader assessment. The FAB includes three sections: Gesture to verbal command (GTC; 25 items) which involves asking the participant to show use of a specific object or execute a gesture such as waving

goodbye. These gestures have a symbolic/communicative meaning and the participant must conjure up the internal representation of the action in order to perform it. The second section involves imitation of symbolic gestures (IMI-meaningful, 25 items) as well as meaningless gestures (IMI-Meaningless, 9 items). The third section involves demonstration of use of an actual tool (GTU, 17 items). In comparison, the postural praxis test (Ayres, 1989) involves imitation of whole-body meaningless actions and has been extensively used as a measure of praxis within the occupational therapy literature (Ayres, 1989; Cermak & May-Benson, 2020). Whereas accuracy scoring on the FAB was not timed, scores on the PPr are dependent on how quickly and accurately the child can assume each posture.

Social skills

Empathy skills were assessed using the interpersonal reactivity index (IRI; Davis, 1983), a 28-item self-report measure consisting of four 7-item subscales, two cognitive empathy scales (perspective-taking and fantasy) and two emotional empathy (empathetic concern, and personal distress). A modified version with child-appropriate language was used (Pfeifer et al., 2008). The Fantasy subscale was not included, due to reliability concerns (Cox et al., 2012) and that this aspect of cognitive empathy was not a primary focus of the current study.

The ToM subscale of the social perception subtest of the developmental neuropsychological assessment (NEPSY-II) served as a ToM measure (Brooks et al., 2009). The measure involves measures of verbal and contextual ToM, including emotion understanding. The ToM subscale of the NEPSY is one of two parts of the Social Perception domain which has adequate internal reliability for 7- to 16-year-olds ($r = 0.80$ or greater), and test-retest reliability correlations are all above 0.5 for ages 8–16 (Korkman et al., 2007). Autistic traits and severity were measured by the SRS-2 in all participants. For the current study, the total score and social communication, restrictive interests (SCI) subscale were used. The SRS-2 has excellent reliability with alphas ranging from 0.94 to 0.96 (APA; Bruni, 2014) and is known to have good content, predictive, and construct validity (Grella et al., 2022).

Statistical analysis

This paper includes secondary analyses of data collected as part of a study that was powered according to its primary outcomes involving brain imaging. Descriptive statistics were performed for the data set. Sex distributions between groups (TD, ASD, DCD) were examined using χ^2 analyses. Although groups did not differ significantly on age, gender or FSIQ (Table 1), all three variables were

included in all group comparison and correlational analysis to control for any effects of each variable known to be associated with social and motor scores. Correlations between social and motor variables of interest and all other variables are listed in the Supplementary materials (Table S1). Throughout the analyses, a two-tailed significance level of $p < 0.05$ (two-tailed) was used. Univariate analysis of covariance (ANCOVA) was used to evaluate differences between groups (TD, ASD, DCD) in relation to covariates (age, sex, FSIQ), motor variables (MABC-2, SIPT PPr, FAB), and social variables (SRS-2, NEPSY-II ToM, IRI). Group comparisons between inclusion variables are used to confirm diagnostic differences in each group respectively. The SCI subscale of the SRS-2 is used to compare autism symptomatology-related social communication differences between groups. We note that while the SCI subscale is not part of inclusion criteria, it does contribute to the overall SRS-2 Total score and therefore significant findings should be considered carefully. Partial correlations were conducted to evaluate the association between motor and social skills in each group while controlling for age, sex, and FSIQ. Across groups, correlations were not conducted since inclusion criteria included group differences in both social and motor skills which would produce artificial correlations. Scatter and box plots were generated for all variables and visually inspected to ensure relationships were not driven by potential outliers.

To evaluate if performance on the praxis skills differed between groups above and beyond motor performance skills, additional ANCOVAs were performed with age, sex, FSIQ, and MABC-2 Total as covariates to examine group differences on praxis skills (FAB, SIPT). The same analysis was performed to evaluate group differences in praxis skills above and beyond individual differences in social skills (i.e., SRS-2 and ToM), as well as to evaluate group differences when MABC-2, SRS-2, and ToM were potentially controlled for according to a step-wise analysis.

