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RESEARCH ARTICLE

Motor, cognitive, and socio-cognitive mechanisms explaining social skills in autism and typical development

Yael Estrugo | Shahar Bar Yehuda | Nirit Bauminger-Zviely

Faculty of Education, Bar-Ilan University, Ramat-Gan, Israel

Correspondence
Nirit Bauminger-Zviely, Faculty of Education, Bar-Ilan University, Ramat-Gan 52900, Israel.
Email: nirit.bauminger@biu.ac.il

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Abstract

Challenges in social functioning are considered a core criterion for diagnosing autism. Although motor skills, executive functioning (EF), and theory of mind (ToM) abilities independently affect social challenges and are interconnected, these abilities' shared contribution to the explanation of social functioning in autism remains under-investigated. To address this disparity, we examined the motor, EF, and ToM abilities of 148 autistic and non-autistic youth (ages 6–16 years), evaluating these variables' impact on social ability and their interconnections. Our mediation model exploring the contribution of motor, EF, and ToM skills explained 85% of the variance in social functioning (Social Responsiveness Scale—SRS-2). Analysis yielded a direct path from study group to SRS-2-social (typically developing-TD > autistic) and two main parallel indirect joint paths: (a) Group → motor → EF → SRS-2-social; and (b) Group → motor → ToM → SRS-2-social. In two secondary indirect paths, autistic children showed lower motor skills, which in turn explained their higher EF and/or ToM impairment, which in turn explained their higher social skills impairment. Put differently, our results suggest that better EF and TOM proficiency may compensate for poorer motor skills. Findings also indicated that the collective impact of motor, EF, and ToM skills on social functioning, along with the mediating role played by EF and ToM on the social-motor linkage, may contribute to understanding individual differences in the social functioning of autistic children. These conclusions call for the inclusion of motor, EF, and ToM activities into daily practices to facilitate social functioning.

Lay Summary

This study investigated the impact of motor skills, executive functioning, and theory of mind (ToM) on autistic children's social functioning. Analyzing 148 children ages 6–16, we found that better social skills were linked with better motor skills, executive functioning, and ToM abilities in both autistic and non-autistic children. Moreover, when jointly combined, these three factors contributed more significantly to better social skills in both groups. Our findings emphasize the importance of incorporating activities targeting these three aspects into autistic children's daily practices, to create possible mechanisms that support social behavior in this population.

KEYWORDS
autism, executive functioning, motor skills, social skills, theory of mind

INTRODUCTION

Many social activities and behaviors involving peers in classrooms or on the playground require gross-motor capabilities (i.e., large muscles in arms, legs, and torso) such as running, chasing, hiding, and jumping as well as fine-motor skills (i.e., smaller hand muscles) such as manual dexterity, reaching, gripping, and manipulating objects during various board and construction games as well as their combination such as in a kick-and-catch ball game. Some motor requirements are more explicit in certain peer-to-peer activities; for example, gross-motor skills are essential for a successful soccer game, whereas the importance of nonverbal movements during conversation (e.g., moving in response to each other, coordinating posture changes, seating position, gestures, facial expressions or head movements) is more implicit. Overall, either explicitly or implicitly, the child's motor functioning is crucial for adaptive social behavior and functioning (e.g., Tschacher, 2018).

"Embodiment" theory best describes the social-motor interlink: Given that human beings make sense of the world through their motor experiences, one's physical body plays a central role in shaping one's experiences, understandings, and interactions in the social world (Klemmer et al., 2006). Body movements are required to fully perceive one's social environment, as when locomotion leads to children's perception of distance from a social partner. Moreover, well-coordinated bodily actions may help not only to improve perception of information from the social surroundings but also may lead to more adequate socially communicative acts during interaction (Adolph & Berger, 2006). Overall, motor development involves the ability to coordinate between gross- and fine-motor movements, which form the basis for a handful of physical activities that are critical for social participation and communication (e.g., Valla et al., 2020).

Challenges in social functioning are one of the two major defining characteristics of autism (autism spectrum disorder; American Psychiatric Association, 2022). Autistic children often encounter difficulties in reciprocating socially, communicating via nonverbal and verbal behaviors, and developing and maintaining social relationships, especially with their age-mates (Zaidman-Zait et al., 2021). Although motor impairment is not considered a core diagnostic criterion for autism, it may provide a distinct explanation for such social difficulties due to its higher prevalence among autistic versus neurotypical children in recent reviews (Bhat, 2020, 2021; Licari et al., 2020; Zampella et al., 2021). Motor difficulties are evident early in autism, at 1.5–2 years (Reynolds et al., 2022; Zhou et al., 2022), in both fine- and gross-motor domains (Liu et al., 2021). Delays in attaining early developmental gross- and fine-motor milestones include walking, jumping, and object grasping (Liu, 2012). Gross- and fine-motor difficulties persist at older ages, manifested in poor balance skills and movement quality (Bhat, 2020; Cho et al., 2022).

Moreover, growing evidence has highlighted the link between motor functioning and social interaction in both autistic and neurotypical children (Bar-Haim & Bart, 2006; Cheung et al., 2022; Estrugo et al., 2023; Fears et al., 2022). A systematic review examining linkages between social and motor skills in autism identified nine studies that reported a positive correlation between overall motor abilities (fine and gross coordination) and social skills test scores within this population (Ohara et al., 2019). For example, Hirata et al.'s (2014) report of manual dexterity difficulties' positive correlation with social deficits, using the Social Responsiveness Scale (SRS) *T*-scores (Constantino & Gruber, 2012), suggested that autistic children (7–16 years) with fine-motor difficulties also display social difficulties. In addition, school-aged autistic children (6–15 years) with better gross-motor skills were found to exhibit better social-communicative skills (MacDonald et al., 2013). Research findings about the associations between social and motor systems and the elevated risk for motor impairment in autism, specifically for those with greater social-communication challenges, call for further exploration of the mechanisms underlying this social-motor link, which may encourage the development of motor-based interventions to enable more efficient motor-skill use during social interactions (Bhat, 2021, 2023; Zampella et al., 2021).

