

## RESEARCH ARTICLE

# Unique deficit in embodied simulation in autism: An fMRI study comparing autism and developmental coordination disorder

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## Abstract

A deficit in pre-cognitively mirroring other people's actions and experiences may be related to the social impairments observed in autism spectrum disorder (ASD). However, it is unclear whether such embodied simulation deficits are unique to ASD or instead are related to motor impairment, which is commonly comorbid with ASD. Here we aim to disentangle how, neurologically, motor impairments contribute to simulation deficits and identify unique neural signatures of ASD. We compare children with ASD ( $N = 30$ ) to children with Developmental Coordination Disorder (DCD;  $N = 23$ ) as well as a typically developing group ( $N = 33$ ) during fMRI tasks in which children observe, imitate, and mentalize about other people's actions. Results indicate a unique neural signature in ASD: during action observation, only the ASD group shows hypoactivity in a region important for simulation (inferior frontal gyrus, pars opercularis, IFGop). However, during a motor production task (imitation), the IFGop is hypoactive for both ASD and DCD groups. For all tasks, we find correlations across groups with motor ability, even after controlling for age, IQ, and social impairment. Conversely, across groups, mentalizing ability is correlated with activity in the dorsomedial prefrontal cortex when controlling for motor ability. These findings help identify the unique neurobiological basis of ASD for aspects of social processing. Furthermore, as no previous fMRI studies correlated brain activity with motor impairment in ASD, these findings help explain prior conflicting reports in these simulation networks.

## KEYWORDS

action imitation, dyspraxia, functional magnetic resonance imaging, mentalizing, mirror neuron system

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## 1 | INTRODUCTION

One way of understanding other people's actions and intentions is to implicitly map other's actions onto one's own motor representations, and pre-cognitively "simulate" others from an embodied first-person perspective (Gallese, 2006). A disruption in these precognitive embodied simulation processes may be related to the social deficits observed in autism spectrum disorder (ASD; Gallagher, 2004; Iacoboni & Dapretto, 2006; Oberman & Ramachandran, 2007; Rizzolatti & Fabbri-Destro, 2010; Williams, Whiten, Suddendorf, & Perrett, 2001). However, the degree in which embodied simulation is utilized may be modulated by one's motor abilities (Yang, 2015; Buccino et al., 2004). Indeed, about 79% of children with ASD have comorbid motor impairments (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Green et al., 2009), including ideomotor praxis and imitation deficits (McAuliffe et al., 2020; Mostofsky & Ewen, 2011; Rizzolatti & Sinigaglia, 2016). Are embodied simulation deficits unique to ASD? Or are they instead related to motor impairment, which may be comorbid with ASD but not exclusive to it? Here, to understand unique neural signature of ASD, we enrolled three groups of participants that vary in both social and motor deficits: ASD (primary impairment considered social), developmental coordination disorder (DCD, commonly called dyspraxia, primary impairment is motor), and typically developing (TD) controls. We correlated symptomology with brain activity for a mainly motor task (imitation) as well as more social tasks (action observation, mentalizing). To our knowledge, this is the first study that compares ASD and DCD groups—groups that commonly show similar motor impairments but differ in the severity of social impairments—in action imitation and observation tasks.

One neural network important for precognitive motor simulation is the mirror neuron system (MNS: pars opercularis of the inferior frontal gyrus [IFGop], ventral premotor cortex, and posterior parietal cortex), which responds both when one performs and observes an action (Rizzolatti & Sinigaglia, 2016). The IFGop in particular, is thought to be the human homolog to primate area F5, the frontal region where mirror neurons are found (Geyer, Matelli, Luppino, & Zilles, 2000). The IFGop has connections with higher visual processing regions (i.e., superior temporal sulcus), emotion-related brain regions (i.e., insula), and prefrontal regions, is thought to play a role in social processing via implicit precognitive sensorimotor simulation (de Waal & Preston, 2017). Activity in the IFGop is involved in social cognition, emotion processing, and empathy (for reviews, see de Waal & Preston, 2017; Jeon & Lee, 2018). Interestingly, several ASD studies show differential functioning in the IFGop during imitation and/or action observation tasks compared to TD peers (Dapretto et al., 2006; Kana, Wadsworth, & Travers, 2011; Williams, 2008), though there have been discrepant findings (for reviews, see Chan & Han, 2020; Yates & Hobson, 2020). However, to date no fMRI studies have considered how motor impairment impacts IFGop activity in ASD, or if IFGop impairment is unique to ASD. Indeed whether or not children with DCD also have hypoactivity in the MNS during motor production tasks remains unclear (for a review, see Kilroy, Cermak, &

Aziz-Zadeh, 2019). By comparing both these groups, we can better understand if IFGop deficits during action observation and imitation are unique to ASD or are common to general motor impairment.

Previous data indicate that when the task involves consciously inferring other people's intentions from their actions using theory of mind, mentalizing regions also are active, and there is increased functional connectivity between the IFG and the dorsomedial prefrontal cortex (dmPFC; Spunt & Lieberman, 2012a, 2012b). However, in such tasks, individuals with ASD show atypical activity in mentalizing regions (Kana, Uddin, Kenet, Chugani, & Müller, 2014) and no increase in connectivity between MNS and mentalizing networks (Cole, Baraclough, & Andrews, 2019).

Thus, here we consider both MNS and mentalizing networks and make three predictions: (a) Activity in the IFGop will correlate with motor ability during action observation, imitation, and mentalizing tasks across ASD, DCD, and TD groups beyond social impairment for both social (face) and less social (hand) actions. By including both face and hand stimuli, we can test the hypothesis that IFGop hypoactivity in ASD is not dependent on the degree of sociality of the stimuli or the inclusion of an object-goal (Hamilton, 2008); (b) For the mentalizing task, activity in the dmPFC will correlate with social ability across groups beyond motor impairment. Hence we predict a double dissociation where the IFGop is correlated with motor ability and the dmPFC is correlated with social ability; (c) While we expect the DCD group to show IFGop hypoactivity during motor production tasks (imitation), we do not expect them to show similar hypoactivity during action observation (due to absence of social deficits as part of their diagnostic criteria); we expect the ASD group to uniquely show a *deficit* during action observation.

## 2 | MATERIALS AND METHODS

### 2.1 | Participants

A total of 86 right-handed individuals ages 8–17 in either ASD (Mean age = 12.02,  $SD = 2.3$ ), DCD (Mean age = 12.08,  $SD = 2.27$ ), or TD (Mean age = 11.96,  $SD = 2.28$ ) groups completed the study. For the observation and imitation tasks, 5 participants were not included in data analysis due to extraneous head movement. For the mentalizing task, 6 participants were not included for the same reason. Participants were recruited from clinics in the greater Los Angeles healthcare system, through local schools, word-of-mouth, and social media advertising. Inclusion criteria for all participants included: (a) IQ of at least 75 on either Full Scale Intelligence Quotient (FSIQ), or Verbal Comprehension Index (VCI) of the Wechsler Abbreviated Scale of Intelligence 2nd edition (WASI-II; Wechsler, 2011); (b) right handed as assessed by a questionnaire adapted from Crovitz and Zener (1962). Exclusion criteria for all participants included: (a) history of head injury with loss of consciousness greater than 5 min; (b) not sufficiently fluent in English or parent who did not have English proficiency; (c) born before 36 weeks of gestation; (d) contraindications to participating in

MRI. All participants and parents were evaluated for their capacity to give informed consent and then provided their written child assent and parental consent in accordance with the study protocols approved by the university's Institutional Review Board.

### 2.1.1 | Participants with ASD (N = 30, 7 female)

Inclusion criteria for the ASD group included a previously received diagnosis either through a clinical ASD diagnostic interview, an ASD diagnostic assessment, or both. Diagnosis was re-assessed by research-reliable staff using the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord et al., 2000), and the Autism Diagnostic Interview-Revised (ADI-R; Lord, Rutter, & Le Couteur, 1994). Two females had sub-threshold ADOS-2 scores, but qualified based on the ADI-R and clinician review. Additional exclusion criteria included a diagnosis of other neurological or psychological disorders except for attention deficit disorders or generalized anxiety disorder (because those are highly comorbid with ASD; Avni, Ben-Itzhak, & Zachor, 2018). Twelve ASD participants were taking prescribed psychotropic medication at the time of data collection.