RESULTS

Preliminary analysis: Demographics and inclusion criteria

Group demographic and variable data are reported in Table 1. All group comparisons are reported in Supplementary materials, Table S2. Chi-square analysis indicated no difference in sex distribution between groups ($p = 0.300$). Separate ANOVAs revealed groups did not differ in age ($p = 0.988$), full scale (FS-IQ; $p = 0.222$), perceptual reasoning (PRI-IQ; $p = 0.492$). The verbal comprehension index (VCI-IQ) did differ between groups ($p = 0.021$). Post hoc *t*-tests revealed that VCI-IQ was significantly higher in the TD group than the ASD group, and trended higher in the DCD group compared

to the ASD group ($p = 0.065$). The groups also differed in degree of ADHD measured by the Conners 3AI ($p = 0.000$), with the ASD group scoring significantly higher (greater ADHD symptoms) than the other two groups, and the DCD group scoring significantly higher than the TD group.

As expected, given our inclusion criteria, Total scores on the SRS-2 and MABC-2 were significantly different between groups ($p < 0.001$). The TD group had significantly better social skills (lower T-scores) measured by the SRS-2 Total score compared to both clinical groups with the DCD group having intermediate scores (Figure 1). On the MABC-2 Total, although MABC-2 score was not an eligibility criteria of the ASD group, ASD participants fell significantly below the TD group into the clinical range with similar MABC-2 Total scores as the DCD group (Figure 1).

AIM 1: Social differences between groups

ANCOVA analysis

Based on normative scoring of the SRS-2, 36% of our DCD group had total scores that fell into the mild or moderate range. One-way ANCOVAs followed by group comparisons were performed comparing social skill scores between groups (Table 1). Similar to the SRS-2 total scores, the SCI subscale of the SRS-2 total differed between groups ($p < 0.00$) with the clinical groups having significantly more impairments than the TD group. Comparing clinical groups, the DCD group had significantly fewer impairments than the ASD group. Significant group differences also were observed in NEPSY-II ToM Total ($p = 0.006$). The ASD group had significantly weaker performance on the NEPSY-II ToM Total score compared to the TD and DCD groups (Table 1). Finally, although the group ANCOVA was not statistically significant ($p = 0.089$), in individual group comparisons the TD group scored significantly higher in the IRI Perspective Taking than the ASD group ($p = 0.039$), while the DCD group scored between the other two groups. There were no other significant differences between groups on the IRI. Overall, individuals with ASD and DCD showed elevated SRS-2 SCI subscale scores compared to the TD group, however, only the ASD group showed reduced ToM skills (NEPSY-II, ToM Total) compared to TDs.

AIM 2: Motor characteristics and differences within and between groups

Group differences in motor skills

According to MABC-2 clinical cutoffs, 85% of the ASD group qualified for DCD. One-way ANCOVAs compared motor performance and praxis subsections between

