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ORIGINAL PAPER

Social-Motor Coordination Between Peers: Joint Action Developmental Trajectories in ASD and TD

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Abstract
Coordinating a physical movement in time and space with social and nonsocial partners to achieve a shared goal – "joint action" (JA) – characterizes many peer-engagement situations that pose challenges for individuals with autism spectrum disorder (ASD). This cross-sectional study examined development of JA capabilities comparing ASD versus typically developing (TD) groups in early childhood, preadolescence, and adolescence while performing mirroring and complementing JA tasks with social (peer) and nonsocial (computer) partners. Results indicated better motor coordination abilities on computerized tasks than in peer dyads, with larger peer-dyad deficits shown by the ASD group. Developmental growth in JA abilities emerged, but the ASD group lagged behind same-age peers with TD. Socio-motor interventions may offer new channels to facilitate peer engagement in ASD.

Keywords Joint action · Peer interaction · Autism · Interpersonal coordination · Motor movements

Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental disorder with core deficits in social communication and with restricted and repetitive behaviors (American Psychiatric Association – APA, 2013). Social interaction, mainly with peers, is considered a challenge for individuals with ASD, beyond age and functioning level (APA, 2013). A substantial body of research has investigated various aspects of peer interaction in ASD, such as social cognition, social attention, social motivation, and socio-emotional functioning (see review in Bauminger-Zviely, 2013). However, the role of dyadic motor coordination in body movement during peer interaction in ASD has not been well explored, notwithstanding that engagement in social interaction requires a full repertoire of co-regulated body movements and that children with ASD demonstrate motor coordination impairments (Emanuele et al., 2021; Licari et al., 2020; Zampella et al., 2021). The current study focused uniquely on the exploration of motor coordination within ecologically relevant peer-to-peer interactions, to narrow this gap in the literature.

The social interactions whereby "two or more individuals coordinate their actions in space and time to bring about a change in the environment" are called joint actions (JAs) (Sebanz et al., 2006, p. 70). Many everyday life activities, especially social interactions between peers, require the ability to coordinate one's own motor movements with those of another individual, such as handing over toys or receiving objects, building a shared block structure, playing catch, tag, or hide-and-seek, walking side by side, and playing organized games like basketball (Cheng et al., 2020; Lampi et al., 2020). Such shared social-motor activities may contribute to participants' sense of social cohesiveness and joint agency (Shiraishi & Shimada, 2021; Wiltermuth & Heath, 2009). Considering that coordinated movements are important building blocks of every interaction, this socio-cognitive-motor ability can (consciously or not) shape social engagement with peers (Honisch et al., 2021; van der Wel et al., 2021).

For children and adolescents with ASD, characteristic social and motor difficulties, poor theory-of-mind abilities, and failure to exchange sensory-social-emotional information with same-age peer partners may affect their movement coordination in time and space during social interaction (McNaughton & Redcay, 2020). Deficiencies in perceiving and responding to the rhythms of social and motor exchanges along development may have serious

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consequences on the ability to adequately participate in such interactions and thereby to capitalize on such experiences in order to develop adequate peer interaction skills. Indeed, recent research reviews (Cerullo et al., 2021; McNaughton & Redcay, 2020) examining JA performed with a social partner clearly revealed lower social-motor coordination in persons with ASD compared to those with typical development (TD). However, most prior JA studies in ASD did not implement comprehensive cross-sectional examination at different developmental stages and, importantly, focused mainly on an adult as the social partner rather than on interactions with peers, which could be more demanding than when adult caregivers or experimenters scaffold the interaction (Hay et al., 2009; Trevisan et al., 2021).

Characteristics of Joint Action Tasks

The performance of JA during social interaction involves social and prosocial behaviors like sharing, joint attention, and turn-taking; social-cognitive abilities like mentalization of others' intentions or understanding of physical actions; and motor skills such as gross or fine motor planning or both, depending on the action goal at hand (Cerullo et al., 2021; Emanuele et al., 2021; Howard et al., 2021; Vesper et al., 2017). Gross motor movements (e.g., ball playing, galloping) are performed via the large muscles, limbs, and torso, while fine motor movements (e.g., gripping and typing) are performed via the small muscles, hands, and fingers (Payne & Isaacs, 2020). The ability to coordinate between gross and fine motor movements can enhance awareness of and reaction to a social partner's actions, forming a strong base for social participation in interactive activities (Valla et al., 2020). The foundation for JA performance during social interaction rests on both motor planning and motor control (Azaad et al., 2021; Sebanz et al., 2005). Motor planning is the ability to think through and act upon a plan for motion in the correct sequence from beginning to end (Wang et al., 2020). Motor control includes the ability for feedforward control – anticipating the social partner's action – and feedback control – adjusting and timing one's own action accordingly (Seidler et al., 2004). Recent ASD studies and reviews have indicated significant motor impairments in both fine and gross motor coordination (e.g., poor upper-limb and lower-limb coordination, grip planning, reaching, grasping) along with inefficient motor planning and misuse of feedforward and feedback motor control mechanisms (Bhat, 2020, 2021; Licari et al., 2020; Mosconi et al., 2015; Zampella et al., 2021).

Furthermore, JA success depends on both partner's abilities to share mental-motoric representations, namely, to observe and assimilate the partner's actions in their minds (Vesper et al., 2017). This social-cognitive-motor process is supported by a social-cognitive mechanism – theory of mind – which enables the attribution and prediction of beliefs, intentions, and emotions in self and others (Scheeren et al., 2013). This mentalization mechanism provides the means for each JA participant to simulate, correct, and predict the partner's movements. Successful JA also requires both partners' exchange of sensory, social, and emotional cues using their bodies (Pezzulo et al., 2019). This involves both partners' accurate communication and interpretation of facial expressions, gestures, postures, and bodily maneuvers. Cognitively able children and adolescents with ASD often exhibit poor theory-of-mind abilities, thus misinterpreting and failing to predict their partner's mental states, intentions, non-communicational signals, and actions, particularly during social engagement (Andreou & Skrimpa, 2020).

The performance of JA during social interaction requires both partners to know *what*, *when*, and *where*. *What* refers to predictions about the kind of action the partner will perform and the intention driving that action (Sebanz & Knoblich, 2009). *When* is the requirement to keep pace with the partner's motions during joint coordination (Schmidt et al., 2011). *Where* relates to each JA partner's effort to effectively distribute common space, avoid collisions, and optimize their movement paths (Sebanz & Knoblich, 2009). Both JA partners then need to share mental-motor representations, predict the other's actions, and plan their own movements in relation to the other's predicted actions (Knoblich & Sebanz, 2008). However, the activation of these social-motor features is reduced among individuals with ASD (Bowsher-Murray et al., 2022).