In addition to motor functioning, cognitive and socio-cognitive factors have been pinpointed by a recent systematic review as explaining the social functioning in autism. Specifically, Bottema-Beutel et al. (2019) identified both theory of mind (ToM)—the ability to attribute mental states, beliefs, and intentions to others and to oneself—and executive functioning—the high-order cognitive processes enabling mental control, flexibility, planning and self-regulation—as correlates of social functioning in autism. The effect of ToM and executive functioning (EF) mechanisms' contribution to social functioning was significant but small, leading Bottema-Beutel et al. to suggest future exploration of a more complex theoretical explanation of social functioning in autism that would consider these correlates' possible shared contribution.

To address this recommendation, the current study offers a novel way to explore the social differences in autism, by looking at the collective impact of motor, cognitive (EF), and socio-cognitive (ToM) mechanisms underlying school-age autistic youngsters' social behavior in comparison to typically developing age-mates. Our study was grounded in embodiment theory, suggesting motor actions' close link with cognitive perceptual knowledge, and in Adolph and Hoch's (2019) theory signifying the relations between individuals' motor actions and their social surroundings including the understanding of other minds' perceptual systems. Exploration of these motor, cognitive, and socio-cognitive factors' links and shared contributions may open a new channel of interventions to support social functioning in autism and explore individual differences in its acquisition, possibly leading to a reduction in the sense of loneliness and social isolation reported for school-age autistic children alongside increases in their sense of social belonging, well-being, and quality of life (Kapp, 2018; Kwan et al., 2020; Schiltz et al., 2021).

Motor-embodied pathways to social functioning through EF and ToM

EF and social functioning

Even if EF entails cognitive mechanisms, it is hard to think about everyday social interactive behaviors such as play, collaboration, social participation on the playground, and even conversation without employing EF processes such as inhibiting undesirable social responses, planning social acts, monitoring behaviors, regulating emotions, and shifting attention between various stimuli within social situations (Baggetta & Alexander, 2016). Considering the difficulties demonstrated by autistic individuals compared to neurotypical peers in some of these possibly socially relevant EF processes like inhibition, working memory, shifting, and planning (e.g., Berenguer et al., 2018), researchers have investigated the associations between autistic children's executive dysfunctions and social challenges (Fong & Iarocci, 2020).

Using the BRIEF measure of EF abilities (Behavior Rating Inventory of Executive Functioning; Gioia et al., 2000), poorer initiation and working memory skills were found to be linked with children's increased playground isolation, while poorer planning and organization were linked with lower peer engagement (Freeman et al., 2017). Also, the BRIEF metacognitive index (i.e., planning, monitoring) predicted children's communication, social motivation, and overall social responsiveness (SRS) scores (Constantino & Gruber, 2012; Torske et al., 2018). In Leung et al. (2016), both the BRIEF's metacognitive and behavior regulation (i.e., inhibition regulation) indexes correlated with children's overall SRS score. Links also emerged between EF initiation skills and social knowledge, and between EF self-monitoring skills and social knowledge and social inferencing (Fong & Iarocci, 2020). Lastly, Chien et al. (2023) reported a longitudinal predictive link between SRS social-communication difficulties in childhood (mean age 11.6 years) and future executive dysfunction (on the BRIEF metacognitive and behavioral regulation indexes) in autistic adolescents and young adults. Indeed, research has highlighted various EF components as correlated with various components of social behavior and understanding; however, these studies have not yet concurrently examined more complex mechanisms explaining social functioning that include the child's motor functioning as playing an important role for adaptive social functioning.

EF and motor functioning

Based on embodiment theory, children's perceptions and actions are intertwined, mutually supportive processes, while early motor behaviors lay the foundation for cognitive development and for higher order cognitive processes like EF (Adolph, 2005; Adolph & Berger, 2006). Indeed, emerging evidence provides support for the interlink between EF and motor functioning. Pan et al. (2024) reported more significant associations in autistic versus typically developing individuals, for example, between fine manual control and manual coordination (motor) and cognitive flexibility (EF), and between manual coordination and inhibitory control (EF). For both Taiwanese and American autistic children, Sung et al. (2024) found that total, gross-, and fine-motor skills were linked with working memory (EF). Albuquerque et al. (2022) found that better EF skills (working memory, inhibitory control, cognitive flexibility, mental planning) correlated significantly with better gross-motor performance (walking, running, jumping, galloping, hopping, sliding, leaping, controlling objects), signifying a predictive link between motor competence and global EF scores. Similarly, Liu et al. (2023) showed that autistic children's (8–14 years) better EF (attention, inhibition) correlated significantly with their better fine- and gross-motor functioning. Moreover, studies have demonstrated that a delay in motor development may affect cognitive processes, particularly in disabled children as compared to nondisabled children (e.g., Dyck et al., 2006; Houwen et al., 2016). Based on the embodiment conceptual basis as well on recent findings demonstrating motor-social links and motor-EF links, this study examined embodied (motor) pathways' contribution to social functioning through EF, to provide a more complex understanding of social functioning correlates.

ToM and social functioning

Differences between autistic and neurotypical children's socio-cognitive processes are considered an important factor in explaining the social challenges facing autistic children because they may exhibit a reduced ToM capacity to explain and infer others' viewpoints and intentions, to detect deception and false beliefs, or to intuitively grasp and respond to emotional states in oneself and others (Baron-Cohen et al., 1985). Accordingly, Bishop-Fitzpatrick et al. (2017) found that better scores on second-order ToM tasks (what people think about other people's thoughts) were associated with better social functioning (social adaptive behavior and problem-solving) in autistic children, adolescents, and adults (9–27 years). Devine and Apperly (2022) found that in neurotypical children (ages 8–13 years), scores on advanced ToM tasks (e.g., deception detection) predicted teacher-rated social interaction performance at school, revealing a direct link between understanding others' minds and social competence (e.g., assertion, social play, social sensitivity, and group entry) throughout the school years.