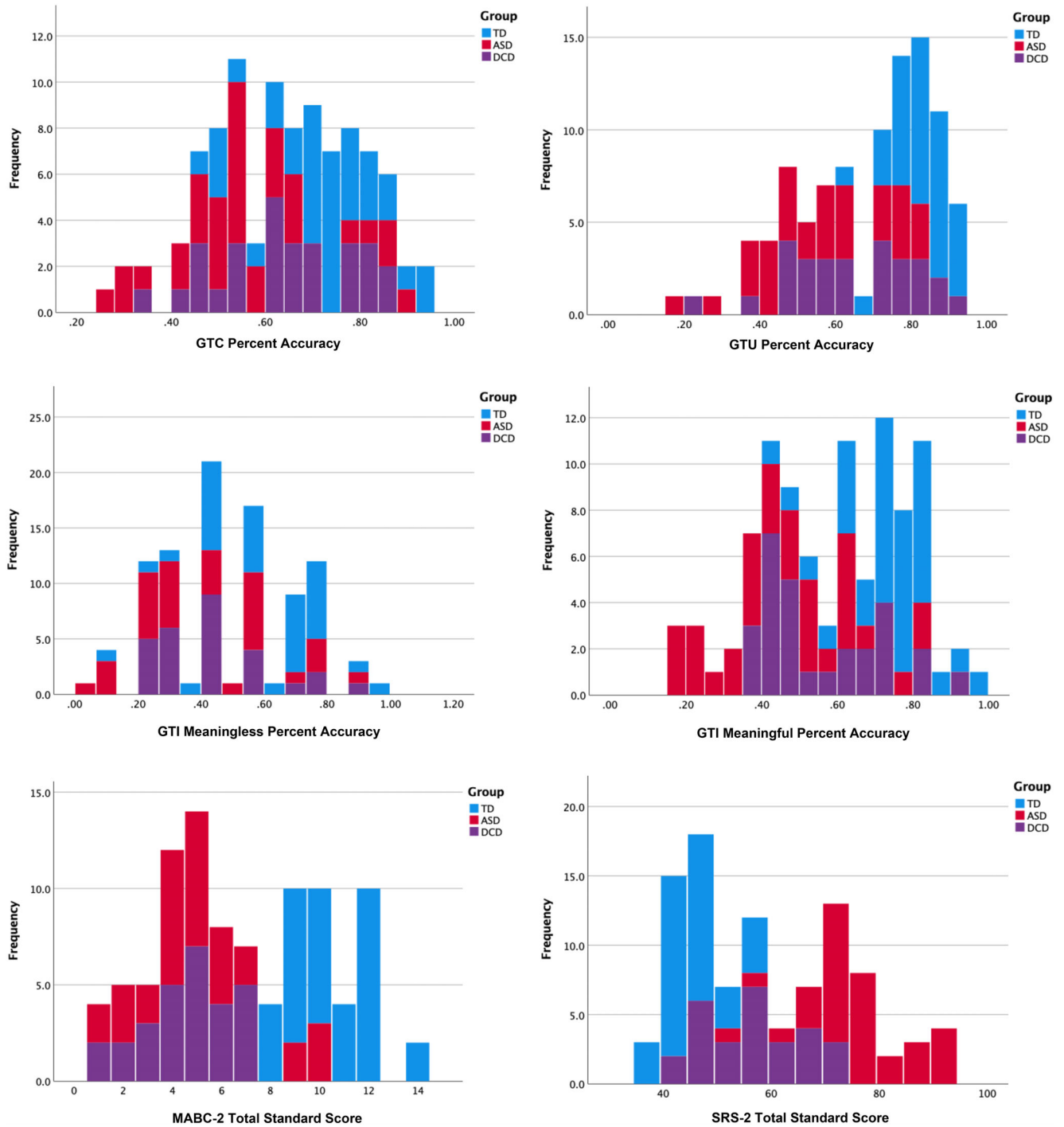


FIGURE 1 Histograms of MABC-2 total score, SRS-2 TOTAL score, and praxis measures (FAB, SIPT) by group. TD: Blue; ASD: Red; DCD: Green. MABC-2, movement assessment battery for children; SRS-2, social responsivity scale

groups controlling for age, sex, and FSIQ. Significant differences were found in all comparisons within MABC-2 and FAB subsections (Table S2). As hypothesized (and expected by our MABC-2 exclusion criteria for the TD group), pairwise comparisons indicated that ASD and DCD groups demonstrated significantly poorer performance than TD peers on all measures of motor perfor-

mance and praxis (Table 1). The clinical groups did not differ from each other in any MABC-2 subsection or SIPT PPr score (p 's > 0.05). However, the DCD group performed significantly better than the ASD group on GTC, GTI Meaningful, and GTU subsections of the FAB ($p < 0.05$), with no between-group difference on the GTI Meaningless subsection of the FAB.

TABLE 2 Significant motor and praxis correlations.

Group		FAB				SIPT
		GTC	GTI ML	GTI MF	GTU	PPr
		<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>
TD	MABC-2 total	0.181	0.076	-0.129	-0.134	0.205
	MABC-2 manual dexterity	0.085	0.329	0.061	0.049	0.226
	MABC-2 balance	0.296	-0.056	0.142	-0.061	0.141
	MABC-2 aiming and catching	-0.08	-0.048	-0.41*	-0.226	0.062
ASD	MABC-2 total	0.095	0.168	-0.068	0.219	0.417*
	MABC-2 manual dexterity	0.134	0.211	-0.055	0.283	0.63*
	MABC-2 balance	0.043	-0.133	-0.003	0.082	0.156
	MABC-2 aiming and catching	0.109	0.342	-0.03	0.2	0.193
DCD	MABC-2 total	0.444*	0.389	0.594**	0.472*	0.22
	MABC-2 manual dexterity	0.395	0.267	0.474*	0.453*	0.261
	MABC-2 balance	0.226	0.066	0.241	0.277	0.044
	MABC-2 aiming and catching	0.29	0.588**	0.502*	0.149	0.41

Note: * $p < 0.05$, ** $p < 0.01$; *** $p < 0.001$, uncorrected.