### 2.1.2 | Typically developing (TD) participants (N = 33, 11 female)

TD controls additionally were excluded if they had: (a) any psychological diagnosis or neurological disorder, including attention deficit disorders or generalized anxiety disorder; (b) first degree relative with ASD; (c) *T*-score above 65 on the Conners 3AI-Parent report (Conners, 2008), indicating a risk for attention deficit and hyperactivity disorder (ADHD); (d) score below the 25th percentile on the Movement Assessment Battery for Children (MABC-2; Henderson, Sugden, & Barnett, 2007) or probable DCD based on the Developmental Coordination Disorder Questionnaire (DCDQ; Wilson, Kaplan, Crawford, Campbell, & Dewey, 2000; Wilson et al., 2009); and (e) *T*-score above 60 on the Social Responsiveness Scale, Second Edition (SRS-2; Constantino & Gruber, 2012) indicating a risk for ASD.

### 2.1.3 | Participants with DCD (N = 23, 10 female)

Eligibility criteria included: (a) performance at or below the 16th percentile on the MABC-2, and (b) no first degree relatives with ASD and no current or previous concerns about an ASD diagnosis. The Conners 3AI-Parent report was used to identify ADHD symptoms but was not used as an exclusion criterion since ADHD is highly comorbid with DCD (Martin, Piek, & Hay, 2006). Two children in the DCD group who had a *T*-score range from 65–74 on the SRS-2 were administered the ADOS-2 but did not meet criteria for ASD and were thus included in the study. Four children were taking prescribed psychotropic medication at the time of data collection.

## 2.2 | Experimental design and statistical analyses

### 2.2.1 | Measures

Participants completed a session of behavioral assessments within 2 weeks prior to their scan date. As mentioned in the inclusion criteria, all participants completed the WASI-II and the SRS-2, which measures social skills impacted by ASD (e.g., social awareness and capacity for reciprocal social interaction; Constantino & Gruber, 2012). All children with ASD, as well as children with DCD with elevated SRS-2 scores, completed the ADOS-2. Parents of children with ASD completed the ADI-R. Parent questionnaires included the highest parental education level from either parent which was used as a proxy measure of socioeconomic status (SES). Motor skills were measured using the MABC-2 (Henderson et al., 2007), which consists of three subtests: Manual Dexterity, Aiming and Catching skills, and Balance. Theory of Mind skills were assessed using the Developmental Neuropsychological Assessment (NEPSY-II), Theory of Mind (ToM) Total Score which consists of ToM verbal scores and ToM Contextual scores within the Social Perception domain (Korkman, Kirk, & Kemp, 2007). The ToM Contextual subscore was used to correlate with neuroimaging data as it most closely aligns with the mentalizing fMRI task and, unlike the ToM Total Score, does not include a measure of verbal ability.

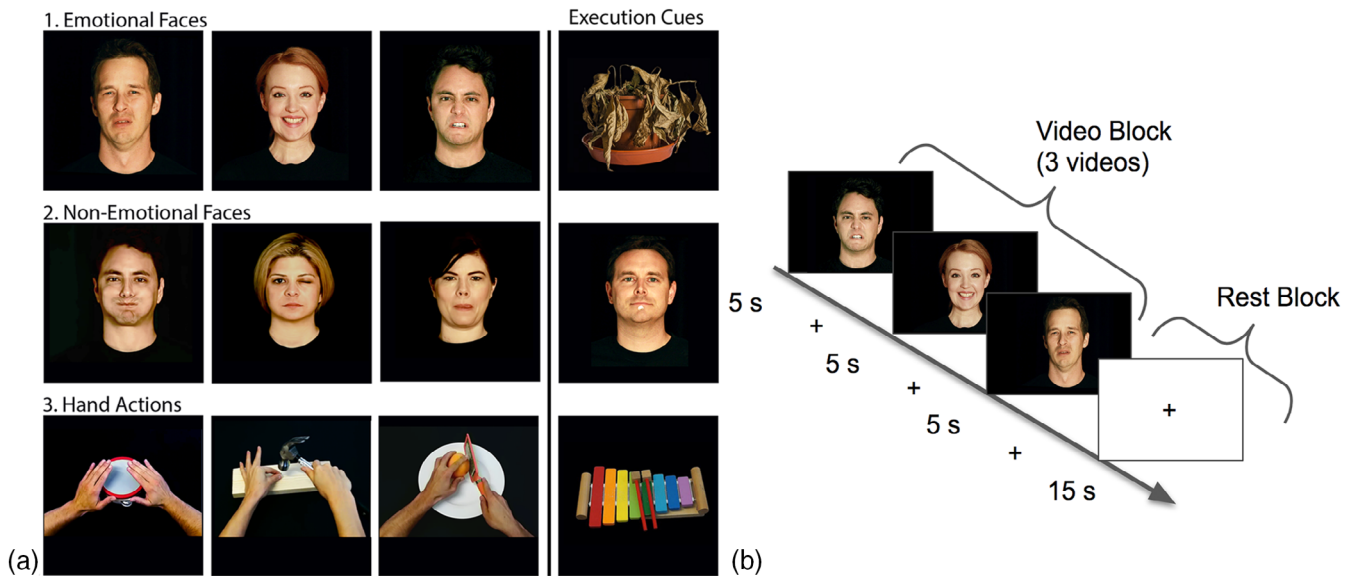
Behavioral measures were analyzed using IBM SPSS Statistics (Version 27). Univariate outliers were identified as data being more than 2.2 interquartile ranges from the first and third quartile (Hoaglin & Iglewicz, 1987), and removed from the analyses. ANOVAs were run to assess the group differences in behavioral measures. The Scheffé post hoc criterion for significance was used to compute differences between individual groups, with significance accepted at  $p < .05$ .

### 2.2.2 | fMRI procedure

All participants completed four different task runs in the following order: action observation, execution, imitation, and mentalizing (see Figure 1). Action Execution was used as a localizer task (see ROI analyses). Participants practiced all tasks in a mock scanner prior to scanning to familiarize participants with the tasks and instruct on minimal head motion. They were also filmed while performing actions in the MRI and video monitored in real time in order to confirm task adherence.

### 2.2.3 | Stimuli

Each fMRI task used video or still photo stimuli from three categories: (a) emotional face actions (e.g., smiling); (b) nonemotional face actions (e.g., tongue to upper lip); (c) bimanual hand actions (e.g., hands playing xylophone; face not shown). All stimuli were specifically developed for this study (Figure 1a). Stimuli were presented for 3.75 s in a block design consisting of three stimuli per block with a 1.25-s black



**FIGURE 1** Stimulus and task design. (a) All stimuli were presented in color. For the first three columns, still images taken from EmStim<sup>®</sup> stimuli videos. Each video played for 3.75 s. The last column illustrates still photos used to cue action for the execution task (dead plant participants to make a sad expression; the whipped cream location on the actor's face cued the participant where to lick; the xylophone cued the participant to pantomime playing the instrument). 1. Emotional face stimuli (left to right: disgust, happy, angry, dead plant). 2. Nonemotional face stimuli (left to right: puffed cheeks, closed eye, tongue to side, whip cream dollop). 3. Hand actions (left to right: drumming, hammering, grating, xylophone). (b) Illustration of the task design. Stimulus blocks included three videos and or stills, presented for 3.75 s followed by a 1.25-s black screen between each stimuli. Each resting block consisted of a 15-s white screen with a black crosshair. Image size: 800 × 600. The stimuli were presented via the Resonance Technology digital goggle system

screen as a transition between each video/still followed by a 15-s rest block (Figure 1b). During the rest blocks, participants were shown a black crosshair in the middle of a white screen. Excluding an initial junk block (see *Within-in Subject Analysis* section), five blocks of each stimulus condition were alternated with rest in a pseudo-random sequence creating a total of 15 different videos for each category per run. Seven different Caucasian adult actors were used to create the stimuli. No stimulus was repeated in the same run and no block contained more than two same sex actors.