ToM and motor functioning

Motor functioning and social-cognitive processes such as understanding other minds (ToM) may be interlinked. Social interactions require the attunement of body movements during communication between partners, as when walking alongside a peer rather than ahead of or behind them. The way one interprets and casts meaning to a social partner's thoughts and feelings relies heavily on motor behaviors like the partner's gestures during an interaction. Accordingly, recent findings support this bidirectional relation between ToM and motor functioning. Obeid et al. (2022) found that better fine-motor skills correlated with better first-order ToM capabilities (what people think about real events) in school-age typically developing children (6.0–10.8 years), after controlling for age, language, and working memory. Fitzpatrick et al. (2018) reported that spontaneous social-motor synchronic movement with a caregiver correlated positively with first- and second-order ToM abilities in autistic adolescents (12–17 years), suggesting an interesting link between motor coordination and the prediction of others' actions and intentions. Overall, delays in the achievement of motor development's early milestones in autism may limit opportunities for social-cognitive learning and practicing during social situations, while misunderstanding others' social cues may lead to fewer opportunities for motor learning, which depends heavily on the ability to observe and imitate others' behaviors. This interlink between ToM and motor functioning emphasizes the need to explore the impact of both mechanisms on social functioning (Bishop-Fitzpatrick et al., 2017).

Motor, EF, and ToM developmental trajectories

The developmental trajectories of motor, EF, and ToM abilities have not yet been extensively examined in autism. Recent investigations of these factors' developmental trajectories in autistic children reported: an improvement in both fine- and gross-motor proficiency from early school ages (6.0–8.5 years) to adolescence (12–16 years) (Poyas Naharan et al., 2024); maturation of working memory (EF) from adolescence (mean age: 14 years) to young adulthood (mean age: 22 years); maturation of inhibition (EF) from preadolescence (mean age: 12 years) to young adulthood (mean age: 22 years) (Fossum et al., 2021); and improved ToM performance from early to middle childhood in autistic children ages 3–11 years (Peterson & Wellman, 2019). However, for all three factors, the performance gap between autistic and same-age typically developing groups persists across development.

Current study

Beyond embodiment theory viewing children's motor actions and capabilities as an important source for children's interactions with and understanding of the world, this study derived from dynamic system theory (Thelen & Smith, 1994), proposing that a delay and/or interruption in one early developmental mechanism, for example motor skills in autism, may influence the development of other mechanisms such as social cognition (ToM) or higher order cognitive processes (EF). Thus, our main study aim was to explore the integrated contribution of motor-embodied pathways to the understanding of social functioning, through EF and ToM, comparing autistic and non-autistic age-mates. Given that motor functioning lays the foundation for exploring social surroundings in infancy (Holloway & Long, 2019), subsequently followed by the emergence of EF and ToM in early childhood (Austin et al., 2014), we entered motor functioning prior to EF and ToM in our mediation model. Although the reviewed literature demonstrated the separate contributions of motor, EF, and ToM skills to social functioning, little exploration has examined the interplay between these three mechanisms. In addition, for motor skills, EF, ToM, and social skills, we also examined group differences (autism/TD) and age difference (early-school-age/preadolescence/adolescence) to elucidate developmental trajectories and identify possible vulnerable periods in autism versus TD.

Thus, first, we hypothesized lower capabilities in autistic versus TD participants in all study measures, across ages. Second, we expected the autistic group to show less improvement than the TD group in motor, EF, and ToM skills along development (per Fossum et al., 2021; Howlin et al., 2000; Peterson & Wellman, 2019). Third, we hypothesized that children with better motor, EF, and ToM abilities would demonstrate better social skills (per Bhat, 2021; Chien et al., 2023; Devine & Apperly, 2022). Finally, we hypothesized that EF and ToM would mediate the link between motor skills and social skills in both groups (autistic and TD).

METHODS

Participants

Participants were 148 mothers who reported on their autistic ($n = 84$, IQ ≥ 70, 14 girls) and TD ($n = 64$, 16 girls) children's motor, EF, ToM, and social abilities. Mothers of autistic and TD children were matched by chronological age and years of education.

TABLE 1 Participant characteristics and clinical phenotyping.

Background measures		Autistic group $n = 84$			Typically developing (TD) group $n = 64$			Statistical test
		Early-school-age $n = 22$	Preadolescence $n = 30$	Adolescence $n = 32$	Early-school-age $n = 22$	Preadolescence $n = 20$	Adolescence $n = 22$	
Mothers								
Age (years)	*M*	44.55	41.00	41.91	46.23	43.30	44.45	$F(2, 142) = 0.07$, *ns*
	SD	7.05	6.34	4.89	5.96	5.77	5.54	
Education[a]	*M*	5.18	4.72	5.22	5.68	5.65	5.82	$F(2, 141) = 1.22$, *ns*
	SD	1.14	1.25	1.31	0.57	1.14	0.73	
Language	Hebrew	17 (77%)	22 (73%)	24 (75%)	22 (100%)	19 (95%)	19 (86%)	$x^2(5)=10.73$, *ns*
	Bilingual	5 (23%)	8 (27%)	8 (25%)	0 (0%)	1 (5%)	3 (14%)	
Families								
Income[b]	*M*	3.75	4.00	4.25	4.45	4.59	5.00	$F(2, 142) = 0.06$, *ns*
	SD	1.30	1.17	1.10	0.91	1.13	1.27	
Children								
Chronological age (months)	*M*	91.86	120.77	169.91	86.77	127.50	172.09	$F(2, 142) = 2.10$, *ns*
	SD	8.53	12.94	16.89	9.76	11.43	19.16	
Sex	Male	20 (91%)	26 (87%)	24 (75%)	18 (82%)	16 (80%)	14 (64%)	$x^2(1)=1.56$, *ns*
	Female	2 (9%)	4 (13%)	8 (25%)	4 (18%)	4 (20%)	8 (36%)	
Cognitive ability[c] (IQ)	*M*	102.27	109.17	100.94	117.95	108.25	116.82	$F(142) = 1.41$, *ns*
	SD	28.15	32.27	32.46	30.54	20.67	15.24	
Autism severity (ADOS-2: Autism Diagnosis Observation Schedule–2nd ed.)	*M*	7.50	6.70	6.41	—	—	—	$F_{\text{Autism}}(81) = 3.70$, $p < 0.05$, Adolescence > early-school-age
	SD	1.44	1.62	1.34				

[a]Mother's education: 1 = elementary, 2 = high-school, 3 = matriculation, 4 = non-academic higher education, 5 = BA, 6 = MA, 7 = PhD.
[b]Income in New Israel Shekels: 1 = under 5000, 2 = 5001–9000, 3 = 9001–15,000, 4 = 15,001–20,000, 5 = 20,001–25,000, 6 = up to 25,001.
[c]IQ = mean score of Vocabulary and Matrices subtests.