JA has two manifestations: mirroring and complementing (Noy et al., 2011; Sebanz et al., 2006). Mirroring emerges when one partner imitates, resonates, or "mirrors" the other partner's actions and movements; thus, both partners perform the same action congruently such as when two children coordinate their side-by-side walking in rhythm and space. A "complementary" body movement develops when one partner harmonically responds to and complements the other partner's movements; thus, partners' behaviors are incongruent but coordinated such as moving in opposite directions while crossing a narrow space or playing throw-and-catch with a ball (Wheatley et al., 2012; Zampella et al., 2020). Complementary JA may be achieved if activation of body-motor representations following observation is suppressed by a joint goal, so that one can perform actions dissimilar from those observed (Rosso et al., 2021). Both JA task manifestations – mirroring and complementing – require the ability to predict the partner's future actions and to plan one's own actions based on that prediction (Colling et al., 2013; Sinha et al., 2014).

Joint Action Across Development

In TD, JA abilities improve with age from childhood through adulthood (Endedijk et al., 2015; Ilari et al., 2018; Kirschner & Tomasello, 2009; McAuley et al., 2006). The development of JA in TD seems to start during the first year of life, as infants gain the ability to coordinate focused attention with another person, appears to continue developing as toddlers begin to integrate actions in their own repertoire with others' actions around age 3 years, and continues to grow as children start to flexibly accommodate a partner's actions from the age of 5 years (Cerullo et al., 2021). This developmental growth continues into adulthood, and indeed, shared drumming was found to be more accurate in TD young adults (20–30 years) than in preadolescents (Kleinspehn-Ammerlahn et al., 2011).

Empirical investigation of JA development for individuals with ASD has been scarce, despite research indicating impairments and delays in the development of social and motor abilities in ASD (Wilson et al., 2018). Few studies have examined links between chronological age and JA in the ASD population. For example, in children with ASD ages 3–8 years, Marsh et al. (2013) found a positive correlation between older chronological age and better performance on a side-by-side rocking JA mirroring task with an adult social partner (their caregiver). In addition, Xavier et al. (2018) reported significant improvement with age on a nonsocial tightrope JA mirroring task performed with a virtual human image, where adolescents (12–19 years) outperformed children (6–12 years) with ASD (IQ > 70).

Joint Action With Social Partners

Studies examining JA task performance in youngsters with ASD compared to TD at various ages have varied in their task partner, including adult, peer, and inanimate partners. The very rare studies that have directly examined peer-to-peer JA performance among children and adolescents demonstrated a clear advantage of the age-matched TD group over the ASD group. In Trevisan et al. (2021), this disadvantage for youngsters with ASD emerged as a lower number of coordinated steps and longer performance time for children ages 6–12 years with ASD (IQ > 70) compared to children with TD when carrying a table in a maze jointly with a peer partner. In Stoit et al. (2011), children and adolescents with ASD (8–18 years; IQ > 70) showed less adaption to, consideration of, and prediction of the peer's actions when jointly lifting a virtual bar using a computer joystick, compared to the TD group.

A substantial body of extant research on JA with adult social partners has yielded the same pattern of findings whereby children and adolescents with ASD showed poorer JA performance compared to age-matched participants with TD when coordinating movement with an adult, across various ages. Examples of such coordinated adult–child action included rocking side-by-side (Marsh et al., 2013), placing a banana card on a moving monkey card (Fulceri et al., 2018), tapping and pat-a-cake playing tasks (Fitzpatrick et al., 2017a; Lampi et al., 2020); swinging a pendulum (Fitzpatrick et al., 2016); and face-to-face handholding and body-swaying (Su et al., 2021). Importantly, the performance of the maze task with an adult experimenter partner in Trevisan et al. (2021) showed a lower gap between the TD and ASD groups than that found with a peer partner, emphasizing peer-interaction challenges for youngsters with ASD, and requiring further examination.

Joint Action with Nonsocial Partners

Even though not many ASD studies have examined the differences between a social partner (i.e., adult) and nonsocial partner (metronome, computer) in JA tasks, the available findings have indicated better coordinating abilities with a nonsocial partner. For example, the drumming of children and adolescents with ASD (11–16 years; IQ > 70) was less asynchronous when performed with a rhythmic cueing partner (metronome) than with an adult experimenter (Yoo & Kim, 2018). Similarly, the swaying movement of children and adolescents with ASD ($M = 12$ years; IQ > 70) was less coordinated when performed with an experimenter than with a nonsocial stimulus – an oscillating bar displayed on a screen (Su et al., 2021). Also, adults with ASD (18–42 years; IQ > 70) were less able to modulate their gripping movement with the movement of a same-age TD partner than with a nonsocial stimulus – a dot displayed on a computer screen (Curioni et al., 2017).

Furthermore, the majority of studies that examined JA tasks (e.g., tapping, swaying, and drumming) only with a nonsocial partner (metronome or a computer) demonstrated preserved JA abilities in ASD compared to TD (de Bruyn et al., 2011; Koehne et al., 2016; Su et al., 2021; Tryfon et al., 2017). However, other research studies have indicated contradicting evidence, where children and adolescents with ASD demonstrated lower JA performance (e.g., shared hand clapping and drumming, coordinated tightrope walking) with a nonsocial partner compared to same-age peers with TD (Kaur et al., 2018; Xavier et al., 2018). Overall, these mixed findings call for further exploration to better assess the breadth of the JA coordination deficit in ASD.

Unlike the ASD group, a clearer pattern of findings is available from JA studies on partner effects in TD, favoring social partners over nonsocial partners. For example, among children (2–4.5 years) and preadolescents (7–10 years) with TD, less accurate shared drumming emerged with a metronome (nonsocial partner) than with a peer social partner (Ilari et al., 2018; Kirschner & Tomasello, 2009).

Current Study Objectives

Taken altogether, the body of available prior research lends some support for a JA deficit in individuals with ASD compared to peers with TD. Although youngsters with ASD have well-documented social-communication and motor deficits (APA, 2013; Bhat, 2020), current understanding remains very limited about the scope of their deficit in coordinating motor movements with a partner, especially in the highly demanding everyday contexts of peer-to-peer interaction. Likewise, little is known about the development of JA abilities with age in ASD. Thus, the current study undertook a novel comprehensive examination of JA development at ages considered to be critical for potential motor coordination failures in ASD, from early childhood to adolescence. The explicit focus on joint motor coordination with peers rather than with adults at different developmental periods may lead to more personalized interventions to facilitate deficient peer interactions in ASD.

The previously inconclusive findings regarding nonsocial JA also call for further research to assess if this coordination deficit goes beyond partner and manifests not only in interactions with a live peer (social) partner but also with a computer-based (nonsocial) partner. Finally, prior empirical evidence remains insufficient as to whether this coordination deficit manifests beyond task, across both types of JA tasks based on theory-of-mind abilities (Sebanz et al., 2006): mirroring (performing the same action) and complementing (performing a different reactive action).