**Video stimuli (observation, imitation, and mentalizing tasks):** No more than two videos per block contained the same valenced emotion (i.e., two high valenced emotions and one low valenced emotion). **Still stimuli (Execution task):** Nine still photos were used to cue 9 different actions for the participant to produce (3 emotional facial expressions, 3 nonemotional facial expressions, 3 hand actions). The emotional face category consisted of photos of a dead plant (cue to make a sad face), a piece of moldy bread (cue to make a disgust face), and a poison bottle (cue to make a fear face). The nonemotional face category consisted of photos of a neutral face with a spot of whip cream on one of three points around the mouth (cue to “lick” tongue at that spot on the lip). The hand category consisted of photos of a xylophone (cue to pantomime playing xylophone), a bunch of grapes (cue to pantomime bimanually picking grapes apart), and a game controller (cue to pantomime playing a video game). Sequences of one still photo (5 s per stimulus) from each of the three categories were presented per 15 s block. Participants were instructed to perform the cued action for the entire time that the stimulus was presented (5 s).

## 2.2.4 | fMRI tasks

Stimuli were presented using MATLAB with the Psychophysics Toolbox (Brainard, 1997). Each task run began with instructions with a total run time of 8 min. (a) *Action Observation Task*. Participants observed videos from each stimulus category described above and were asked to passively observe the actions. (b) *Action Execution Task*. Participants were instructed to execute the appropriate action when cued by still images as described above (see Video Stimuli section). Participants were instructed to perform the cued actions for the entire duration of the stimulus presentation. (c) *Imitation Task*. Participants were instructed to watch the same videos used in the action observation run and imitate the emotional facial expressions, nonemotional facial expressions and hand actions. (d) *Mentalizing Task*. Viewing the same videos, participants were instructed to silently think about why the actor was performing the emotional face, nonemotional face, and hand action presented. For example, if they saw someone cutting paper, they might think that the actor intends to create an art project; if they saw someone smile, they might think they were happy because they received a present. In a practice session prior to scanning, if participants labeled actions (i.e., “they are happy”) instead of stating “why” an actor was performing an action (i.e., “they received a present”) they were instructed to try again. Outside the MRI, a post-task mentalizing behavioral task was performed to measure the accuracy and quality of participant's mentalization responses. During this task, participants saw the same videos with the same timing, and were asked to perform the task again, this time saying what they thought in

their head out loud. The task was recorded, transcribed, and scored by two raters (interrater reliability 94%, Cohen's  $\kappa = 0.81$ ) for accuracy and quality of responses (3-point scale). Responses were coded as either non-mentalizing (0), weak mentalizing (1), or strong mentalizing (2). For example, if a smiling facial expression was presented: (a) non-mentalizing response, "he is smiling," (b) weak mentalizing response, "something made him happy," and (c) strong mentalizing response, "he is happy because he just opened a birthday present he loved." Between group analyses were performed using independent t-tests.

## 2.3 | MRI data acquisition and analysis

### 2.3.1 | Scanning parameters

MRI data were acquired on a 3 Tesla MAGNETOM Prisma (Siemens, Erlangen, Germany) with a 20-channel head coil. A 5-min structural T1-weighted MPRAGE was acquired for each participant (TR = 1950 ms, TE = 3.09 ms, flip angle =  $10^\circ$ ,  $256 \times 256$  matrix, 176 sagittal slices, 1 mm isotropic resolution). Each functional scan consisted of an echo-planar imaging (EPI; 150 whole-brain volumes) acquired with the following parameters: TR = 2 s, TE = 30 ms, flip angle =  $90^\circ$ ,  $64 \times 64$  matrix, in-plane resolution  $2.5 \times 2.5$  mm, and 41 transverse slices, each 2.5 mm thick, covering the whole-brain with a multiband factor of three. Spin Echo EPI field mapping data was also acquired in AP and PA directions with identical geometry to the EPI data for EPI off-resonance distortion correction (TR = 1,020 ms, TE1 = 10 ms, TE2 = 12.46 ms, flip angle =  $90^\circ$ , FOV =  $224 \times 224 \times 191$  mm<sup>3</sup>, voxel size = 2.5 mm isotropic).

### 2.3.2 | Within-subject analyses

Subject-level functional imaging analyses were completed using FSL 6.0 (Jenkinson, Beckmann, Behrens, Woolrich, & Smith, 2012). The following preprocessing steps were taken: (a) brain extraction for non-brain removal; (b) spatial smoothing using a Gaussian kernel of FWHM 5 mm; (c) B0 unwarping was performed in the y-direction; (d) standard ICA-AROMA (Pruim et al., 2015), which uses a robust set of theoretically motivated temporal and spatial features to remove motion and physiology-related spurious noise; (e) a high pass filter with a cutoff period of 90 s; (f) realignment of functional volumes using MCFLIRT.

Functional images were registered to the high-resolution anatomical image using a 7-degrees of freedom linear transformation. Anatomical images were registered to the MNI-152 atlas using a 12-degree of freedom affine transformation, and then this transformation was further refined using FNIRT for nonlinear registration (Jenkinson, Bannister, Brady, & Smith, 2002; Jenkinson & Smith, 2001). Experimental stimulus conditions were then each modeled with a separate regressor derived from a convolution of the task design and a double gamma function to represent the hemodynamic response, and the temporal derivative of each task regressor was also included as an additional regressor. Subject-specific motion correction parameters were entered as nuisance

regressors. The first stimuli block (extra hand stimulus condition) was modeled separately as a junk block and discarded to account for the effects of the initial gradient field stabilization and the time required for the brain tissue to reach excitation (Soares et al., 2016).

### 2.3.3 | Head motion

All subjects with head movement exceeding absolute motion of 1.55 mm were excluded from further analysis (ASD = 3; DCD = 2). Further, group differences for head movement using a  $3 \times 3$  ANOVAs (3 fMRI tasks and 3 participant groups) revealed no significant interaction of tasks and groups in either absolute or relative head motion. Further, there were no significant differences in absolute head motion between groups within each task, nor were there significant differences in relative head motion between groups in the imitation and mentalizing tasks. However, there was a significant difference in relative head motion between groups in the observation task ( $p = .017$ ). In the observation task, the DCD group had significantly more motion than the TD group (Scheffe's  $p = .029$ ), but there were no significant differences between the DCD group compared to the ASD group or the ASD group compared to the TD group. To correct for potential differences in signal due to confounding motion, the six motion parameters were included in the first-level analysis model with additional motion correction using ICA-AROMA. As an extra precaution, we refrained from putting too much weight on significant differences in TD versus DCD contrasts in the observation task; results involving this comparison were not in brain regions relevant to our hypotheses (i.e., pons) and are not discussed.

*Within-group analyses.* All three groups were entered into multivariate linear regression models for each task for exploring main effects, between-group comparisons, and correlations with motor and social behavioral measures. In all whole-brain analyses, in line with previous literature and our own data (cf. Supporting Information) suggesting that IFG activity correlates with age (Casey, Tottenham, Liston, & Durston, 2005; Uddin, Supekar, & Menon, 2013), age was entered as a covariate along with sex and FSIQ (WASI-II). In all models, all covariates were mean-centered across participants. Individual participants' statistical images were entered into the higher level mixed-effects analyses using FSL's FLAME Stage 1 algorithm. Resulting group level images for all models were thresholded using FSL's cluster probability algorithm, with a cluster-forming threshold of  $Z > 3.1$  and a cluster size probability threshold of  $p < .05$ . All significant findings between groups and within each stimulus condition are reported below.

### 2.3.4 | Main effects

To identify networks elicited by observation, imitation, and mentalizing compared to rest, the three stimulus conditions (emotional face, nonemotional face, and hand actions) were collapsed to determine the main effect of each task compared to resting baseline. Similar analyses were performed for each stimulus condition (e.g., emotional faces) within each task.

### 2.3.5 | Between-group analyses

For between group analyses (TD > ASD, TD > DCD, DCD > ASD, ASD > TD, ASD > DCD, DCD > TD), all three groups were entered into the multivariate linear regression models. Additionally, small volume corrections (SVC) were performed using voxelwise correction in our main regions of interest: left and right anatomical IFGop (using hand-drawn anatomical masks; Damasio, 1995), and in the mentalizing task, a dmPFC ROI as defined by a previous study (Spunt & Adolphs, 2014) for our contrasts of interest (TD > ASD, TD > DCD, DCD > ASD, ASD > DCD).