Abbreviations: ASD, autism spectrum disorder; DCD, developmental coordination disorder; FAB, Florida Apraxia Battery; GTC, gesture to command; GTI MF, gesture to imitation meaningful; GTI ML, gesture to imitation meaningless; GTU, gesture to tool use; MABC-2, movement battery for children; SIPT PPr, the sensory integration and praxis tests, postural praxis; TD, typically developing.

Differences in praxis skills when controlling for motor performance skills

Except for GTI Meaningless, results showed significant group differences on scores from all FAB sections (Supplementary 1.1). For all significantly different FAB sections, the TD group performed significantly better than both clinical groups (all $ps < 0.05$). The ASD group performed significantly worse than the DCD group in GTC ($p = 0.021$); GTI Meaningful ($p = 0.042$) and GTU ($p = 0.001$). The PPr did not differentiate between clinical groups when controlling for motor performance skills ($p = 0.409$).

Motor performance and praxis correlations within groups

Partial correlations between motor performance skill scores (MABC-2) and praxis scores (FAB, SIPT PPr) were conducted controlling for age, sex, and FSIQ within each group (Table 2).

Aim 3: Relationship between motor and social skills measures

Differences in praxis skills when controlling for social skills

ANCOVAs with age, FSIQ, sex and social skills (SRS-2 SCI, ToM Total) as covariates examined group differences in the percent correct for each of the FAB sections

and for SIPT PPr; between ASD and DCD group. Results are in Table 3. For all FAB components, both clinical groups performed worse than TD (all $ps < 0.005$; Table S2), and the ASD group performed significantly worse than the DCD group on all FAB components ($ps < 0.05$) except for imitation of meaningless gestures. ASD performed significantly worse than DCD on GTC ($p = 0.010$) and GTI Meaningful ($p = 0.006$). PPr also differentiated between groups when controlling for SRS-SCI $p = 0.031$; with TD performing better than both clinical groups ($ps < 0.05$), and DCD and ASD performing similarly to each other ($p = 0.568$).

When controlling for ToM total scores, results showed significant group differences on the SIPT PPr (Table S2). Post hoc analysis found that for the PPr, the TD performed better than ASD ($p = 0.000$) and DCD ($p = 0.003$); the DCD and ASD did not differ ($p = 0.468$). There were significant group differences in all four FAB sections ($ps < 0.05$; Supplementary 1.2). As expected, the TD group performed significantly better on all components compared to both clinical groups (all $ps < 0.05$). In contrast, the clinical groups performed similarly to each other on all FAB scores and PPr, with the exception of GTI Meaningful, where DCD performed significantly better than ASD ($p = 0.049$). However, modeling simultaneously for the three potential confounders (MABC-2, SRS-2, ToM) is important since some confounders may move associations in different directions than others. Thus, for parsimony, we used a stepwise model to verify significant control variables (Table 3). The model kept SRS-2 and MABC-2 in some instances but rejected ToM in all FAB subsection models. Specifically, when adjusting for SRS-2 and MABC-2, the

TABLE 3 FAB percent accuracy ANCOVA results for ASD versus DCD analysis controlling for different variables in addition to age, sex, and FS-IQ.

Praxis measure	Significant ANCOVA findings of group					Stepwise regression	
	No additional control variables	MABC-2	SRS-2 SCI	ToM Total	VC-IQ	ToM Total, VC-IQ (no FS-IQ)	Forced variable: Age, sex, IQ, stepwise: MABC-2, SRS-2 SCI, ToM total
FAB GTC	DCD > ASD*	DCD > ASD*	DCD > ASD**	n.s.	DCD > ASD*	n.s.	DCD > ASD $p = 0.0023$ (MABC*, SRS*)
FAB GTI MF	DCD > ASD*	DCD > ASD**	DCD > ASD**	DCD > ASD*	DCD > ASD*	DCD > ASD [†]	DCD > ASD* (n.s. variables of interest)
FAB GTI ML	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s. (n.s. variables of interest)
FAB GTU	DCD > ASD*	DCD > ASD*	n.s.	n.s.	DCD > ASD [†]	n.s.	n.s. (n.s. variables of interest)
SIPT PPr	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s. (MABC-2*)

Note: T, $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s., not significant.