As seen in Table 1, most mothers were monolingual Hebrew speakers, and those from bilingual families were fluent Hebrew speakers. Groups were also matched according to family income (see Table 1). Children in the two groups (autism/TD) spanned three developmental periods: early-school-age (6–8.5 years), preadolescence (8.6–12 years), and adolescence (12–16 years) (see Balasundaram & Avulakunta, 2023). Children's inclusion criteria for the autistic group were an ADOS-2 total calibrated severity score within the autism range (Lord et al., 2012) and Wechsler IQ score above 70 (WISC-IV-HEB, Wechsler, 2010), administered by a clinical psychologist. As seen on Table 1, children in the two groups were matched for chronological age, sex, and cognitive ability. Matching of cognitive ability (IQ scores) between groups derived from the vocabulary (verbal) and matrices (perception) WISC-IV-HEB subtests, which reliably reflected cognitive ability in prior studies (Brezis et al., 2017; Trevisan et al., 2021).

Measures

Motor abilities

Using the 15-item parent-rated Developmental Coordination Disorder Questionnaire (DCDQ; Wilson et al., 2009) for children ages 5–15 years, mothers assessed three categories of their child's motor functioning: (a) gross-motor (six items; e.g., Your child throws a ball in a controlled and accurate fashion; Your child jumps easily over obstacles found in a yard or play environment); (b) fine-motor (four items; e.g., Your child's printing or writing or drawing in class is fast enough to keep up with the rest of the classmates; Your child cuts out pictures and shapes accurately and easily); and (c) general coordination (five items; e.g., Your child is interested in and likes participating in sports or active games requiring good motor skill; Your child is quick and competent in tidying up, putting on shoes, tying shoes, dressing). Mothers rated items on a 5-point scale from Not at all like your child (1) to Extremely like your child (5), with a total motor score of 15–75, where higher scores indicated lesser motor difficulty. The total DCDQ score was used due to its high correlations with its subscales ($r = 0.90$ for gross-motor, $r = 0.78$ for fine-motor, and $r = 0.94$ for coordination, $p < 0.001$). Internal reliability (Cronbach α) for mothers' total DCDQ questionnaire was 0.84.

EF skills

Using the 86-item parent-rated Behavior Rating Inventory of Executive Function (BRIEF; Gioia et al., 2000) for children ages 5–18 years, mothers assessed two domains of their child's EF performance: (a) behavior regulation, comprising inhibition, shifting, and emotional control (e.g., "gets out of control more than friends," $\alpha = 0.95$); and (b) metacognition, comprising initiations, working memory, planning, organization, and monitoring (e.g., "has trouble remembering things, even for a few minutes," $\alpha = 0.97$). Mothers rated items on a scale of 1–3, where lower scores indicated lesser executive dysfunction. Children's standard scores were determined according to their sex and chronological age and ranged from 31 (the lower) to 82 (the highest). Mothers' total BRIEF score was used due to its high correlations with subscales ($r = 0.91$ for regulation, $r = 0.97$ for metacognition, $p < 0.001$), showing good internal reliability of $\alpha = 0.98$. The measure also demonstrated acceptable 3-week test–retest reliability ($r = 0.72$–0.84; Gioia et al., 2000).

ToM skills

The 60-item parent-rated Theory of Mind Inventory (ToMI) for evaluating children's ToM (Hutchins et al., 2012) has been shown to differentiate autistic from TD individuals and to correlate significantly with other teacher-rated and parent-rated measures of social-communication abilities (e.g., Social Responsiveness Scale-2; Vineland Adaptive Behavior Scales-2, Greenslade & Coggins, 2016). Its examination in autistic children and adolescents (3–17 years) showed evidence for ToM challenges along development (Hutchins et al., 2012; Lerner et al., 2011). The ToMI assesses three developmental levels. The 14-item early level (typically at ages 3–5 years) taps ToM skills for understanding relations between another person's intentions/thoughts and actions; describing another's thoughts about real-life events; and applying joint attention skills (e.g., "My child recognizes when someone needs help"). The 23-item basic level (typically at preschool ages, 4–5 years) taps ToM skills for predicting another person's thoughts and actions; constructing mental representations; understanding pretense; and understanding that seeing leads to knowing (e.g., "My child understands that when someone puts on a jacket, it's probably because they are cold"). The 23-item advanced level (typically at early school ages, 6–8 years) taps ToM skills for presenting and detecting deception; social judgment; and understanding sarcasm (e.g., "If it were raining and I said in a sarcastic voice 'Gee, looks like a really nice day outside,' my child would understand that I didn't actually think it was a nice day"). Mothers rated items on a 0–20 scale where higher scores indicated better ToM abilities. Mothers' total ToMI raw score was used due to its significant moderate to high correlations with subscales ($r = 0.49$ for early, $r = 0.97$ for basic, and $r = 0.98$ for advanced, $p < 0.001$), showing internal reliability of $\alpha = 0.93$. Children's overall raw scores were ranged from 7 (the lowest) to 20 (the highest) mean score was 16 with a standard deviation of 3.21.

Social abilities

The 65-item Social Responsiveness Scale-Second Edition (SRS-2; Constantino & Gruber, 2012) is a standardized, norm-referenced, caregiver-rated questionnaire assessing five subdomains of social abilities. For the current study examining mechanisms underlying social deficit, mothers completed only the four social subdomains comprising 53 items—social awareness (eight items, e.g., "Focuses his or her attention to where others are looking or listening"); social cognition (12 items, e.g., "Becomes upset in a situation with lots of things going on"); social communication (22 items, e.g., "Avoids eye contact or has unusual eye contact"); and social motivation (11 items, e.g., "Seems much more fidgety in social situations than when alone")—without the 12-item subdomain of restricted, repetitive behaviors and interests. Mothers rated their child's behavior over the past 6 months on a 4-point Likert scale from Not true (1) to Almost always true (4), with a total SRS-2-social score of 36–98, where lower scores indicated lesser social deficit. Mothers' total SRS-2-social score was used due to its significant moderate to high correlations with subscales ($r = 0.40$ for social awareness, $r = 0.50$ for social cognition, $r = 0.50$ for social communication, and $r = 0.49$ for social motivation, $p < 0.001$), showing high internal reliability of $\alpha = 0.94$. In addition, the SRS-2 showed good test–retest reliability (intraclass correlations = 0.75–0.85; Gau et al., 2013).