### 2.3.6 | Whole-brain activation related to motor and social ability

To determine whether motor or social scores correlated with blood oxygen level dependent response to the action observation, imitation, and mentalizing tasks across groups, separate regression analyses were performed with both the mean-centered MABC-2 Total Scores, ToM Contextual scores, and SRS-2 scores, separately. Additionally, for the ASD group, a regression analysis was performed with mean-centered ADOS-2 comparison scores in each functional task.

### 2.3.7 | Region of interest (ROI) analyses

*Definition of ROIs.* (a) *Conjunction analyses for identifying MNS regions within the IFGop.* A conjunction analysis was performed across all participants using FSL to identify areas selectively activated both during observation and execution of all stimulus conditions compared to rest (Figure 3,  $Z > 2.3$ , cluster size corrected). Based on previous findings showing differences in the IFGop in ASD, we focused our analysis on this MNS ROI, and masked the resulting bilateral IFGop cluster by a hand-drawn anatomical IFGop masks (Damasio, 1995). (b) *Mentalizing region: dmPFC.* The dmPFC ROI was defined by a previous study (Spunt & Adolphs, 2014). While we originally planned to also look at the temporoparietal junction (TPJ), this region was ultimately not included as it was not significantly active during the mentalizing task as compared to rest. *Outlier removal.* Percent signal change was extracted from defined ROIs using Featquery in FSL. For all ROI analyses, we removed data from participants whose mean percent signal change in the queried ROI were outliers as defined by being more than 2.2 times the interquartile range from the first and third quartile relative to the entire group (Hoaglin & Iglewicz, 1987). For all regression analyses, scatter plots between significant activation and respective behavioral measure were plotted to ensure the results were not driven by outliers or by differences between groups (Makin & de Xivry, 2019).

*ROI Behavioral correlations.* For each ROI, partial correlations were conducted, relating activity in that ROI with behavioral measures, while controlling for other variables. MABC-2 Total Score, SRS-2 Total Score, and ToM Contextual Score correlations were performed for all participants (both within and across groups); additionally two indices of autism severity—the ADOS-2 Comparison Score and ADI-R

Reciprocal Social Interaction (RSI) score—were correlated with ROI activity in ASD participants. All correlations controlled for age. For correlations with the ADOS-2 Comparison Score, we also controlled for sex, given possible interactions with sex with this score (Adamou, Johnson, & Alty, 2018). Additionally, partial correlations were conducted to control for social measures when exploring motor correlations, and vice versa. For all correlational analyses, scatter plots of significant correlations were plotted to ensure the results were not driven by outliers or by differences between groups (Makin & de Xivry, 2019).

## 3 | RESULTS

### 3.1 | Behavioral data

There was no association between group and sex according to the Chi-Square Tests of independence ( $p = .159$ ). An analysis of variance showed that groups did not significantly differ on age, IQ, nor SES ( $ps < .05$ ). As expected, the ASD group had significantly greater social impairment as measured by SRS-2 Total scores than the TD and DCD group ( $p < .001$ ), though the DCD group also was more impaired than the TD group ( $p < .001$ ; Table 1). In addition, the TD group had significantly better motor skills as measured by the MABC-2 Total Score and MABC-2 subscores than either the ASD or DCD group (all  $ps < .0001$ ; Table 1). The ASD and DCD groups did not differ in any measure of motor skill ( $ps > .05$ ; Table 1).

Across groups, there were significant correlations between social (SRS-2 Total and subscores) and motor scores (MABC-2 Total and subscores;  $ps < .05$ ). However, within each group, the SRS-2 Total and subscores did not significantly correlate with motor skills (MABC-2 Total and subscores;  $ps > .095$ ). Additionally, motor scores did not correlate with the ADOS-2 comparison score or ADI-R in the ASD group ( $ps > .163$ ).

For mentalizing ability, the ToM Total score was significantly lower in the ASD group compared to the TD group. The DCD group scored between the ASD and TD groups, but was not significantly different from either group. The ToM Contextual score did not correlate with motor scores ( $p > .05$ ). Furthermore, in our post-mentalizing task, while the total number of items mentalized did not significantly differ between any groups, the ASD group compared to the TD group showed a trend toward overall lower quality of all mentalized responses ( $p = .07$ ), and the ASD group had a higher number of poor responses ( $p = .05$ ). Within the TD group, there was a significant correlation between MABC-2 Catching and Aiming Subscore and ToM Total scores ( $r = -.371$ ,  $p = .034$ ).

### 3.2 | Imaging data

#### 3.2.1 | Observation task

*Observation task: Main effect and between group comparisons*

As Figure 2a shows, during action observation of all actions (vs. fixation), all groups showed widespread significant activation including regions in

**TABLE 1** Descriptive group statistics and group comparison

Group		Descriptive statistics					Scheffe's test value		
		N	Minimum	Maximum	Mean	SD	TD	ASD	DCD
TD, <i>F</i> = 10	Age	33	8.36	17.84	11.963	2.283		0.994	0.980
	WASI-II FSIQ	33	93	153	114.0	12.367		0.641	0.847
	WASI-II VCI	33	86	151	115.12	12.108		0.225	0.977
	WASI-II PRI	33	84	152	110.61	14.718		0.993	0.681
	MABC-2 Manual Dexterity*	33	6	15	9.88	2.147		0.000	0.000
	MABC-2 Aiming Catching*	33	5	18	10.63	3.439		0.000	0.000
	MABC-2 Balance*	33	8	15	10.97	2.498		0.000	0.000
	MABC-2 Total*	33	8	14	10.47	1.717		0.000	0.000
	SRS-2 Total*	33	37	55	45.00	4.956		0.000	0.000
	NEPSY-II ToM total*	33	20	28	24.97	1.912		0.015	0.692
	NEPSY-II ToM contextual	33	3	6	5.12	.893		0.608	0.925
ASD, <i>F</i> = 7	Age	30	8.62	17.39	12.025	2.308	0.994		0.995
	WASI-II FSIQ	30	72	142	110.10	19.461	0.641		0.958
	WASI-II VCI	30	76	151	108.27	18.75	0.225		0.392
	WASI-II PRI	30	63	154	110.03	21.52	0.993		0.756
	MABC-2 Manual Dexterity*	29	1	13	5.62	2.846	0.000		0.872
	MABC-2 Aiming Catching*	30	2	14	6.37	3.449	0.000		0.997
	MABC-2 Balance*	30	1	13	6.60	2.955	0.000		0.202
	MABC-2 Total*	39	1	10	5.24	2.488	0.000		0.399
	SRS-2 Total*	30	53	90	75.87	9.627	0.000		0.000
	NEPSY-II ToM total*	27	17	28	23.15	3.134	0.015		0.003
	NEPSY-II ToM contextual	27	3	6	4.89	0.934	0.608		0.437
	ADOS-2	27	1	10	6.66	2.109	—		—
	ADI-R RSI	28	10	29	18.71	5.597	—		—
DCD, <i>F</i> = 11	AGE	23	8.65	15.45	12.088	2.273	0.980		0.995
	WASI-II FSIQ	23	74	141	111.43	17.278	0.847		0.958
	WASI-II VCI	23	87	146	114.22	15.969	0.977		0.392
	WASI-II PRI	23	71	154	106.17	20.27	0.681		0.756
	MABC-2 Manual Dexterity*	23	1	10	5.26	2.359	0.000		0.872
	MABC-2 Aiming Catching*	23	2	13	6.43	2.936	0.000		0.997
	MABC-2 Balance*	23	1	10	5.26	2.562	0.000		0.202
	MABC-2 Total*	23	1	7	4.48	1.755	0.000		0.399
	SRS-2 Total*	23	42	72	56.74	8.672	0.000		0.000
	NEPSY-II ToM total*	23	22	28	25.52	1.831	0.692		0.003
	NEPSY-II ToM Contextual	23	3	6	5.22	0.850	0.925		0.437

Note: Values are presented as mean, SD, and range. The Scheffé post hoc criterion for significance was used for differences between groups.