Therefore, this study aimed to comprehensively explore the similarities and differences in JA performance between two study groups (ASD vs. TD) in relation to three developmental groups (early childhood vs. preadolescence vs. adolescence) while comparing two JA partners (social peer vs. nonsocial computer) and comparing two types of JA tasks (mirroring vs. complementing). With regard to group, we predicted better coordinated movement with a social partner (peer) in the TD group than in the ASD group. Regarding partner, within the TD group, we predicted better coordinated movement with the social compared to the nonsocial partner. Due to the paucity of relevant empirical literature, we did not formulate a prediction for the direction of social versus nonsocial partners in the ASD group. With regard to development over age, we predicted JA growth with age in both study groups and with both social and nonsocial partners, although prior research on JA development in ASD has been very limited. Finally, due to the lack of previous data looking specifically at the differences between mirroring and complementing in ASD and TD, we did not formulate a hypothesis for JA tasks. Appendix A presents this theoretical model.

Method

Participants

Participants were 148 children and adolescents (118 males, 30 females) ages 6–16 years in two study groups: 84 cognitively able participants with ASD (IQ $\geq$ 70) and 64 participants with TD. Each study group consisted of three age groups (early childhood, preadolescence, adolescence). Inclusion criteria for the ASD group were: (a) a score within the ASD range on the Autism Diagnosis Observation Schedule (ADOS—2nd edition, Lord et al., 2012), administered by the first author, and (b) a score of 70 + on the Wechsler (WISC-IV-HEB, 2010), administered by a clinical psychologist. Participants in the TD group were matched to the ASD group on chronological age, sex, mother's education, and cognitive ability. Cognitive ability in the TD group was assessed using the mean IQ score from two WISC-IV-HEB subtests, vocabulary (verbal) and matrices (perception), which prior studies demonstrated as reliably reflecting cognitive ability (Brezis et al., 2017; Trevisan et al., 2021). See Table 1 for participants' details.

Measures

This study's six mirroring and complementing JA tasks comprised four social tasks and two nonsocial tasks, developed based on the literature examining joint walking, improvisation, and drumming (Cheng et al., 2020; Kirschner & Tomasello, 2009; Noy et al., 2015; Van der Wel et al., 2021) and on the results of a pilot study (see Appendix B). The four social JA tasks with a peer partner included two mirroring tasks (walking; hand & body) and two complementing tasks (corridor; soccer). Participants performed these four social tasks in peer dyads that were matched by sex, chronological age (no more than 12 months between partners), and cognitive ability (no more than one standard deviation between partners). Each social task was performed twice, each lasting 30 s, to enable the participants to change roles as leaders and followers. Sequence of partners' turns in the dyad was counterbalanced across the tasks. The two nonsocial JA tasks involved interacting with a computer, including one mirroring task (triangle) and one complementing task (ping-pong). Each nonsocial task was performed once, for 30 s.

Table 1 Participant characteristics and clinical phenotyping

Background measures		ASD group $n=84$			TD group $n=64$			Statistical test
		Early childhood $n=22$	Pre-adolescence $n=30$	Adolescence $n=32$	Early childhood $n=22$	Pre-adolescence $n=20$	Adolescence $n=22$	
Chronological age	*M*	91.86	120.77	169.91	86.77	127.50	172.09	$F(142)=2.10$
	SD	8.53	12.94	16.89	9.76	11.43	19.16	
Mother's education[a]	*M*	5.18	4.72	5.22	5.68	5.65	5.82	$F(141)=1.22$
	SD	1.14	1.25	1.31	0.57	1.14	0.73	
Sex	Male	20 (91%)	26 (87%)	24 (75%)	18 (82%)	16 (80%)	14 (64%)	$x^2(1)=1.56$
	Female	2 (9%)	4 (13%)	8 (25%)	4 (18%)	4 (20%)	8 (36%)	
Cognitive ability[b] (IQ)	*M*	102.27	109.17	100.94	117.95	108.25	116.82	$F(142)=1.41$
	SD	28.15	32.27	32.46	30.54	20.67	15.24	
ASD severity (ADOS)	*M*	7.50	6.70	6.41				$F_{ASD}(81)=3.70$* Adolescence > Early childhood
	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]In TD group, mean score of vocabulary and matrices subtests

*$p < .05$

To assess participants' JA performance, percentages of coordinated movement were calculated for each task. Each task yielded a coordinated movement score for each participant based on the duration or frequency (per task condition) of that participant's movement in relation to the partner's (peer's or computer's) movement. Performance on all tasks was videotaped from three different angles simultaneously (left, right, and center) using surveillance cameras and was analyzed via the INTERACT micro-analysis social behavior observation coding software, which enabled the coding of social-motoric behaviors with frame-by-frame precision (in milliseconds) and the comparison of both partners' co-occurring movements (Adamson et al., 2019; Glüer, 2018).

Trained observers (while masked to study group and age group assignment) coded each participant's observed movements using the JA coordination coding scale (Bauminger-Zviely et al., 2017), developed for the current study in line with recent JA literature (Fitzpatrick et al., 2017a, 2017b; Vesper et al., 2017), the Laban movement analysis principles of shape (the relationship between body and environment – carving) and space (the movement of body in space – kinesphere) (Samaritter & Payne, 2017; Tsachor & Shafir, 2019), and consultation with a dance and movement therapist. Two raters performed coding of 35 dyads (47%) selected randomly from both study groups' social and nonsocial tasks. All disagreements were discussed until raters reached consensus. Interrater agreement of 88% was obtained (κ = 0.86) for tasks with a social partner and 95% (κ = 0.93) for tasks with a nonsocial (computer) partner, on average. Interrater kappa and agreement percentages for each observed JA task are detailed in Appendix C. The six JA tasks' description and coding are presented next.

Mirroring JA Tasks with a Social (Peer) Partner

In the *walking* task, partners stood side by side, while we instructed one participant to walk continuously from one side of the 5 m room to the other and then the other participant to walk exactly like the partner. Frequency of steps was coded as the interface between the participant's feet and the floor (in milliseconds). The coordinated steps (JA) percentage score was calculated as the ratio between the number of co-occurring steps (performed simultaneously by both participants) by congruent (right-right, left-left) and incongruent (right-left) feet, and the total number of steps (right and left foot) that each participant performed.

In the *hand & body* task, partners faced each other at a half-meter distance, while we instructed one participant to perform unlimited hand and body movements, without moving their feet, and then the other participant to move exactly like the partner. Within this duration, each participant's hands' and body's movements were coded for location in space (using a direction grid: right, left, forward, backward up, down). The coordinated hand & body movement (JA) percentage score was calculated as the ratio between the duration (in milliseconds) of co-occurring movements (performed simultaneously by both participants) in a congruent direction (side-side, forward-forward, up-up, down-down), and the total hand & body movement duration (in milliseconds) that each participant performed.