Abbreviations: ASD, autism spectrum disorder; DCD, developmental coordination disorder; FAB, Florida Apraxia Battery; GTC, gesture to command; GTI MF, gesture to imitation meaningful; GTI ML, gesture to imitation meaningless; GTU, gesture to tool use; IRI, interpersonal reactivity index; MABC-2, movement battery for children; NEPSY, developmental neuropsychological assessment; PPr, postural praxis; SRS-2 SCI, social responsiveness scale, social communication and interaction; ToM, theory of mind.

DCD group still performed significantly better than the ASD group. Although ToM did not make it into the stepwise model, forcing its inclusion did not alter the findings (DCD > ASD; data not shown).

Partial correlations between motor performance skill scores (MABC-2, Praxis, SIPT PPr) and social scores (ADOS-2, NEPSY-II ToM, SRS-2, IRI) were conducted controlling for age, sex, and FS-IQ within each group. Table 4 shows, contrary to our hypotheses, no significant correlations were found within each clinical group between social measures and praxis subscores. However, components of the MABC-2 correlated with aspects of social skills (empathy and ToM skills).

DISCUSSION

The current study sought to identify common and unique patterns of motor and social impairment in ASD and DCD and elucidate how motor impairment relates to the severity of social impairments and autism symptoms. Our study provides evidence to support both overlapping and unique social and motor deficits in both clinical groups and corroborates recent studies suggesting that motor deficits may be either a core impairment in ASD or an extremely common comorbidity. In comparison, social deficits in DCD warrant further investigation to more fully elucidate the pattern and types of social impairments in this group. Prominent findings are discussed below.

Social skills among clinical groups

This study compared social abilities and impairments between all three groups. As expected, the ASD group had increased ASD symptoms (SRS-2 total and subscores) compared to the TD and DCD groups. In line

with our hypothesis, individuals with DCD also had elevated scores on the SRS-2 compared to the TD group, with 36% falling in the ASD clinical range. Consistent with the latter finding, the mean scores on the SRS-2 SCI subscale were significantly worse in the DCD group than the TD group, falling between the TD and ASD groups (Table 1). Thus, social and communication skill impairments related to ASD symptomatology are elevated in at least a subgroup of children and adolescents with DCD, though not of the same magnitude as those observed in ASD. This is consistent with the findings of Sumner et al. (2016) who also compared children with ASD and DCD and reported that across all social measures they used, the ASD and the DCD groups scored more poorly than the TD group. However, the ASD and DCD groups did not differ on the Benton face processing and Bruce emotion-recognition measures, but the ASD group scored more poorly than the DCD group on the VABS Socialization and the SCQ (Sumner et al.). Future research is needed to explore possible subgroups of DCD that present social impairments and better understand whether such impairments are primary or secondary symptoms. Longitudinal research may help in answering these questions.

In regard to empathy, we find no significant cognitive or affective empathy differences between the DCD and TD groups, consistent with prior studies (Tal Saban & Kirby, 2019). However, individuals with ASD have reduced cognitive empathy compared to TDs but are not impaired in affective empathy. Specifically, the ASD group showed a significant reduction in Perspective Taking on the IRI. Further, we found a significant reduction in ToM skills in the ASD group compared to the TD group. These findings support previous studies indicating cognitive empathy and ToM deficits in ASD compared to TD groups (Bellebaum et al., 2014; Castelli, 2002; Deschamps et al., 2014; Frith & Happé, 2005; Jolliffe & Baron-Cohen, 1997; Zalla et al., 2009). We note,

TABLE 4 Partial correlations between social and motor measures controlling for age, sex, and IQ by group.