Abbreviations: ADOS, Autism Diagnostic Observation Schedule; ADI-R RSI, Autism Diagnostic Interview Revised Reciprocal Social Interaction; ASD, autism spectrum disorder; DCD, developmental coordination disorder; F, female; FSIQ, Full-Scale IQ; MABC-2; Movement Assessment Battery for Children; NEPSY-II, Theory of Mind skills were assessed using the Developmental Neuropsychological Assessment; PRI, Perceptual Reasoning Index IQ; SRS, Social Responsivity Scale; TD, typically developing; ToM, theory of mind; VCI, verbal composite index IQ; WASI-II, Wechsler Abbreviated Scale of Intelligence 2nd edition.

\**p* < .001.

the bilateral IFGop, premotor cortex, superior parietal cortex, the anterior cingulate cortex, lateral occipital regions, cerebellum, and right STS. When comparing groups, during observation of all stimuli conditions we found

the contrasts TD > ASD and DCD > ASD both showed less activation in the right IFGop (*p* < .05, SVC; Figure 3a), and the TD > DCD contrast showed less activity in the pons (Table 1).

### Observation task correlation with motor skills

As predicted, across groups, the MABC-2 Total Score was positively correlated with activity in the bilateral IFGop extending into ventral premotor regions across observation of all stimulus conditions, as well as when observing hand actions and emotional expressions (Figure 2b). The mean percent signal change was extracted from significant voxels in the right IFGop (across all stimulus conditions) and plotted against the MABC-2 Total Score for visualization of the correlation and to identify outliers (Figure 2b). Additional regions positively correlated with motor ability include: for all stimulus conditions, the bilateral lateral occipital cortices; and for hand stimuli, the left premotor cortex and the superior division of the lateral occipital cortex.

### Observation task correlation with social skill

Across groups, the SRS-2 and ToM Contextual Scores were not significantly correlated with any brain regions for action observation. In the ASD group, the ADOS-2 comparison score was positively correlated with the bilateral cerebellum during observation of hand actions.

## 3.3 | Imitation task

### Main effects and between group contrasts

During action imitation (vs. fixation), across all stimulus conditions, all groups showed widespread activation including regions in the bilateral IFG, premotor and motor cortices, superior parietal cortex, lateral occipital regions and right STS (Figure 2a). When comparing groups, we found more activity for TD compared to ASD when imitating emotional faces in the right superior frontal gyrus/SMA and right IFGop ( $p < .05$ , SVC; Figure 3b). In the TD > DCD contrast, activity was found in the right IFGop during hand action imitation (Figure 3b) and in the right superior frontal gyrus/SMA during imitation of all actions.

When comparing the DCD and ASD groups, we found significantly less activity in the ASD group in the postcentral gyrus, and less activity for the DCD group in a number of frontal cortical regions (the mPFC, middle frontal gyrus, entorhinal cortex, and the pars triangularis of the IFG), as well as the angular gyrus (Table 1).

### Imitation task correlations with motor skills

Across groups, the MABC-2 Score was positively correlated with the right IFGop during imitation of hand actions. Parameter estimates were extracted from the right IFGop to visualize the correlation and to ensure it was not driven by outliers (Figure 2b).

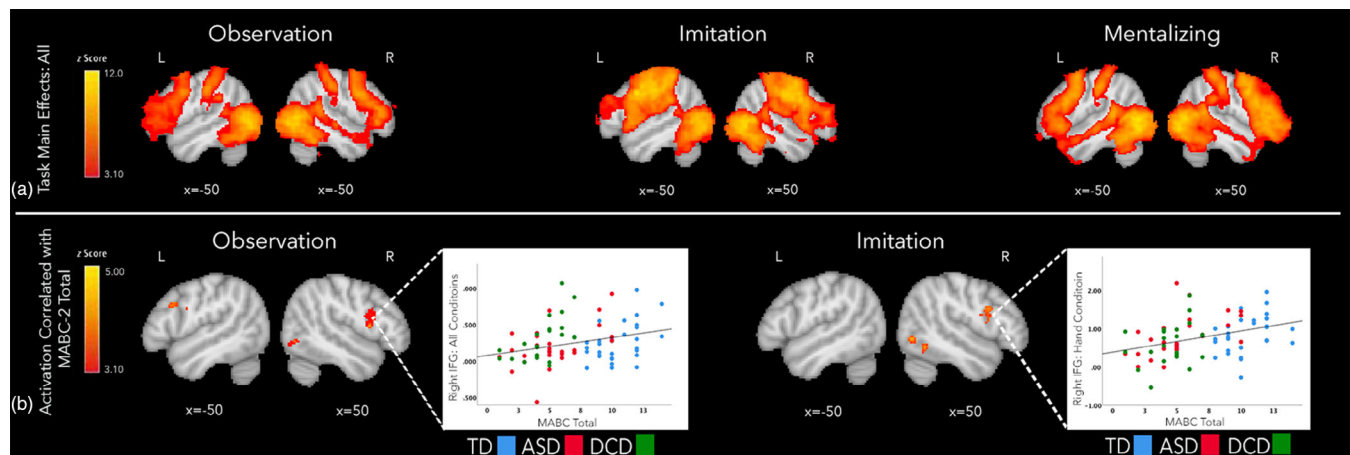
### Imitation task correlations with social skills

The ToM Contextual Score was positively correlated in the left cerebellum across conditions and when imitating nonemotional expressions. No regions were significantly correlated with the SRS-2 nor with the ADOS-2 comparison score.

## 3.4 | Mentalizing task

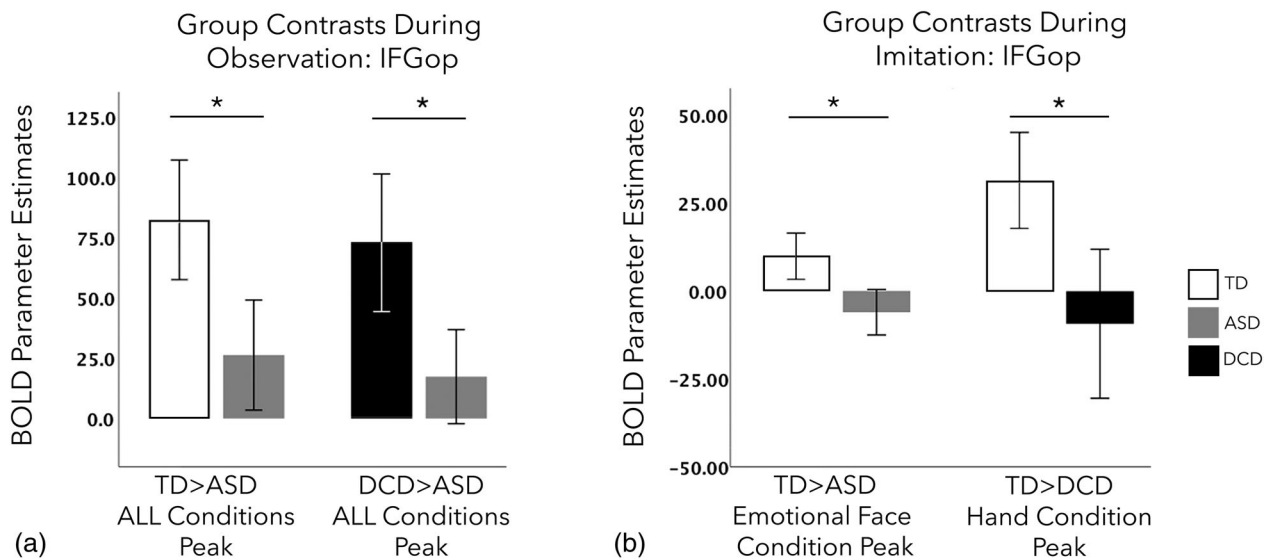
### Main effects and between group contrasts

During mentalizing about all actions (vs. fixation), all groups showed widespread significant bilateral activation including regions in the dmPFC, IFGop, premotor cortex, superior parietal cortex, STS, the anterior cingulate cortex, lateral occipital regions, and cerebellum (Figure 2a). For between group comparisons, when mentalizing about all actions (as well as when examining separately emotional or nonemotional facial expressions), we found TD > ASD activation in the dmPFC ( $p < .05$ , SVC), as well as the left IFGop, triangularis, and orbitalis as well as the left middle frontal gyrus/premotor cortex. For TD > DCD for mentalizing about all actions, significant activity was found in the dmPFC ( $p < .05$ , SVC), the bilateral activity in the right frontal pole, IFG pars triangularis, the bilateral