Complementing JA Tasks with a Social (Peer) Partner

In the *corridor* task, partners faced each other at opposite sides of an imaginary long narrow corridor created by masking tape lines on the floor (4 m length, 0.5 m width). Partners were instructed to cross the lengthy corridor simultaneously and reach the other end without stepping outside the marked lines. When meeting in this narrow space, participants had to attune their body position to accommodate the partner's body, for example, turning sideways to pass one another. Coding of body positioning movements began when participants began attuning their body position and ended when participant realigned to a regular walking-forward position. Within this duration, body positioning movements were coded for their location in space (using a direction grid: right, left, forward, backward, up, down). The coordinated body positioning movement (JA) percentage score was calculated as the ratio between the duration (in milliseconds) of the attuned complementary co-occurring body positioning movements and the total body positioning movement duration (in milliseconds) that each participant performed walking from one side to the other.

In the *soccer* task, partners faced each other at a 1.5 m distance and were instructed to play virtual soccer, where one partner was instructed to kick the imaginary ball and the other to complement the partner's kicking movement and move to catch the ball. Participants' kick-and-catch movements' frequency were coded for location in space (using a direction grid: right, left, center). The coordinated kick-and-catch movement (JA) frequency percentage was calculated as the ratio between the number of consecutive kick-and-catch movements performed by both participants in complement (center-center, right-left, left–right direction), and the total number of kick-and-catch movements that each participant performed.

Mirroring JA Task with a Nonsocial (Computer) Partner

In the *triangle* task, each participant used a finger on a computer screen to trace the computer-generated random movement direction (side, up, down) of a red triangle displayed for 30 s. The participant's finger movement while mirroring the virtual red triangle's movement was coded for location in space (using a direction grid: side, up, down). The coordinated finger-tracing (JA) movement percentage was calculated as the ratio between the duration (in milliseconds) of co-occurring movements (performed simultaneously by both computer and participant) in a congruent direction (side-side, up-up, down-down), and the total duration (in milliseconds) of the movements each participant performed.

Complementing JA Task with a Nonsocial (Computer) Partner

In the *ping-pong* task, each participant played a virtual ping-pong game displayed on a computer screen by moving an actual racket toward a virtual served ball to complement the computer-generated random movement direction (center, right, left) of the ball served 30 times over 30 s. The participant's hand movement while complementing the virtual ping-pong ball movement was coded for location in space (using a direction grid: center, left, right). The coordinated ball-return movement (JA) percentage was calculated as the ratio between the number of consecutive serve-hit movements performed by both computer and participant in complement (center-center, right-left, left–right direction), and the total number of hit movements that each participant performed.

Procedure

This cross-sectional study reports part of a larger study that examined the role played by motor functioning in social interaction, including several additional measures that are outside the scope of the current paper. The total sample comprising 212 children and adolescents (128 with ASD and 84 with TD) was recruited through advertisement of the study objectives to parents, colleagues, advocating organizations, and social media, after receiving approval from the university ethical committee. A subset of 64 was excluded from the current study: those with an IQ below 70 ($n=30$ with ASD) and those with chronological age 12 + months over their potential partners ($n=14$ with ASD, $n=20$ with TD). After receiving written parental consent, two sessions were held at the Bar-Ilan University autism research lab. In the first session, we evaluated participants' ASD diagnosis (in the ASD group) and cognitive ability (in both groups). In the second, we carried out the six JA tasks in counterbalanced order.

Data Analyses

Due to our cross-sectional data's dyadic nature, the statistical analytic procedure included the generalized linear mixed model (GLMM) and the generalized estimating equations (GEE) to integrate the dyadic effect, that is, the repeatedly measured individuals within dyads (Fitzmaurice et al., 2009). To explore differences and similarities in dyads' coordination during the social mirroring and complementing tasks in the ASD and TD groups in relation to the three developmental periods, we used a two-level GLMM approach (e.g., Snijders & Bosker, 1999), to determine main effects (Group/Age) and interactions (Group X Age). Our analysis was computed using Mplus V.8.3 (Muthén & Muthén, 2018). We also used GLMM as the analytic procedure for the nonsocial JA tasks.[1] To further examine developmental effects using age as a continuous variable and to verify the group X age-group results, we conducted a series of Pearson tests to examine social and nonsocial JA tasks' correlations with age in each group.

Likewise, the GEE allowed us to integrate the two-level structure of the data, namely, individuals' scores within a dyadic framework (Hardin & Hilbe, 2013). Put differently, this modeling structure ensured that the group, task, and age effects were not obscured by the within-dyad child effect. We used GEE to test for differences between the social and nonsocial JA tasks. Wald's χ^2 test was used to assess significance. Predicted marginal means for each group were calculated and compared. The source of the interaction in all analyses was determined using post hoc pairwise comparisons adjusted by Bonferroni's (1936) correction, subject to the $p < 0.05$ rejection criterion.

Results

Social Mirroring and Complementing: Group and Age Differences on JA Tasks Performed with Peers

Table 2 presents the GLMM results for the four dyadic social JA tasks, two mirroring and two complementing tasks performed with peers. Consistently across the various peer JA tasks, a significant main effect of group (ASD vs. TD) emerged, yielding better coordinated JA capabilities in the dyads with TD compared to the dyads with ASD, beyond age group (see model effects and marginal means of TD vs. ASD in Table 2). Likewise, a significant main effect of age emerged, indicating consistent development in JA with increasing age, on average, beyond study group. More specifically, the main effects and marginal means for age shown in Table 2 reveal better coordinated JA capabilities among the oldest group (adolescents) compared to the youngest (early childhood) for all social JA tasks, beyond study group. The differences between preadolescence and early childhood followed the same trend but were less robust, with nonsignificant results for the hand & body movements and a near-significant finding ($p = 0.07$) for the corridor task. Overall, the predicted marginal means for age indicate that the two older groups showed better JA capabilities on average than the younger group, with no significant difference between them.

Findings for the group by age interaction effects showed age differences between the ASD and TD groups for two of the JA tasks – the walking and corridor tasks. As seen in Table 2, for the walking (mirroring) task, this interaction with study group was significant only for the preadolescents ($b = -16.64$, $p < 0.05$). Multiple pairwise comparison showed that only preadolescents with TD produced higher percentages of shared steps with their partner compared to the youngest group ($M_{preadol} = 74.51$ vs. $M_{young} = 51.49$, "b" vs. "a" on Table 2). The preadolescent and adolescent groups with TD did not differ significantly ($M_{adol} = 64.18$ vs. $M_{preadol} = 74.51$, "b" vs. "b"). Thus, it can be concluded that only in the TD group did older children demonstrate higher peer coordination of movement than younger children while walking together. Among the ASD dyads, no age difference was found ($M_{adol} = 52.82$, $M_{preadol} = 53.00$, $M_{young} = 46.61$, all "a"). It is important to note that the two groups (ASD, TD) achieved similar percentages of joint steps at the youngest age ("A" on Table 2), on average, but at older ages, the dyads with TD achieved a higher percentage of shared steps ("B" vs. "A") compared to the dyads with ASD. Moreover, the pairwise comparison indicated nonsignificant differences between the youngest TD group and all three ASD age groups ("A," $p > 0.05$). On the whole, the older ASD participants showed similar percentages of joint steps to the young TD participants.