Group	Motor skill variable	ADOS-2	NEPSY-II ToM	SRS Total	SRS SCI	IRI Total	IRI EC	IRI PD	IRI PT
TD	MABC-2 total	—	−0.242	0.109	0.035	0.198	0.156	−0.095	0.347 ^t
	MABC-2 manual dexterity	—	0.079	−0.159	−0.096	0.042	−0.016	−0.062	0.07
	MABC-2 balance	—	−0.008	0.143	0.042	0.171	0.22	−0.165	0.354
	MABC-2 aiming and catching	—	−0.411 [*]	0.187	0.126	0.055	0.004	−0.035	0.149
	FAB GTC	—	0.164	0.307 ^t	0.225	0.014	0.069	−0.253	0.209
	FAB GTU	—	0.41 [*]	−0.023	0.059	−0.292	−0.247	−0.101	−0.16
	FAB GTI meaningful	—	0.082	0.059	0.101	−0.128	−0.058	−0.193	−0.053
	FAB GTI meaningless	—	0.156	−0.286	−0.222	−0.19	−0.113	−0.232	0.115
	SIPT total raw	—	0.056	−0.069	−0.067	−0.211	−0.313 ^t	0.169	−0.308 ^t
ASD	MABC-2 total	0.004	−0.361 ^t	−0.118	−0.033	0.118	0.039	−0.047	0.365 ^t
	MABC-2 manual dexterity	−0.222	−0.241	−0.118	−0.016	0.197	0.11	0.151	0.159
	MABC-2 balance	0.343 ^t	−0.254	−0.14	−0.09	0.189	0.007	−0.124	0.489 ^{**}
	MABC-2 aiming & catching	−0.287	−0.153	0.113	0.147	−0.248	−0.039	−0.18	0.012
	FAB GTC	0.086	−0.054	0.225	0.261	−0.164	0.106	−0.34 ^t	−0.094
	FAB GTU	−0.06	0.017	−0.121	−0.072	−0.173	−0.148	−0.111	0.017
	FAB GTI meaningful	0.153	0.002	0.291	0.333	−0.202	−0.152	0.01	−0.158
	FAB GTI meaningless	−0.095	−0.09	0.051	0.071	0.03	0.086	0.026	−0.118
	SIPT total raw	−0.18	0.172	−0.086	0.004	−0.166	−0.001	−0.133	−0.129
DCD	MABC-2 total	—	0.101	−0.086	−0.08	−0.12	−0.022	−0.218	−0.18
	MABC-2 manual dexterity	—	0.396 [*]	−0.139	−0.175	−0.356 ^t	−0.068	−0.248	−0.381 ^t
	MABC-2 balance	—	−0.197	0.095	0.112	0.172	0.097	−0.05	0.068
	MABC-2 aiming & catching	—	−0.003	−0.18	−0.139	−0.02	−0.047	−0.162	0.072
	FAB GTC	—	0.094	0.09	0.071	−0.073	−0.069	−0.097	−0.28
	FAB GTU	—	0.024	0.068	0.089	−0.06	0.001	−0.179	−0.078
	FAB GTI meaningful	—	0.187	−0.056	−0.061	−0.157	−0.154	−0.043	−0.27
	FAB GTI meaningless	—	0.032	−0.183	−0.155	−0.087	−0.058	−0.225	−0.087
	SIPT total raw	—	−0.071	0.219	0.237	−0.037	−0.154	−0.069	0.17

Note: T, $p < 0.01$, $*p < 0.05$, $**p < 0.01$, uncorrected.

Abbreviations: ADOS-2, autism diagnostic observation schedule; ASD, autism spectrum disorder; DCD, developmental coordination disorder; EC, empathic concern; FAB, Florida Apraxia Battery; GTC, gesture to command; GTI, gesture to imitation; IRI, interpersonal responsivity inventory; MABC-2, movement battery for children; NEPSY-II, developmental neuropsychological assessment; PD, personal distress; PT, perspective taking; SCI, social communication, restrictive interests; SIPT PPr, the sensory integration and praxis tests, postural praxis; SRS-2, social responsivity scale; TD, typically developing; TU, gesture to tool use.

however, that other researchers have found differences in perspective taking skills when providing explicit versus implicit instructions for perspective taking in children with ASD (Asaoka et al., 2019; Cole et al., 2018), and here we do not make this distinction. However, compared to the DCD group, the ASD group showed significant reduction only in ToM ability, consistent with prior reports measuring ToM and overall empathy skill differences between the clinical groups (Tal Saban & Kirby, 2019; Wisdom et al., 2007). Thus, our data support the notion that ToM skills significantly differentiate ASD and DCD groups. Nevertheless, one prior study found that individuals with comorbid ASD and DCD as compared to a DCD group showed significant differences on the Empathy Quotient, a measure which does not distinguish between cognitive and affective empathy (Tal Saban & Kirby), indicating that perhaps other measures of empathy may render different results. However, we

suggest that when studying empathy in ASD, it is more informative to assess affective and cognitive empathy separately.