Procedure

This study was part of a larger project examining socio-communication and motor links, including several additional measures outside the scope of the current paper. For the larger project, families of 212 children and adolescents (128 autistic, 84 TD) were initially recruited via advertisement of study objectives to parents, colleagues, advocating organizations, and in social media, after receiving approval from the institutional ethics committee. The project participants were clustered to generate dyads of autistic and TD peers with similar ages and IQ levels. Thus, to meet inclusion criteria for the large project, 64 of the initially recruited youngsters were excluded: 30 autistic candidates who showed IQ below 70; and 34 candidates ($n = 14$ autistic, $n = 20$ TD) whose chronological age was 12+ months over their potential partners. After receiving written parental consent, two sessions were held at our autism research laboratory by the research team (including the first and second authors). In the first session, we evaluated participants' autism diagnosis (in the autistic group) and cognitive ability (in both groups). In the second session, their mothers spent approximately an hour completing the four questionaries.

Data analyses

To evaluate group, age, and group × age effects on the mother-rated quality of children's and adolescents' motor (DCDQ), EF (BRIEF), ToM (ToMI), and social (SRS-2-social) abilities, we conducted a series of analyses of variance (ANOVAs). The source of significant group × age interactions was determined using post hoc pairwise comparisons adjusted by Bonferroni's (1936) correction, subject to the $p < 0.05$ rejection criterion.

To examine correlations among the motor, EF, ToM, and social measures, we conducted Pearson correlation tests. To account for possible age effects, Pearson results were compared with partial correlations while controlling for age.

To further understand how the relations between motor skills, EF, and ToM may contribute to social skills, we employed the SPSS add-on PROCESS macro moderated mediation model 81 (Hayes, 2018). This procedure allows for examination of direct and indirect effects of predictor X (study group) on dependent variable Y (SRS-2-social) through the mediation of DCDQ, BRIEF, and ToMI measures, while controlling for age (e.g., Traversa et al., 2023). Significance of the mediation effect was estimated using 95% CI, calculated based on bootstrapping of 5000 samples.

Regarding sex differences, due to small number of girls per each developmental period, we could not compare boys and girls in this study. We repeated all our analyses while controlling for girls, which mirrored our original results.

RESULTS

Group and age differences

To examine differences between study groups (autistic/TD) and between age groups (early-school-age/preadolescence/adolescence) on participants' motor, EF, ToM, and social abilities, we conducted a series of 2 × 3 ANOVA tests for the DCDQ [$F_{\text{study-group}}(1,142) = 131.19$, $p = 0.000$; $F_{\text{age-group}}(2,142) = 0.80$, $p = 0.454$], BRIEF [$F_{\text{study-group}}(1,142) = 211.22$, $p = 0.000$; $F_{\text{age-group}}(2,142) = 1.50$, $p = 0.227$], ToMI [$F_{\text{study-group}}(1,142) = 190.51$, $p = 0.000$; $F_{\text{age-group}}(2,142) = 6.31$, $p = 0.002$], and SRS-2-social scores [$F_{\text{study-group}}(1,142) = 377.41$, $p = 0.000$; $F_{\text{age-group}}(2,142) = 0.12$, $p = 0.886$], respectively. Table 2 presents means and standard deviations for participants' scores, and Table 3 shows the F values and η_p^2 effect size values for the main group and age effects and interaction effects. As predicted, ANOVAs yielded significant main effects for study group across all four measures (DCDQ, BRIEF, ToMI, SRS-2-social) in favor of the TD group versus the autistic group. In contrast, a significant main effect of age beyond study group emerged only for ToMI scores, with adolescents outperforming early-school-age participants.

Due to the fact that our distribution was not normal for the TD group, we reanalyzed our data using a-parametric tests (Mann Whitney for our two study groups' comparisons and Kruskal Wallis for our three age groups' comparisons), which mirrored our ANOVA results.

Interaction effects

As seen in Table 3, study measures revealed different patterns of group by age statistical interactions. For motor skills (DCDQ), the interaction was non-significant [$F(2,142) = 0.45$, $p = 0.636$]. This finding, together with the non-significant age-group effect and significant study-group effect, indicated a consistent difference in motor functioning between TD and autistic groups that did not change with age. For EF skills (BRIEF), the group by age interaction was significant [$F(2,142) = 3.74$, $p = 0.026$], but examination of its source indicated age differences only for the TD study group. Better EF functioning emerged with age in the TD group, where adolescents outperformed early-school-age participants. For ToM skills (ToMI), the group by age interaction was close to significant [$F(2,142) = 2.88$, $p = 0.059$]. Examination of its source indicated significant age differences only for the autistic study group. Better ToM skills emerged with age in autistic participants, where autistic adolescents showed better ToM capabilities than in early-school-age and preadolescence. To be noted, despite improvements in ToM capabilities with age in autism, these adolescents still lagged behind their TD age-mates. Similarly, for social skills (SRS-2-social), the group by age interaction was significant [$F(2,142) = 4.17$, $p = 0.017$], but examination of its source indicated age differences only for the autistic study group. Better social skills emerged with age in the autistic group, where adolescents surpassed preadolescents. Yet again, despite their progress along development, the gap between autistic and TD groups' social functioning remained significant in adolescence.

TABLE 2 Means and standard deviations for mother-rated study variables by study group (autistic/TD) and age group (early-school-age/preadolescence/adolescence).