For the corridor JA task, the interaction effects with group were significant for the preadolescents ($b = -17.48$, $p < 0.05$) and for the adolescents ($b = -18.63$, $p < 0.05$). Overall, results for this complementing JA task yielded a similar picture to the walking (mirroring) task. Older dyads in the TD group showed higher percentages of coordination while crossing one another in the corridor ($M_{adol} = 79.37$ and $M_{preadol} = 78.24$ vs. $M_{young} = 61.79$, "b" vs. "a"), while

[1] To additionally examine the effect of age as a continuous variable, we performed further analyses. First, we treated age as a continuous variable in our GLMM analyses of Group X Age, but this analytic method lost two important Group X Age interactions (for walking and corridor) that had been significant using the categorical treatment of age, probably due to scale sensitivity, sample size, and the need to control for the dyad. In addition, we also performed a model with age as a log transformed independent variable, and the same results were obtained as in the GLMM for group and age. Thus, we kept our analyses that treated age as a categorical variable comprising three

Footnote 1 (continued)

age groups because they yielded the most informative data about the development of JA between and within groups.

Table 2 GLMM Dyadic Modeling Results for the Peer Social JA Tasks, with Group and Age Effects and Their Interactions

	Mirroring		Complementing	
	Walking	Hand & body	Corridor	Soccer
M	56.35	59.02	68.79	66.57
SD	16.84	16.99	20.89	19.75
ICC	.943	.945	.073	.922
Main effects (b)				
Group	− 12.76*** (3.40)	− 11.88*** (3.54)	− 8.54* (3.45)	− 13.93** (4.01)
Preadolescents vs. Young	13.82*** (4.23)	6.00 (4.40)	7.97† (4.38)	10.61* (4.99)
Adolescents vs. Young	9.58* (4.16)	11.73** (4.33)	8.38* (4.27)	15.81** 4.90
Marginal means for main effects (subgroup mean)				
TD	78.84^{B} (5.57)	77.19^{B} (5.80)	83.95^{B} (5.73)	91.55^{B} (6.57)
ASD	66.07^{A} (5.16)	65.31^{A} (5.37)	75.41^{A} (5.24)	77.62^{A} (6.08)
Young	42.67^{a} (3.52)	47.59^{a} (3.66)	59.06^{a} (3.73)	51.19^{a} (4.14)
Preadolescents	56.49^{b} (3.19)	53.58^{ab} (3.32)	67.03^{b} (3.27)	61.80^{b} (3.76)
Adolescents	52.25^{b} (3.10)	59.31^{b} (3.23)	67.44^{b} (3.10)	67.01^{b} (3.66)
Interactions of group by age (b)				
Group X Preadolescents	− 16.64* (8.29)	− 4.37 (8.79)	− 17.48* (8.59)	− 9.53 (9.96)
Group X Adolescents	− 6.47 (8.13)	10.09 (8.62)	− 18.63* (8.38)	1.02 (9.76)
Marginal means for interactions				
TD Young	51.49^{aA} (4.24)	56.91 (4.49)	61.79^{aA} (4.24)	63.72 (5.08)
TD Preadolescents	74.51^{bB} (4.44)	65.02 (4.71)	78.24^{bB} (4.44)	79.77 (5.33)
TD Adolescents	64.18^{bB} (4.24)	74.14 (4.49)	79.37^{bB} (4.24)	78.67 (5.08)
ASD Young	46.61^{aA} (4.24)	50.14 (4.49)	66.17^{aA} (4.68)	52.60 (5.08)
ASD Preadolescents	52.99^{aA} (3.63)	53.88 (3.84)	65.13^{aA} (3.76)	59.11 (4.35)
ASD Adolescents	52.83^{aA} (3.51)	57.28 (3.72)	65.11^{aA} (3.51)	68.57 (4.21)

GLMM generalized linear mixed model. $N_{children} = 148$, $N_{dyads} = 74$. Lower-case Latin letters denote age-group mean ranking, with "a" for lowest, based on multiple-pairwise comparisons. Capital letters denote between-group differences, with “A” for lowest Model Fit: CFI, TLI > .09, denote above acceptance threshold Walking: $\chi^2 = 0.59$, df = 2, $p = .75$; CFI = 1.00, TLI = 1.00; RMSEA < .001, $SRMR_{within} = .003$, $SRMR_{between} = .022$

Hand & body: $\chi^2 = 0.59$, df = 2, $p = .75$; CFI = 1.00, TLI = 1.00; RMSEA < .001, $SRMR_{within} = .003$, $SRMR_{between} = .019$

Corridor: $\chi^2 = 0.79$, df = 2, $p = .67$; CFI = 1.00, TLI = 1.00; RMSEA < .001, $SRMR_{within} = .007$, $SRMR_{between} = .060$

Soccer: $\chi^2 = 0.59$, df = 2, $p = .75$; CFI = 1.00, TLI = 1.00; RMSEA < .001, $SRMR_{within} = .004$, $SRMR_{between} = .021$

$^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$; $^{\dagger}p = .07$

among the ASD dyads this improvement with age was not evident ($M_{adol}=65.11$, $M_{preadol}=65.13$, $M_{young}=66.17$, all "a"). Also, older participants with ASD showed percentages of coordination on the joint corridor task similar to those of the young TD participants, but the pairwise comparisons for the difference between preadolescents with TD and young children with ASD only neared significance ($p=0.06$).

The model's goodness-of-fit was above the acceptance threshold for all analyses (e.g., CFI, TLI > 0.9).

Nonsocial Mirroring and Complementing: Group and Age Differences on Computerized JA Tasks

Table 3 presents the GLMM empirical results for the two nonsocial JA tasks performed with the computer. A main effect of group (ASD vs. TD) emerged for both the triangle (mirroring) and ping-pong (complementing) tasks, showing better coordinated JA capabilities in the TD group than in the ASD group, beyond age group (see model effects and marginal means in Table 3). Likewise, a significant main effect of age emerged, indicating a clear advantage for the oldest group (adolescents) over the youngest group (early childhood) on both nonsocial tasks (triangle and ping-pong). However, the age effect for the difference between the youngest group and the preadolescents was less robust, reaching significance only for the complementing (ping-pong) task, in favor of the older group. Thus, better performance on nonsocial JA tasks appeared to be a function of age, beyond group. The group by age interaction effect did not reach significance, indicating that this pattern of age effects was relevant for both study groups.