**FIGURE 2** Main effects of task and whole-brain correlation with motor skills. (a) Activation maps of main effects across all subjects for observation, imitation and mentalizing of all actions ( $Z > 3.1$ , cluster corrected). (b) Brain regions that positively correlated with MABC-2 Total score during observation of all actions and imitation of hand actions ( $Z > 3.1$ , cluster corrected). Scatter plots of positive activation within the IFGop illustrating the correlation. TD, typically developing; ASD, autism spectrum disorder; DCD, developmental coordination disorder





**FIGURE 3** Bar charts depicting signal change in the IFGop from the peak voxel significantly active in group comparisons of: (a) Action observation of all actions for TD > ASD and DCD > ASD contrasts ( $p < .05$ , SVC); (b) Imitation of hand actions for the TD > DCD contrast ( $Z > 3.1$ , cluster corrected) and emotional facial expressions for the TD > ASD contrast ( $p < .05$ , SVC). Error bars indicate SE multiplier of 2.2; \* indicates  $p = .001$ . ASD, autism spectrum disorder (gray); DCD, developmental coordination disorder (black); TD, typically developing (white)

superior frontal gyrus/SMA, middle frontal gyrus/premotor cortex, cerebellum. For the ASD > TD contrast, significant activity was found for the nonemotional face stimulus condition in the right Heschl's gyrus. For ASD > DCD for mentalizing about all actions, we found activity in the frontal pole, the right IFG pars triangularis, middle frontal gyrus/premotor cortex and angular gyrus (Table 2).

#### Mentalizing task correlation with motor skills

Across groups, when mentalizing about emotional facial expressions, MABC-2 Score significantly correlated with activity in the bilateral occipital pole. When mentalizing about hand actions, MABC-2 Score was correlated with the left inferior temporal cortex at the temporoparietal junction. For the IFGop, please see correlations with specific ROIs during all three tasks below.

#### Mentalizing task correlation with social skills

The ToM Contextual scores correlated with brain activity when mentalizing across all conditions in the right premotor cortex and when mentalizing about nonemotional facial expressions in the bilateral superior frontal gyrus, extending into the frontal pole, and the bilateral middle frontal gyrus, extending into the IFG pars triangularis. The SRS-2 and ADOS-2 comparison scores did not correlate with mentalizing in any stimulus condition.

### 3.5 | ROI analyses

#### 3.5.1 | IFG ROI analyses: Correlations with motor and social measures

**Observation:** Across all participants, we found that activity in the left and right hemisphere (LH, RH) IFGop ROIs were positively correlated

with MABC-2 Total Score (while controlling for age) during observation of all actions (Figure 4a), as well as for observation of hand actions, and in the right IFGop for observation of emotional expressions (All stimuli: LH  $r = .254$ ,  $p = .024$ ; RH  $r = 0.363$ ,  $p = .001$ ; Emotional expressions: RH  $r = 0.244$ ,  $p = .030$ ; Hand actions: LH  $r = 0.275$ ;  $p = .014$ ; RH  $r = 0.346$ ,  $p = .002$ ). Within each group, motor scores significantly correlated with activity in the left and right IFGop during observation of all stimuli and hand actions in the ASD and DCD groups. Additionally, for observation of emotional facial expressions, significant correlations were found in the right IFGop for the TD group and in the left IFGop for the DCD group (All stimuli: ASD: LH  $r = 0.484$ ,  $p = .011$ ; RH  $r = 0.421$ ,  $p = .029$ ; DCD: LH  $r = 0.485$ ,  $p = .026$ ; RH  $r = 0.468$ ,  $p = .032$ ; Hand Actions: ASD: LH  $r = .688$ ,  $p = .000$ ; RH  $r = .587$ ,  $p = .001$ ; DCD: RH  $r = .522$ ,  $p = .015$ ; emotional facial expressions: TD: RH  $r = 0.388$ ,  $p = .038$ ; DCD: LH  $r = .443$ ,  $p = .044$ ). In the right IFGop, all correlations remained significant after controlling for social measures (partial correlation with SRS-2 Score or ToM Contextual Score). In the left IFGop, all correlations remained significant after controlling for social measures except for within the DCD group for emotional face stimuli, which was no longer significant after controlling for the ToM Contextual Score. No significant correlations with social measures (SRS-2, ToM Contextual, ADOS-2 Comparison, and ADI-R Scores) were found across groups or within each clinical group ( $p > .05$ ).

**Imitation:** Across all participants, we found that activity in the right IFGop ROI was positively correlated with MABC-2 Score (while controlling for age) during imitation of all actions (RH  $r = 0.250$ ,  $p = .026$ ; Figure 4b), and bilaterally during the imitation of hand actions (LH:  $r = 0.227$ ,  $p = .046$ ; RH:  $r = 0.312$ ,  $p = .005$ ). The correlation with hand actions was also significant within the ASD group in the right IFGop (RH  $r = 0.445$ ,  $p = .020$ ). Correlations remained

**TABLE 2** Significant whole-brain group contrasts

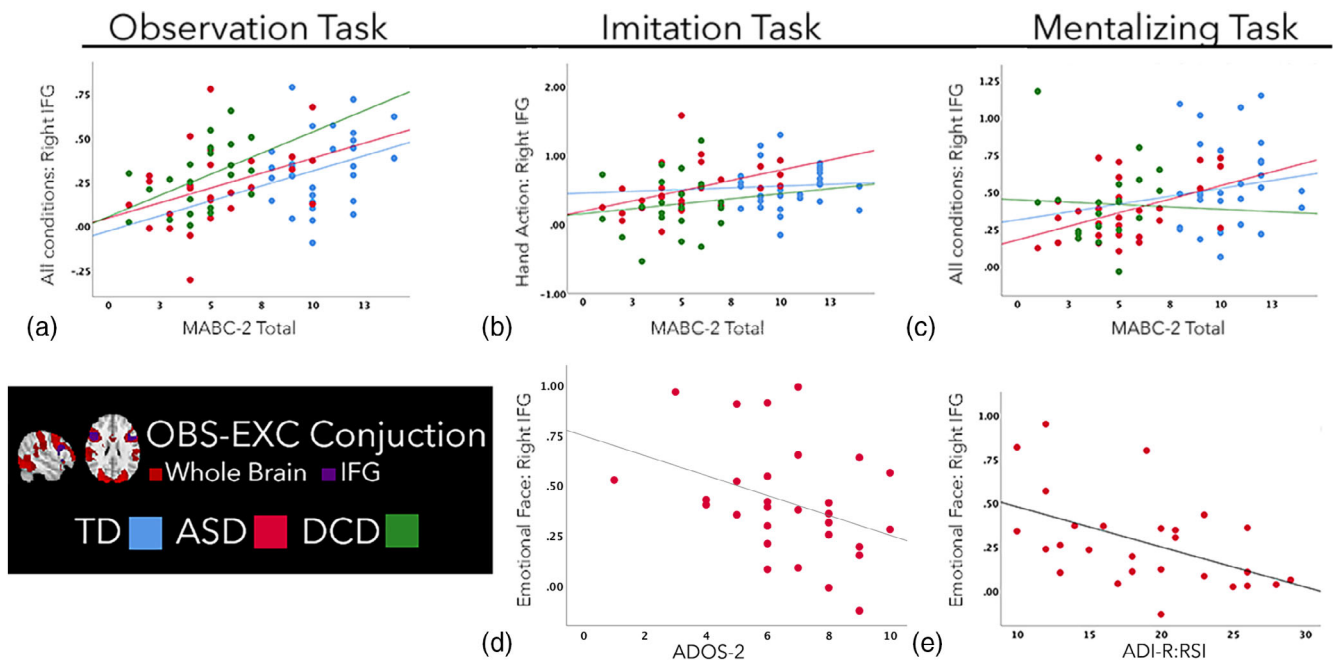
	Contrasts	Max Z score	Max X	Max Y	Max Z	Region
<b>Observation</b>						
ALL	TD > DCD	4.55	-20	-80	-34	Left pons
SVC ALL	TD > ASD	4.01	58	26	20	Right inferior frontal gyrus, pars opercularis
	DCD > ASD	3.98	56	26	10	Right inferior frontal gyrus, pars opercularis
<b>Imitation</b>						
ALL	TD > ASD	4.27	8	14	66	Right superior frontal gyrus/SMA
	ASD > DCD	4.26	18	52	30	Right frontal pole/mPFC
		4.4	42	20	56	Right middle frontal gyrus
		5.43	-12	36	-14	Left frontal medial cortex/entorhinal cortex
		4.23	62	-52	32	Right angular gyrus
		3.8	44	32	4	Right inferior frontal gyrus, pars triangularis
	TD > DCD	3.81	12	18	60	Right superior frontal gyrus/SMA
	DCD > ASD	4.48	58	-18	42	Right postcentral gyrus
SVC Emo	TD > ASD	3.67	42	12	10	Right inferior frontal gyrus, pars opercularis
<b>Mentalizing</b>						
ALL	TD > ASD	4.79	-56	30	10	Left IFG pars triangularis
		4.38	-54	8	44	Left middle frontal gyrus/M2
		4.21	-56	20	20	Left IFG pars opercularis
		4.9	-46	36	-18	Left IFG pars orbitalis
	TD > DCD	4.82	6	26	48	Right superior frontal gyrus/SMA
		3.79	-10	20	50	Left superior frontal gyrus/SMA
		5.39	20	50	24	Right frontal pole
		4.41	40	22	54	Right middle frontal gyrus/M2
		4.35	42	38	2	Right IFG pars triangularis
		4.03	-38	-78	-36	Left cerebellum
		4.43	-52	8	48	Left middle frontal gyrus/M2
		4.02	8	-84	-34	Right cerebellum
	ASD > DCD	4.47	44	-54	36	Right angular gyrus
		4.37	22	58	34	Right frontal pole
		4.45	40	16	56	Right middle frontal gyrus/M2
		4.39	42	40	0	Right IFG pars triangularis
SVC ALL	TD > ASD	3.71	-10	62	32	Dorsal medial prefrontal cortex
	TD > DCD	3.96	-16	52	32	Dorsal medial prefrontal cortex