Study measures		Autistic ($n = 84$) Early-school-age ($n = 22$)	Autistic Preadolescence ($n = 30$)	Autistic Adolescence ($n = 32$)	Typically developing (TD) ($n = 64$) Early-school-age ($n = 22$)	TD Preadolescence ($n = 20$)	TD Adolescence ($n = 22$)
Motor (DCDQ)	*M*	46.82	42.40	43.19	65.73	65.65	64.00
	(*SD*)	(13.16)	(9.95)	(14.21)	(7.16)	(6.59)	(10.78)
Executive (BRIEF)	*M*	64.45	67.53	64.03	42.82	43.85	49.00
	(*SD*)	(9.19)	(9.35)	(8.73)	(6.09)	(6.05)	(8.76)
Theory of mind (ToMI)	*M*	13.18	13.16	15.15	17.99	18.98	18.96
	(*SD*)	(2.28)	(2.48)	(2.74)	(1.62)	(0.88)	(1.16)
Social (SRS-2-social)	*M*	71.36	74.57	68.72	43.23	41.30	45.50
	(*SD*)	(10.55)	(9.72)	(10.38)	(4.79)	(4.22)	(8.44)

Abbreviations: BRIEF, Behavior Rating Inventory of Executive Function; DCDQ: Developmental Coordination Disorder Questionnaire; SRS-2-Social, four social subdomains of Social Responsiveness Scale; ToMI: Theory of Mind Inventory.

TABLE 3 F values and η_p^2 effect size values for mother-rated study variables' main effects and interaction effects.

Study measures	Study group F (1,142) (η_p^2)	Age group F (2,142) (η_p^2)	Age-group differences with Bonferroni correction	Study-group by age-group interaction F(2,142) (η_p^2)	Age-group differences with Bonferroni correction
Motor (DCDQ)	131.19*** (0.48)	0.80 (0.01)	-	0.45 (0.01)	-
Executive (BRIEF)	211.22*** (0.60)	1.50 (0.02)	-	3.74* (0.05)	$Adol_{TD}$ > $Early_{TD}$
Theory of mind (ToMI)	190.51*** (0.57)	6.31** (0.08)	Adol > Early	2.88† (0.04)	$Adol_{Autistic}$ > $Early_{Autistic}$, $Preadol_{Autistic}$
Social (SRS-2-social)	377.41*** (0.73)	0.12 (0.002)	-	4.17* (0.06)	$Adol_{Autistic}$ < $Preadol_{Autistic}$

Abbreviations: Adol, adolescence; BRIEF, Behavior Rating Inventory of Executive Function; DCDQ, Developmental Coordination Disorder Questionnaire; Early, early-school-age; Preadol, preadolescence; ToMI, Theory of Mind Inventory; SRS-2-Social, four social subdomains of Social Responsiveness Scale.
*p <0.05.
**p < 0.01.
***p < 0.001.
†p < 0.06.

Correlations

Pearson and partial correlation tests (controlling for chronological age) were computed among the study variables for each group. As seen in Table 4, in both study groups, both with and without controlling for age, the SRS-2-social measure revealed significant correlations with the other three measures (negatively with DCDQ and ToMI and positively with BRIEF). Thus, better social skills were linked with better motor, EF, and ToM skills in both study groups.

Mediation model for social skills

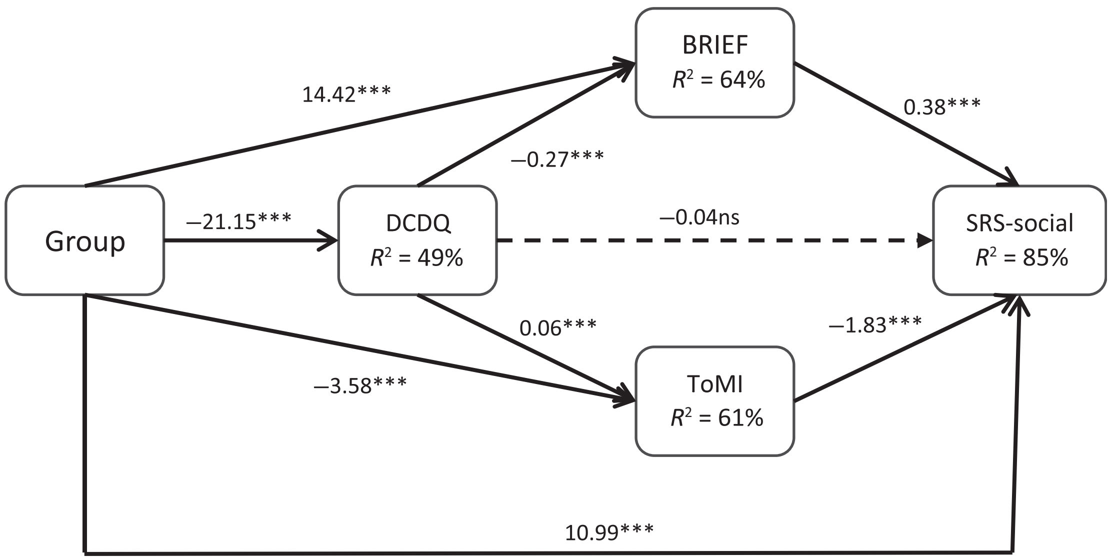
Using PROCESS macro mediation model 81 (Hayes, 2018), we examined how relations between motor, EF, and ToM measures may mediate the study groups' link with social skills (see Figure 1, Table 5). Mediation analysis indicated a significant group effect (autistic/TD) on SRS-2-social via DCDQ in the first step and via BRIEF and ToMI in the second step. Study group directly explained differences in children's social abilities ($B = 10.99$, $p < 0.001$). However, complementary explanations of study groups' relations with SRS-2-social scores pinpointed several significant indirect effects. The joint mediation effects of children's motor ability together with their EF emerged (indirect Path 4, $B = 2.16$, 95% CI [1.06, 3.41]), as well as a parallel indirect path of motor ability together with socio-cognitive ToM skills (Path 5, $B = 2.17$, 95% CI [0.93, 3.79]) in the second stage. Thus, children's social skills were explained by the direct path from group and also by these two main indirect paths (4 and 5).

These variables appeared to explain social functioning in different ways. The direct path indicated a significant difference in social functioning between study

TABLE 4 Pearson correlation and partial correlation tests between SRS-2-Social, DCDQ, BRIEF, and ToMI, with and without controlling for age.