Links Between Social and Nonsocial JA Tasks and Chronological Age

As can be seen in Table 4, the results of correlational analyses between JA and CA (using age as a continuous variable) demonstrated significant correlations for all JA tasks in both groups, except for the walking task ($r=0.16$, $p=0.07$) and the corridor task that yielded a very low correlation effect ($r=0.18$, $p=0.051$) in the ASD group. These results support our former GLMM results for the effect of development as measured using the three age groups (adolescence, preadolescence, and early childhood). Findings also support the group X age-group interaction results found for the walking and corridor tasks. All in all, older children produced better JA, but this effect was stronger for the TD group.

Table 3 GLMM modeling results for group and age effects on the computer-based nonsocial JA tasks

	Triangle – mirroring	Ping-pong – complementing
M	66.03	93.56
SD	8.63	11.24
ICC	.298	.138
Main effects (b)		
Group	− 8.96*** (1.20)	− 3.33* (1.71)
Preadolescents vs. Young	2.45 (1.49)	7.90*** (2.13)
Adolescents vs. Young	4.74*** (1.46)	10.20*** (2.09)
Marginal means		
TD	75.75^{B} (1.96)	107.164^{B} (2.81)
ASD	66.80^{A} (1.82)	103.834^{A} (2.60)
Young	59.61^{a} (1.24)	85.73^{a} (1.77)
Preadolescents	62.06^{ab} (1.12)	96.63^{b} (1.60)
Adolescents	64.35^{b} (1.09)	95.93^{b} (1.56)

GLMM generalized linear mixed model. $N_{children}=148$, $N_{dyads}=74$. Lower-case Latin letters denote age-group mean ranking, with "a" for lowest, based on multiple-pairwise comparisons. Capital letters denote between-group differences, with "A" for lowest

Model Fit: CFI, TLI > .09, denote above acceptance threshold. Triangle: $\chi^2=1.17$, df = 2, $p=.55$; CFI = 1.00, TLI = 1.00; RMSEA < .001, $SRMR_{within}=.026$; Ping-pong: $\chi^2=1.17$, df = 2, $p=.55$; CFI = 1.00, TLI = 1.00; RMSEA < .001, $SRMR_{within}=.021$

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

Mirroring and Complementing JA Task Types By Partner, Group, and Age

As seen on Table 5, the GEE modeling yielded significant main effects for partner, group, and age for both mirroring and complementing JA task types. The significant partner effect indicated higher percentages of coordination in tasks performed with the computer than in tasks performed with a peer, both for mirroring (66.50 vs. 58.17) and for complementing (93.75 vs. 66.42) task types, beyond group and age. Likewise, participants with TD showed significantly better coordination than those with ASD, beyond partner and age, both on mirroring tasks (67.64 vs. 57.02) and on complementing tasks (84.35 vs. 75.82). Similarly, a significant age effect emerged beyond group and task, indicating higher coordination percentages in adolescence and preadolescence compared to early childhood, for both mirroring tasks (65.39 and 63.83 vs. 57.76) and

Table 4 Pearson Results for Correlations between Joint Action (JA) Tasks and Chronological Age per Group

Group	Social JA tasks								Nonsocial JA tasks			
	Mirroring				Complementing				Mirroring		Complementing	
	Walking		Hand & body		Soccer		Corridor		Triangle		Ping-pong	
	ASD	TD	ASD	TD	ASD	TD	ASD	TD	ASD	TD	ASD	TD
Age (in months)	$.16^{.07}$	$.27^{*}$	$.23^{*}$	$.44^{***}$	$.34^{***}$	$.46^{***}$	$.18^{.051}$	$.41^{***}$	$.26^{**}$	$.36^{***}$	$.26^{**}$	$.41^{***}$

$^{*}p<.05$. $^{**}p<.01$. $^{***}p<.001$

Table 5 GEE Results for the JA Mirroring and Complementing Task Types: Model's Main Effects and Descriptive Statistics for Group, Partner, and Age Comparisons

JA task type	Age group	Study group			Partner			Age	
		ASD *M*(SE)	TD *M*(SE)	Model effect $Wald_{group}$	Peer (social) *M*(SE)	Computer (nonsocial) *M*(SE)	Model effect $Wald_{task}$	Total *M*(SE)	Model effect $Wald_{age}$
Mirroring	Young	53.81 (1.91)	61.68 (1.52)	87.53** ASD < TD	51.38 (2.03)	64.11 (1.31)	54.16** Social < Nonsocial	57.7 (1.24)	27.56*** Pre-adolescents, Adolescents > Young
	Preadolescents	57.95 (1.50)	70.03 (1.23)		61.30 (1.71)	66.67 (0.94)		63.83 (1.01)	
	Adolescents	59.68 (0.91)	71.29 (1.17)		62.05 (1.12)	68.91 (0.86)		65.39 (0.73)	
	Total	57.02 (0.85)	67.64 (1.12)		58.17 (0.97)	66.50 (0.60)		62.33 (0.58)	
Complementing	Young	69.52 (3.05)	75.94 (2.45)	31.49*** ASD < TD	58.06 (2.96)	87.40 (2.09)	329.27*** Social < Nonsocial	72.74 (1.96)	33.60*** Pre-adolescents, Adolescents > Young
	Preadolescents	77.02 (1.70)	87.65 (1.16)		69.16 (1.88)	95.51 (1.05)		82.14 (1.10)	
	Adolescents	81.19 (1.39)	89.44 (1.03)		73.03 (1.48)	97.60 (1.09)		85.37 (0.92)	
	Total	75.82 (1.20)	84.35 (0.97)		66.42 (1.26)	93.75 (0.89)		80.08 (0.79)	