Note: All significant peak coordinates are reported at  $Z > 3.1$ , cluster corrected for the whole brain, unless specified as a small volume correction (SVC) at  $p < .05$  for the inferior frontal gyrus, pars opercularis (IFGop) and dorsomedial prefrontal cortex (dmPFC).

Abbreviations: All, all stimuli; Emo, emotional facial expressions.

significant even after controlling for social measures (partial correlation with SRS-2 Score or ToM Contextual Score). None of the social measures correlated with activity in these ROIs across all groups for any stimulus condition. When looking only in the ASD group, after controlling for motor skills, there was a correlation between the SRS-2 and the right IFGop across all conditions ( $r = -0.406$ ;  $p = .040$ ). The ADOS-2 comparison score was significantly correlated with the left IFGop during imitation of all stimuli (LH  $r = -0.398$ ,  $p = .049$ ) and with the bilateral IFGop during imitation of emotional expressions (LH:  $r = -0.479$ ,  $p = .015$ ; and RH:  $r = -0.443$ ,  $p = .027$ ; Figure 4d).

**Mentalizing:** When mentalizing about other peoples' face and hand actions, across all participants as well as within the ASD group, activity in the left and right IFGop were positively correlated with MABC-2 Score (All participants: All stimuli: LH  $r = 0.286$ ;  $p = .011$ ; RH  $r = 0.323$ ,  $p = .004$  Figure 4c; Emotional expressions: LH  $r = 0.230$ ,  $p = .043$ , RH  $r = 0.269$ ,  $p = .018$ ; Hand actions: LH  $r = 0.252$ ,  $p = .026$ , RH  $r = 0.383$ ,  $p = .001$ ; ASD: All stimuli: RH  $r = 0.505$ ,  $p = .007$ ; Emotional expressions: LH  $r = .402$ ,  $p = .037$ , RH  $r = 0.397$ ,  $p = .04$ ; Hand actions: RH  $r = 0.592$ ,  $p = .001$ ). For the right IFGop, across all stimuli conditions (and emotional face or hand stimuli), the correlation with



**FIGURE 4** Scatterplots of ROIs with motor ability and autism severity. (a–c) All correlations shown are in the right IFGop across stimulus conditions for action observation and mentalizing tasks, and for hand actions in the imitation task. (a) Observation task: All participants:  $r = .363$ ,  $p = .001$ ; TD:  $r = .277$ ,  $p = .145$ ; ASD:  $r = .421$ ,  $p = .029$ ; DCD:  $r = .468$ ,  $p = .032$ . Similar patterns were found for the left IFGop ROI in the ASD and DCD groups (not shown). (b) Imitation Task: All participants:  $r = .312$ ,  $p = .005$ ; TD:  $r = -.054$ ,  $p = .780$ ; ASD:  $r = .445$ ,  $p = .020$ ; DCD:  $r = .124$ ,  $p = .594$ . Similar results were found for the left IFG ROI across all participants (not shown). (c) Mentalizing Task: All participants:  $r = .321$ ,  $p = .004$ ; TD:  $r = .115$ ,  $p = .545$ ; ASD:  $r = .505$ ,  $p = .007$ ; DCD:  $r = -.113$ ,  $p = .645$ . (d–e) In the ASD group, significant correlations with autism severity in the right IFGop for the emotional face stimulus condition. (d) Imitation: Activity in the right IFGop for imitation of emotional faces is negatively correlated with ADOS-2 comparison score ( $r = -.443$ ,  $p = .027$ ). Similar results were found in the left IFGop ROI across stimuli and for emotional facial expressions (not shown). (e) Mentalizing: Activity in the right IFGop for mentalizing about emotional faces is negatively correlated with ADI-R RSI score ( $r = -.494$ ,  $p = .010$ )

MABC-2 remained significant across groups when controlling for SRS-2 or ToM Contextual Scores. For the ASD group, the correlations remained significant when controlling for the SRS-2. When controlling for ToM Contextual, all correlations remained significant except for emotional expressions, which approached significance (RH  $r = 0.400$ ,  $p = .059$ ). For the left IFGop, across groups, the correlation with MABC-2 remained significant for all stimuli when controlling for the ToM Contextual Score. For the ASD group, it remained significant for emotional expressions when controlling for SRS-2, and approached significance when controlling for ToM Contextual score (LH  $r = .403$ ,  $p = .057$ ).

For social skills, there were significant correlations between activity in the left and right IFGop and SRS-2 scores across groups for mentalizing of all actions and emotional expressions, however these correlations did not remain significant when controlling for motor ability ( $ps > .2$ ). In the ASD group, mentalizing about emotional facial expressions in the right IFGop was inversely related to parent-reported social impairments (ADI-R RSI;  $r = -.493$ ,  $p = .010$ , Figure 4e). This relationship remained significant after controlling for motor impairment. No correlations were significant with the ADOS-2 comparison score or the ToM Contextual Score.

**2.4b dmPFC ROI:** In the observation and imitation tasks, no significant correlations between activity in the dmPFC and any behavioral

measures were found. However, for the mentalizing task, we found a significant positive correlation between the dmPFC and ToM Contextual Score across participants and within the DCD group when mentalizing about all stimuli and about emotional or nonemotional faces (All participants: All stimuli:  $r = 0.313$ ,  $p = .006$ ; Emotional expressions:  $r = 0.240$ ,  $p = .037$ ; nonemotional expressions:  $r = 0.375$ ,  $p = .001$ ; DCD: All stimuli:  $r = 0.514$ ,  $p = .044$ , nonemotional expressions:  $r = 0.467$ ,  $p = .044$ ). This relationship survived when controlling for age, MABC-2 Score, and SRS-2 across groups, as well as within the TD and DCD groups and at a trend level in the ASD group (TD: nonemotional expressions  $r = 0.406$ ,  $p = .032$ ; DCD: All stimuli:  $r = 0.596$ ,  $p = .011$ ; Emotional expressions:  $r = .493$ ,  $p = .045$ ; nonemotional expressions:  $r = .579$ ,  $p = .015$ ; ASD: nonemotional expressions:  $r = 0.375$ ,  $p = .085$ ).

## 4 | DISCUSSION

This study examined whether embodied simulation deficits are unique to ASD and how they may interact with motor impairment. As predicted, we found: (a) Activity in the IFGop correlated with motor ability across tasks and stimuli above and beyond social ability; (b) Activity in the dmPFC correlated with mentalizing ability, above

and beyond motor ability; (c) When examining group differences, the IFGop was hypoactive during action observation only in the ASD group, consistent with a deficit in motor simulation processing.