	Social (SRS-2-social)			
	Pearson correlation		Partial correlation controlling age	
	Autism	Typically developing	Autism	Typically developing
Motor (DCDQ)	−0.30**	−0.25*	−0.32**	−0.25*
Executive (BRIEF)	0.52***	0.69***	0.52***	0.70***
Theory of mind (ToMI)	−0.65***	−0.39**	−0.64***	−0.44***

Abbreviations: BRIEF, Behavior Rating Inventory of Executive Function; DCDQ: Developmental Coordination Disorder Questionnaire; SRS-2-Social, four social subdomains of Social Responsiveness Scale; ToMI: Theory of Mind Inventory.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.



*** p<.001.

FIGURE 1 Mediation Model 81 for Direct and Indirect Relations Between Group (Autistic/TD) and Social Skills (SRS-2-Social) via Motor (DCDQ), Executive (BRIEF), and Theory of Mind (ToMI) Skills, Controlling for Age ($N = 148$). ***$p < 0.001$. BRIEF, Behavior Rating Inventory of Executive Function; DCDQ: Developmental Coordination Disorder Questionnaire; SRS-2-Social, four social subdomains of Social Responsiveness Scale; ToMI: Theory of Mind Inventory. Direct effect: Group → SRS-2-social: C' = 10.99***. Indirect effects: Path 1, Group → DCDQ → SRS-2-social: $a_1*b_1 = 0.75$, ns. Path 2, Group → BRIEF → SRS-2-social: $a_2*b_2 = 5.53$ significant. Path 3, Group → ToMI → SRS-2-social: $a_3*b_3 = 6.54$ significant. Path 4, Group → DCDQ → BRIEF → SRS-2-social: $a_1*a_4*b_2 = 2.16$ significant. Path 5, Group → DCDQ → ToMI → SRS-2-social: $a_1*a_5*b_3 = 2.17$ significant.

groups, where the TD group presented better performance than the autistic group. The indirect Path 4 indicated that autistic children showed lower motor skills, which in turn explained their higher EF impairment, which in turn explained their higher social skills impairment. The indirect Path 5 indicated that autistic children showed lower motor skills, which in turn explained their lower ToM abilities, which in turn explained their higher social skills impairment.

In addition, as seen on Figure 1 and Table 5, two secondary significant paths contributed to the explanation of children's SRS-2-social score: Paths 2 and 3. The indirect Path 2 from study group through the BRIEF to the SRS-2-social measure ($B = 5.53$, 95% CI [3.08, 8.32]) suggested that autistic children showed higher EF impairment, which in turn explained their higher social skill impairment. The indirect Path 3 from study group through the ToMI to the SRS-2-social measure ($B = 6.54$, 95% CI [4.31, 9.15]) suggested that autistic children showed lower ToM, which in turn explained their higher social skills impairment. Overall, the model explained 85% of variance in children's social functioning.

TABLE 5 Indirect relations (mediation model 81) between group (autistic/TD) and social skills (SRS-2-Social) via motor (DCDQ), executive (BRIEF), and theory of mind (ToMI) skills, controlling for age ($N = 148$).

	B	SE	*t*	*p*	95% CI Lower	95% CI Upper
DCDQ predicted by group						
Group	−21.15	1.81	−11.68	0.000	−24.73	−17.57
BRIEF predicted by group and DCDQ						
Group	14.42	1.84	7.82	0.000	10.78	18.07
DCDQ	−0.27	0.06	−4.39	0.000	−0.39	−0.15
ToMI predicted by group and DCDQ						
Group	−3.58	0.47	−7.67	0.000	−4.51	−2.66
DCDQ	0.06	0.02	3.65	0.000	0.03	0.09
SRS-2-social as predicted variable						
Group	10.99	1.88	5.84	0.000	7.27	14.72
DCDQ	−0.04	0.05	−0.67	0.506	−0.14	0.07
BRIEF	0.38	0.07	5.27	0.000	0.24	0.53
ToMI	−1.83	0.29	−6.36	0.000	−2.39	−1.26
Conditional indirect effects						
Path 1	0.75	1.24	-	-	−1.52	3.28
Path 2	5.53	1.35	-	-	3.08	8.32
Path 3	6.54	1.22	-	-	4.31	9.15
Path 4	2.16	0.60	-	-	1.06	3.41
Path 5	2.17	0.73	-	-	0.93	3.79
Total	17.15	1.95	-	-	13.28	21.07

Note: Path 1: Group → DCDQ → SRS-2-social; Path 2: Group → BRIEF → SRS-2-social; Path 3: Group → ToMI → SRS-2-social; Path 4: Group → DCDQ → BRIEF → SRS-2-social; Path 5. Group → DCDQ → ToMI → SRS-2-social.
Abbreviations: BRIEF, Behavior Rating Inventory of Executive Function; DCDQ: Developmental Coordination Disorder Questionnaire; SRS-2-Social, four social subdomains of Social Responsiveness Scale; ToMI: Theory of Mind Inventory.

DISCUSSION

The main contribution of the current study is its novel demonstration of the multiplex connections underlying adaptive social functioning in both autistic and TD youngsters, revealing possible sources of individual differences and novel intervention directions including through the motor channel. As predicted, two motor-embodied indirect pathways to adaptive social functioning were found, one through cognitive EF processes and the second through socio-cognitive ToM processes. These two pathways coincide with our embodiment conceptual basis, which highlights body-motor experience as the foundation for the development of cognitive (EF) and socio-cognitive (ToM) knowledge and abilities (e.g., Klemmer et al., 2006), but also indicate the mutual reciprocal relationships between body-motor experiences and each of these two correlates of social functioning (Adolph & Hoch, 2019).

The significance of motor skills in social interaction and their impact on early development are well established in the literature (Bar-Haim & Bart, 2006; Estrugo et al., 2023). The current study supports this social-motor connection and proposes a model elucidating mechanisms underlying social functioning, where motor skills alone are insufficient to account for social proficiency. Instead, EF skills like planning, control, flexibility, working memory, and emotional regulation, along with ToM abilities involving empathy, understanding intentions and desires, and anticipating others' reactions, appear to act as crucial mediators bridging the gap between motor skills and social functioning. According to our model, EF and ToM development depends on motor skills' development, emphasizing the shared contribution of these three factors to social skills.