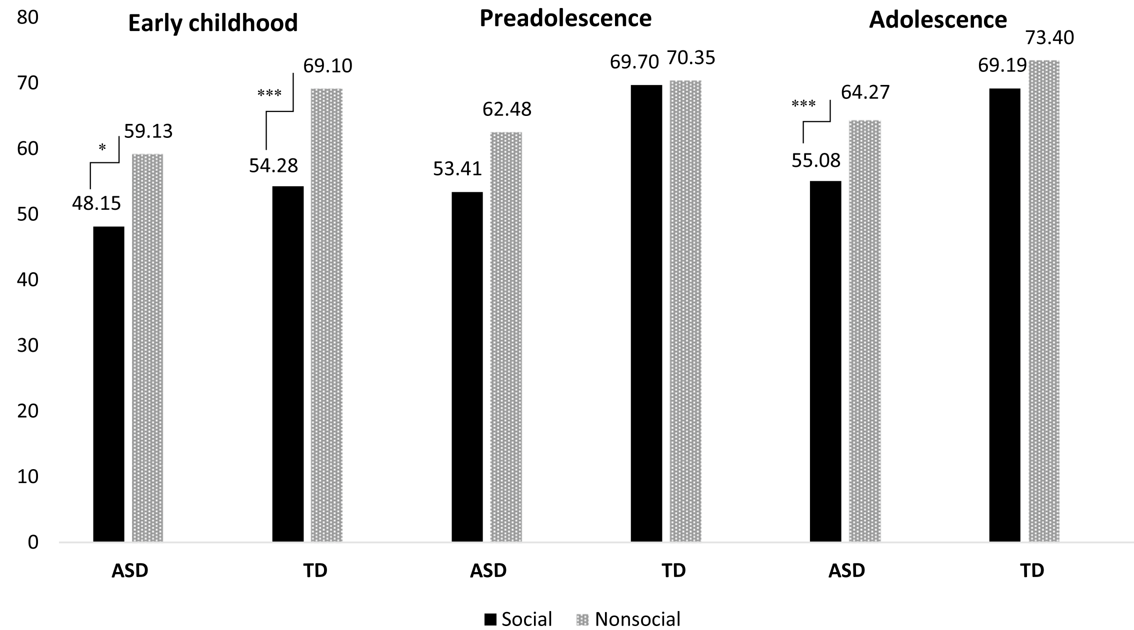
$^{***}p<.001$, $^{**}p<.01$, $^{*}p<.05$. *GEE* generalized estimating equations. $N_{children}=148$, $N_{dyads}=74$

for complementing tasks (85.37 and 82.14 vs. 72.74). The difference between the two older groups (adolescents and preadolescents) was nonsignificant.

With regard to interaction effects for mirroring JA tasks, only the age by partner interaction reached significance (Wald = 6.27, $p<0.05$). Examination of the interaction source, using pairwise comparison with Bonferroni correction for multiple comparisons, revealed the following: When performing JA mirroring tasks with a social peer partner, the two older groups showed significantly better coordination than the youngest group (Adolescents: $M=62.05$, $SE=1.12$; Preadolescents: $M=61.30$, $SE=1.71$; Early Childhood: $M=51.38$, $SE=2.03$; $p<0.05$). However, when performing nonsocial mirroring (computer-based triangle task), only the oldest group ($M=68.91$, $SE=0.86$) showed a significant advantage ($p<0.05$) over the youngest group ($M=64.11$, $SE=1.31$). None of the other interaction effects reached significance.

With regard to interaction effects for complementing JA tasks, only the group by partner interaction reached significance (Wald = 13.23, $p<0.001$). Examination of the interaction's sources revealed a significant advantage in coordination ($p<0.05$) in the TD group ($M=73.53$, $SE=1.44$) over the ASD group ($M=59.96$, $SE=2.03$) but only for the JA complementing tasks performed with a peer social partner. Level of coordination in the nonsocial JA complementing task (computer-based ping-pong) was similar between the two study groups (TD: $M=95.16$, $SE=1.08$; ASD: $M=91.86$, $SE=1.30$; $p>0.05$).

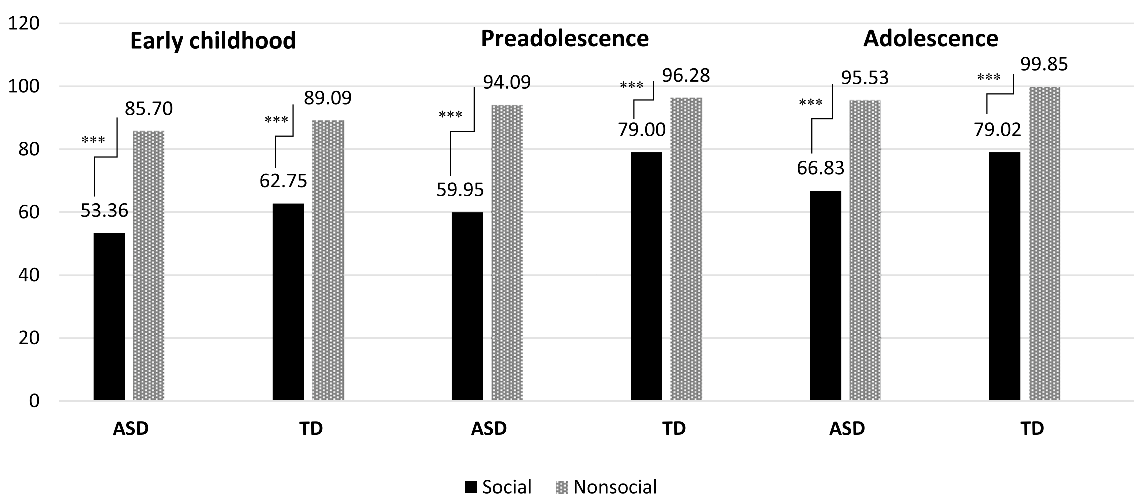
Despite the nonsignificant finding for the group by age by partner interaction, we examined trends for each study group and age to compare social and nonsocial partners using pairwise comparison with Bonferroni correction for



Note. ASD = autism spectrum disorder. TD = typical development.

* *p*=.06. ****p*=.001.

Fig. 1 Mirroring joint action coordination: differences between social and nonsocial partners by study group (ASD/TD) and Age (Early Childhood, Preadolescence, Adolescence)



Note. ASD = autism spectrum disorder. TD = typical development.

****p*=.001.

Fig. 2 Complementing joint action coordination: differences between social and nonsocial partners by study group (ASD/TD) and Age (Early Childhood, Preadolescence, Adolescence) multiple comparisons (see Figs. 1 and 2). In line with significant main effect found for task, performance with a nonsocial partner surpassed performance with a social partner; however, this was stronger for complementing than mirroring tasks. As seen in Fig. 1, on the mirroring JA tasks, the social versus nonsocial partner difference was significant (nonsocial > social) only in early childhood (for TD and a trend in ASD, $p = 0.06$) and in adolescence (for ASD only). In contrast, as seen in Fig. 2, on the complementing tasks, differences were significant for all age and study groups, where nonsocial JA coordination surpassed that performed with a social partner.

Discussion

This comprehensive cross-sectional examination of dyadic motor coordination in body movement provided novel information on JA development from early childhood to adolescence not only in TD but also in ASD, while investigating the phenomenon during both social peer interaction and nonsocial computer-based interaction during performance of multiple mirroring and complementing motor coordination tasks. Differently from previous studies that focused mostly on child–adult interactions, this study explored peer-to-peer JA in dyads matched for chronological age, IQ, sex, and clinical group.