#### 4.1 | Activity in IFGop correlates with motor ability for social and non-social stimuli

Here we found using both whole-brain analyses and ROI analyses, activity in the IFGop during action observation, imitation, and mentalizing tasks was correlated with motor ability, across TD, DCD, and ASD groups above and beyond social ability. This correlation was also observed within each group during action observation, and within the ASD group during the imitation and mentalizing tasks, especially in the right IFGop. The TD and DCD groups may have suffered from ceiling and floor effects respectively in motor scores, making it difficult to find correlations within those groups. Thus previously reported discrepancies, with some studies showing differential activity in the IFGop in ASD while others found no differences (for reviews, see Chan & Han, 2020; Yates & Hobson, 2020), may be explained by heterogeneity in motor ability across TD and ASD groups as well as within the ASD group, which prior studies did not assess.

We investigated differences in IFGop activity in ASD not only when processing facial expressions, but also hand actions. In particular, hypoactivation of the IFGop in ASD was found for all actions for observation and mentalizing tasks, and emotional faces for imitation. While we did not find IFGop hypoactivity for hand imitation in ASD, we did find strong correlations with motor ability in the IFGop during hand imitation across groups—as well as within the ASD group—suggesting that IFGop activity for hand imitation may be particularly dependent on motor ability. Thus, IFGop hypoactivity in ASD is found not only for highly social stimuli (facial expressions), but also for hand actions, especially when motor skills are compromised. These data do not support the notion that only actions without object-oriented goals show IFGop differences in ASD (Hamilton, 2008). For the DCD group, interestingly IFGop hypoactivity was found only for hand stimuli both during the imitation (whole-brain and ROI analyses) and mentalizing tasks (ROI analysis, see Supporting Information). This may be consistent with DCD deficits with hand coordination and handwriting, and potential subtypes of DCD (Vaivre-Douret, 2014; Vaivre-Douret, Lalanne, & Golse, 2016), with some children primarily showing impairment in fine motor skills, others in gross motor skills, and others in both (Asonitou & Koutsouki, 2016).

#### 4.2 | Activity in dmPFC correlates with ToM ability: Double dissociation between IFGop and dmPFC

As predicted, we found a double dissociation between the IFGop and the dmPFC. Specifically, across groups, while activity in the IFGop was positively correlated with motor ability above and beyond social ability, activity in the dmPFC was positively

correlated with mentalizing ability (in particular, for facial expressions) above and beyond motor ability and general social skill (SRS-2). Thus, these two brain regions may be differentially implicated, according to the level and type of impairment in ASD. Given that individuals with ASD may exhibit a range of motor and mentalizing impairments and that our behavioral data indicate that these impairments are not correlated in ASD, these results may be important for targeted therapy (Odeh, Martell, Griffin, Johnson, & Gladfelter, 2020). Specifically, strategies utilizing sensorimotor versus cognitive approaches may be differentially called for depending on individual symptomatology.

While social impairment is the hallmark feature of ASD, there is ample evidence that motor ability is affected in ASD (Fournier et al., 2010; Odeh et al., 2020). Indeed, we found 83% of our ASD sample had strong motor deficits, consistent with previous reports indicating about 79% of the ASD population evidenced motor impairment (Fournier et al., 2010; Green et al., 2009). Our results indicate that social and motor behavioral deficits may arise from different brain regions—the dmPFC may be more related to mentalizing difficulties while the IFGop may be more related to motor impairments. Nevertheless, these networks are known to work together (Spunt & Lieberman, 2012a) as well as in concert with other brain regions (e.g., other motor regions, emotion-related brain regions), and individuals with ASD have been found to have abnormal connectivity between MNS and mentalizing brain regions (Cole, Barraclough, & Enticott, 2018; Fishman, Keown, Lincoln, Pineda, & Müller, 2014; Libero et al., 2014). However, in the DCD group, which also showed significantly lower SRS-2 Total scores compared to the TD group (though not clinically significant, as reflected by diagnosis and ADOS-2 scores), we similarly find atypical activity in the dmPFC in the mentalizing task. Thus, differential activity in mentalizing regions, which may interact with the MNS (Forbes, Wang, & Hamilton, 2017; Khalil, Tindle, Boraud, Moustafa, & Karim, 2018; Wang & Hamilton, 2012), may not be unique to ASD.

#### 4.3 | Unique deficits in ASD: Motor simulation deficit during action observation

Many regions that were hypoactive in the ASD group were also hypoactive in the DCD group (compared to TD). Not surprisingly, these were largely motor regions (e.g., supplementary motor cortex, premotor cortex in the imitation and/or mentalizing tasks) and likely reflect motor impairments common to the two clinical groups. Interestingly, only two regions were uniquely hypoactive in ASD. The first region is the left pars orbitalis for mentalizing about all actions. The mentalizing task requires covert speech, and the left pars orbitalis has been strongly implicated in language processing (Bookheimer, 2002; Liakakis, Nickel, & Seitz, 2011). In particular, a recent meta-analysis indicated that the ventral sector of the orbitalis (which overlaps with our peak coordinate) may link emotional and semantic processing (Belyk, Brown, Lim, & Kotz, 2017), which is consistent with our task of mentalizing about emotional and nonemotional actions. Thus

hypoactivity in the left pars orbitalis may reflect deficits linking emotions with semantics, which are common in ASD compared to the other groups (Kinnaird, Stewart, & Tchanturia, 2019).

The second region that is uniquely hypoactive in ASD is the right IFGop during action observation of all actions. As predicted, we find both the ASD and DCD groups show reduced right IFGop activity compared to TD when performing actions (imitation), but only the ASD group shows right IFGop hypoactivity when observing other people's actions (in fact, we see significantly less right IFGop activity in the ASD group compared to either the DCD or TD group). This indicates that, unlike the ASD group, DCD IFGop hypoactivity may be restricted to motor planning or production, rather than for motor simulation/mirroring during action observation, which is consistent with their motor rather than social deficit. Thus, during action observation, the ASD group uniquely shows hypoactivity for motor mirroring in the right IFGop. Indeed, behavioral studies suggest that individuals with ASD compared to TD use less embodied strategies in solving simulation tasks (Conson et al., 2015), especially when their body posture is constrained (Conson et al., 2016). It may be that for the ASD group, the degree of their ability to correctly perform motor actions leads to these simulation impairments. Consistent with these hypotheses, as well as previous reports (Dapretto et al., 2006), we find that autism severity correlates with IFGop activity (but not with the dmPFC).

These results also are consistent with previous electromyographic data suggesting an ASD deficit in activating chained organized motor acts both during action execution and observation (Cattaneo et al., 2007). In that study, when grasping food to eat or observing another do so, individuals with ASD do not show typical patterns of activating the mouth muscles at the onset of the grasping action. Thus, the action's final goal (eating) is not activated at the onset of the action, suggesting that individuals with ASD are not processing the intent of another person's actions. This may account for an ASD deficit in understanding other people's intentions from a non-cognitive first-person perspective (Rizzolatti & Fabbri-Destro, 2010). The current data show that during action observation, this deficit is unique to ASD, and motor simulation deficits do not necessarily arise from general motor deficits. Thus, while individuals with DCD may have motor planning and production deficits, those impairments may not be in chained motor acts, and thus may not arise as embodied simulation deficits. Alternatively, differences between groups may be related to differential involvement of dorsal versus ventral pathways involved in action production versus observation (Borra & Luppino, 2017). Future work will be important in addressing these possibilities.

## 5 | CONCLUSION

Our results indicate that children with ASD show a unique profile of hypoactivation in brain regions that support precognitive motor simulation, and that this deficit interacts with motor skills and may be generalized to a variety of action stimuli. Furthermore, as no previous fMRI studies related brain activity with motor impairment in ASD, these findings may help reconcile prior conflicting reports of MNS dysfunction in

ASD. Finally, by highlighting how ASD symptomatology is related to differential activity in key social neural networks, these results may provide guidance for developing individualized treatment plans.

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## DATA AVAILABILITY STATEMENT

Our data is currently available on the NIH NDAR system.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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