Motor performance and praxis skills among groups

Two dominant questions in the field of ASD are: (1) whether motor impairments should be considered a hallmark of the diagnosis; and (2) whether these motor deficits are distinct from those seen in DCD and whether a unique motor impairment pattern is integral to ASD. However, motor assessments alone are not sufficient to screen for ASD given the high rates of motor skill impairments in other disorders such as DCD; a more nuanced understanding of ASD specific motor impairment is needed to better inform screening tools and therapies. Thus, the second aim

of this study was to compare groups on a range of motor performance and praxis skills.

Motor performance and praxis skills in ASD versus TD

Consistent with our hypothesis we find that 85% of our ASD sample showed clinical levels of motor performance impairment as measured by the MABC-2. While there is no cut-off threshold for praxis impairment on the FAB, the ASD group had significantly worse performance than the TD group on all FAB sections (Figure 1). These findings are consistent with prior studies (Bhat, 2020; Dowell et al., 2009; Fournier et al., 2010; Mostofsky et al., 2006; Nebel et al., 2016; Wilson et al., 2018; Wymbs et al., 2021) and add to the literature suggesting that motor impairments are characteristic of the ASD population and either may be considered a diagnostic criteria of ASD, similar to the recent addition of impairments in sensory processing (APA, 2013), or considered a common comorbidity. Further, motor related screening should be part of ASD evaluations (Bhat, 2021; Miller et al., 2014).

Motor performance and praxis skills in ASD versus DCD

To better understand if motor impairments are distinct between ASD and DCD, we compared motor performance skills and praxis skills between these groups. We note that given the MABC-2 was used as an inclusion criterion of the DCD group and not the ASD group, we refrain from drawing many conclusions from those between group comparisons, especially when comparing MABC-2 total scores. Nevertheless, in line with our hypothesis and consistent with the existing research (Caçola et al., 2017), both groups showed poor performance on all MABC-2 total scores and subsections (balance, catching and aiming, manual dexterity) with no significant differences between the groups.

Further, we hypothesized that, compared to the TD and DCD groups, the ASD group would have more severe impairments on praxis measures, which may be considered more social in nature than motor performance scores from the MABC-2. When comparing the clinical groups on praxis skills, we found that the ASD group performed worse than the DCD group on representational gesture sections of FAB (GTC, GTI meaningful, GTU), while no between group differences were found for non-representative praxis imitation measures (GTI meaningless and SIPT PPr). Further the effect sizes between the ASD and DCD groups were much larger for gesture to command, imitation of meaningful gestures, and tool use compared to MABC-2 scores. These findings indicate that groups may differ based on aspects of praxis ability. Moreover, when controlling for MABC-2,

differences between the groups on representational gesture sections remain, suggesting that individuals with ASD have praxis impairments above and beyond motor performance deficits (Dewey et al., 2007). However, when controlling for SRS-2 total, gesture to command and imitation of meaningful gestures were the only FAB subsections that distinguished ASD from DCD participants. Thus, although we find differences between the clinical groups in several praxis subsections, these may be explained in part by group differences in social skills, except for gesture to command and imitation of meaningful gestures. The FAB utilizes more communicative gestures and is vaguer in instruction compared to the MABC-2 and thus may require more social understanding and/or more explicit instructions (Asaoka et al., 2019; Cole et al., 2018) to correctly perform. Therefore, controlling for social skills is informative for comparing the two clinical groups in praxis skills and may explain discrepancies in previous literature. Interestingly, controlling for ToM (negatively associated with ASD) alone mitigates ASD versus DCD between-group differences in gesture to command, but those differences remain significant when other variables (specifically, SRS-2 and MABC-2 which are strongly associated with ASD) are additionally controlled for. These findings suggest ToM may not significantly affect clinical differences in some praxis measures. Overall, our findings indicate that both meaningful imitation and gesture to command deficits show robust differences between the ASD and DCD groups.