The collective impact of this multiplex model (Path 4 showing Group → DCDQ → BRIEF → SRS-social and Path 5 showing Group → DCDQ → ToMI → SRS-social) may provide a theoretical framework to explain a vast number of social interactive conditions that explicitly involve integration between social and motor capabilities, such as various ball games, group activities, and dyadic interactions that are very common throughout development. Children with autism show specific difficulty during such activities, suggesting that these multiplex relations between motor, EF, and ToM abilities may help unpack their social functioning.

Let's illustrate this complexity with the example of complex social-motor interactions during a soccer game (Ribeiro et al., 2017). While proficient motor skills are essential for adequate participation in such group activity, alone they prove insufficient. Beyond motor proficiency, soccer team players must strategize their movements in accordance with game rules (EF), regulate their emotional and behavioral responses (EF), adapt to rapidly changing situations (EF), interpret opponents' intentions (ToM), and anticipate teammates' maneuvers (ToM). Accordingly, the concurrent activation of all three factors together—motor, EF, and ToM—enables children to navigate and excel in their shared play.

Nonetheless, due to the mutual interrelations among these three factors, the opposite direction of events is also possible. That is, in the case of lower motor skills as characterizing the autism group, stronger EF and/or ToM capabilities may provide compensatory mechanisms for adaptive social functioning. For example, if children's EF skills are facilitated, like flexible thinking, ability to plan ahead, or regulation of emotions, these may be associated with improvements in the children's abilities for motor learning and motor planning. By the same token, if children's mentalizing processes (ToM) are strengthened, they may be able to better regulate and synchronize their motor actions with another partner, thereby leading to improvement in many types of socio-motor activity and play situations (e.g., hide and seek, Simon says, dodgeball, group rope skipping). These common social experiences require children's integration of motor actions with the anticipation and prediction of others' behavior. As such, strengthening both EF and ToM may correlate with improved motor functioning, while serving as two alternative compensatory mechanisms to adaptive social functioning.

Furthermore, results of the mediational model also revealed two indirect paths from study group to social functioning that bypass the motor channel: Path 2 through EF (Group → BRIEF → SRS-social) and Path 3 through ToM (Group → ToMI → SRS-social). These paths may reflect various social interactive experiences that do not heavily depend on motor qualifications, such as card games or board games that physically require only rolling dice, moving pieces, pulling cards, and handling paper money. Yet, such games do require EF skills to plan actions (e.g., decide in which order to make moves in the game) and inhibit responses (e.g., hide one's cards), and they also necessitate ToM skills like recognizing bluffing or predicting other players' possible future moves (e.g., in tic-tac-toe, checkers) to successfully complete the game.

Taken together, the various direct and indirect paths to social functioning that were discovered through the mediational model may lead to better, more accurate understanding of the various correlates underlying social functioning across diverse social contexts and experiences. These paths may also offer compensatory mechanisms to achieve successful and adaptive social functioning as described. Future studies would do well to map the type of social situation more closely to its unique underlying mechanism/s, to obtain a more complex understanding of social functioning and its correlates.

Our findings hold important theoretical and practical implications. Theoretically, past studies and the current findings indeed showed that motor skills (e.g., Ohara et al., 2019), EF abilities (e.g., Freeman et al., 2017), and ToM capabilities (Bishop-Fitzpatrick et al., 2017) are each important ingredients of social functioning. Yet, the current study extended prior research by demonstrating these factors' shared contribution and alternative paths leading to social improvement. Practically, the present findings suggest that children's strengths in EF and/or TOM may be used as channels for promoting progress in adaptive social functioning while compensating for deficits in motor skills.

As expected, our exploration of group and age differences for social functioning and for its underlying mechanisms revealed consistent study group differences, namely, the TD group exhibited better performance than the autism group. To be noted, developmental growth did occur in the autism group, for ToM abilities and social abilities, but it did not reach the adaptive level of functioning shown by TD age-mates. These findings coincide with the American Psychiatric Association (2022) definition of autism and with former studies reporting this group's challenges versus TD (e.g., Estrugo et al., 2023). However, our mediation results emphasize the need to find alternative paths to promote improvements in social functioning in autism.

Our study also has several limitations. Utilization of total scores for study measures was justified statistically and enabled a reduced data load; however, further studies should look beyond general categories and screen out specific EF components or ToM complexity levels that contribute to more efficient social functioning either through the motor channel or not. Despite our large sample, its size did not permit examination of these EF and ToM specifics. Moreover, it should be noted that directionality or causality of observed relations between the variables of interest should be carefully taken into consideration due to the concurrent correlational study design, but in our interpretation, we emphasized the importance of the bi-directional relations between our correlates to the explanation of social functioning.

In addition, this study collected parents' reports about children's social functioning using the SRS-2 questionnaire, which is well-documented in autism research; however, direct observation of children's interactive spontaneous peer activities, EF, ToM, and motor capabilities may add important information to complement parents' reports and provide more objective information because parents' subjective reports may be biased or incomplete. Finally, to gain a more comprehensive understanding of children's social, motor, socio-cognitive, and cognitive skills, future studies should also include fathers' and not only mothers' reports, as well as a larger number of girls and also autistic participants with IQs lower than 70.

In conclusion, in light of the hallmark social challenges in autism and their possible consequences for poor adaptation and higher levels of social isolation and depression (Schiltz et al., 2021), our findings offer alternative routes toward promoting social functioning through children's motor, cognitive, and socio-cognitive channels, while opening routes for understanding the contribution of individual differences in these abilities for social success.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Participant's parents. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the author(s) with the permission of Participant's parents.

ETHICS STATEMENT

The study involving humans were approved by the Faculty of Education Ethics Committee. The study were conducted in accordance with the local legislation and institutional requirements. The participants' legal guardians/next of kin provided written informed consent for participation in this study.

ORCID

Nirit Bauminger-Zviely https://orcid.org/0000-0002-8153-3575

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