Relationship between motor performance and praxis skills in ASD and DCD

We further investigated the relationship between motor performance and praxis skills within ASD and DCD. While in the DCD group, components of the MABC-2 correlate with all praxis components, in the ASD group, MABC-2 components only correlate with the FAB Tool Use and the SIPT PPr. Thus, in the DCD group, motor performance skills are more tightly linked with praxis skills. This finding indicates the deficits found in the ASD group for gesture to command and imitation of meaningful gestures cannot solely be attributed to poor motor performance skills. These findings along with the ones discussed above (group differences controlling for MABC-2) indicate that motor performance ability and some measures of praxis ability may be decoupled in ASD.

Relationship between social and motor skills in ASD and DCD

Finally, we aimed to explore the relationship between social and motor skills and hypothesized unique patterns

of correlations given the complexity of both ASD and DCD symptomology. Overall, we find ToM and cognitive empathy (IRI Perspective Taking) are positively related to motor performance skills in DCD and ASD groups respectively. These findings are consistent with our previous brain imaging study indicating that both across and within ASD, DCD, and TD groups, motor ability, as measured by the MABC-2, correlates with activity in the IFGop (Kilroy et al., 2021), a brain region also commonly found to be involved in perspective taking (Shamay-Tsoory et al., 2009). In comparison, affective empathy does not appear to be related to motor performance or praxis skills, consistent with prior studies showing individual differences in affective empathy is correlated with activity in emotion-related brain regions (Bernhardt & Singer, 2012; Gonzalez-Liencrez et al., 2013; Lamm et al., 2011).

With our current dataset, we do not find significant correlations between praxis and social measures in the ASD group. However, the number of social measures collected here were limited and largely restricted to questionnaires, and we note that many other studies have found relationships between imitation and various social skills, including language ability (Charman et al., 2000; Dawson & Adams, 1984; Ingersoll & Meyer, 2011; McDuffie et al., 2007; Pittet et al., 2022; Poon et al., 2012; Stone & Yoder, 2001; Toth et al., 2007), joint attention (Carpenter et al., 2002; Ingersoll & Schreibman, 2006; Rogers et al., 2003), functional and symbolic play (Libby et al., 1997; Stone et al., 1997; Vivanti et al., 2013), social reciprocity (McDuffie et al.; Young et al., 2011), cooperation (Colombi et al., 2009), ToM (Perra et al., 2008), and autism severity (Rogers et al.; Ingersoll & Meyer, 2011; Zachor et al., 2010, Pittet et al.). The discrepancy between the current results and prior results may have to do with the measures collected, and is a topic for future research.

Limitations

There are several limitations including reliance on self- and parent-reported questionnaires for some of the social measures (SRS-2 and IRI). However, ToM and motor skill measures provided multiple performance indicators. Second, given the large number of measures already collected, for the FAB we limited our analysis to only include percent correct which provides a broader clinical characteristic of praxis impairments. Thus, our FAB analysis did not consider praxis error type which may identify additional patterns between the clinical groups. Finally, the sample size was relatively small, precluding precise estimates of effect sizes, and potentially limiting the heterogeneity of the sample, and generalizability of the results. This is particularly true since participation required average IQ scores. Future studies with more diverse IQ ranges, a lower age range, and inclusion of ambidextrous and left-handed individuals, so that effects

of handedness can be considered, is recommended along with a larger sample size to refine effect estimates.

Conclusion

Individuals with ASD and DCD show both overlapping and unique patterns of social and motor skills. Specifically, ASD shows greater impairment than DCD on ToM. Additionally, 36% of children with DCD show elevated scores on the SRS-2, indicating that therapies focusing on social skills may also be beneficial to some individuals with DCD. Both clinical groups showed deficits in motor performance and praxis skills compared to TD children. However, gesture to command and imitation of meaningful gestures distinguished ASD from DCD, even when controlling for social deficits. Furthermore, different correlational patterns between motor performance and praxis skills were identified in ASD and DCD groups, suggesting the need to examine neuropathology between the groups. These findings have strong implications for screening and diagnosis of ASD and DCD and may have a translational impact on motor, imitation-based, and social skills interventions for each group/subgroup. Further research is needed to determine whether motor coordination and praxis deficits should be considered a cardinal feature of ASD as suggested by Fournier et al. (2010) or whether DCD and ASD are distinct but highly comorbid disorders as posited by Caçola et al. (2017).

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DATA AVAILABILITY STATEMENT

All data are available on the National Institute of Mental Health Data Archive: https://nda.nih.gov/edit_collection.html?id=2254.

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