Overall, our results demonstrated a broad coordination deficit in the peer dyads with ASD compared to their counterparts with TD, showing a significant main effect of group across developmental stages (early childhood, preadolescence, adolescence), across interaction partners (social and nonsocial), and across JA task types (mirroring and complementing). We found an overall coordination deficit in ASD compared to TD that went beyond partner and task type, thereby showing a wider scope than our hypothesized better coordination in the TD group than the ASD group on the JA tasks with a social partner. These findings coincide with other literature that examined JA in child–adult situations (Lampi et al., 2020; Yoo & Kim, 2018) or in movement interactions with a nonsocial partner (Su et al., 2021; Vishne et al., 2021). Both mirroring and complementing tasks, whether social or nonsocial, require an ability to predict the partner's movement (Satta et al., 2017; Vesper et al., 2013). Thus, one interpretation of the coordination deficit in peer dyads with ASD may be related to feedforward control complexities (Mosconi et al., 2015). Indeed, Sinha et al. (2014) described autism as a disorder of prediction, suggesting that such predictive impairments might have an impact on youngsters' perception of others' actions – an integral part of any social and motor engagement (Vesper et al., 2010). Furthermore, perceiving, interpreting, and predicting others' nonverbal signals, emotions, and intentions can motivate, and to a large extent determine, the nature of one's engagement with others' actions (Sebanz & Knoblich, 2021).

Another possible explanation for the ASD group's greater JA difficulties than the TD group may involve the ability to perceive and imitate body positions and movements (Edwards, 2014; Taylan et al., 2021). A case in point is the phenomenon often described in the literature as the "chameleon effect" that occurs in social situations (Chartrand & Bargh, 1999), where one unconsciously mimics the interaction partner's postures, mannerisms, speech inflections, and facial expressions, thereby passively and unintentionally changing one's behavior to match that of others in the current social environment. Research has indicated that individuals with ASD may have chameleon effect deficiencies, possibly due to their delayed acquisition of motoric milestones (Bhat et al., 2011; Posar & Visconti, 2022) and reduced exposure to new motor and social arenas during early childhood (Ingersoll, 2008).

Other potential explanations for the ASD group's overall lower movement coordination may relate to a less attuned response to their partner's action, perhaps resulting from their difficulty in maintaining social and motor attention to their partner's nonverbal motor behavior (Fitzpatrick et al., 2016; Mukai et al., 2018), as well as their difficulty in processing sensory information during face-to-face encounters (Pezzulo et al., 2019). Thus, impairments in attention to social-motor stimuli and in processing social and sensory information may hinder their activation of feedback control mechanisms and thereby the coordination of their own body movement to that of others (Mosconi et al., 2015; Peper et al., 2016; Wolpert et al., 2003).

Social and Nonsocial Partners

All in all, these speculations provide some potential explanations for the social coordination deficit in ASD but less so for their nonsocial coordination deficit. Indeed, looking beyond the main effect for study group, subtle differences emerged for age, task type, partner, and their interactions, suggesting that the ASD group may demonstrate a more robust deficit on interpersonal JA tasks, mainly those that require social complementing, compared to nonsocial or mirroring tasks. First, at odds with our hypothesis for the TD group, the comparison between social and nonsocial JA tasks indicated a better ability to coordinate physical action with the computer than to coordinate movement with a peer partner for both groups. This suggests that the social nature of coordinating movement with a peer partner is more demanding and challenging than coordination with the movements provided by an inanimate partner. Whereas the computerized task involves mainly eye-hand coordination while processing merely a single stimulus (i.e., geometric shape or ping-pong ball), the peer social task requires many more simultaneous visuomotor-perceptual and mentalization processes (i.e., looking at the peer's whole-body movement and moving accordingly to resonate or complement the peer's action; projecting the partner's intentions).

Second, the significant interaction that emerged between partner and group on complementing JA tasks showed that only when attempting to complement a peer social partner's motor behavior did the TD group outperform the ASD group (73.53 versus 59.96). This group effect did not occur when attempting to complement computer-generated movements. This finding suggests that predicting a human partner's body movement in order to complement it, by performing an opposite or incongruent responsive action, was more challenging for the ASD group than merely predicting where to move one's virtual racket to meet an onscreen ping-pong ball.

In addition, a closer look at Figs. 1 and 2 indicates that, throughout development, youngsters similarly performed mirroring JA tasks with a peer and with the computer (except in the youngest TD subgroup and oldest ASD subgroup), whereas for complementing JA tasks significant effects emerged across groups and ages in favor of computer-based movement coordination, possibly suggesting the more challenging nature of social-interpersonal coordination with a peer partner, even for the TD group, across development.

It is important to note here that the current study's focus on peer dyads rather than an adult partner for JA tasks placed more social demands on the ASD group because adults tend to scaffold and mediate the interaction (Hay et al., 2009). Indeed, Trevisan et al. (2021) recently found that an adult partner mitigated the coordination deficit for ASD compared with TD. This provides additional support for the well-documented peer interaction deficit in ASD (APA, 2013).

Complementing and Mirroring Tasks

Complementing another's movement appears to require higher mentalization and socio-cognitive processes than merely mimicking the other's movement, thus making complementary motor coordination harder for youngsters with ASD based on their well-documented social, motor, and mentalization deficits (Andreou & Skrimpa, 2020; Bauminger-Zviely, 2013; Bhat, 2021). Thus, resonating or mimicking another person's current and emergent body-behavior movements seemed easier than creating incongruent behaviors that require reactive or opposing actions based on the prediction of the partner's future action movements and their consequences (e.g., Noy et al., 2011; Sebanz et al., 2006). Thus, these findings lend novel support to a continuum in the levels of socio-cognitive mentalization as well as the motor planning capabilities that are required from both partners during JA tasks. This continuum ranges from mere imitation, which is required in the mirroring JA, to divergent coordinated behavior that requires the ability not only to predict the partner's current movements but also future ones, such as predicting the future direction of the ball in the space based on the partner's imaginary kicking direction during the soccer task or adjusting one's body posture based on the prediction of the partner's future body posture when crossing a narrow corridor. Furthermore, complementing actions during interaction challenge the action-perception processes. Complementary social interactions start from the simulation of another's movement, go on to the prediction of the peer's future actions, followed by the production of an appropriate incongruent response (dissimilar to the observed behavior), and are completed by integrating one's own actions' predicted effect with the other's actions (e.g., Sartori & Betti, 2015). This continuum from imitation to divergent incongruent coordination interactions may have specific translational implications, possibly lending support to neuro-rehabilitation intervention programs in ASD.

Developmental Trends

In line with our hypothesis that JA capabilities would develop in both groups with age, general progress with age was noted, as a main effect beyond study group. Thus, the youngest children in early childhood (6–8.5 years) showed the lowest body-movement coordination, differing significantly from the adolescent group for all social and nonsocial JA tasks, and differing significantly from the preadolescent group for three of the six JA tasks (expect for the social mirroring hand & body task, the social complementing corridor task, and the nonsocial triangle mirroring task). The two older groups did not differ from one another, suggesting that the major growth in JA capabilities emerges throughout early childhood and stabilizes at preadolescence. This novel finding has both theoretical and therapeutic implications as detailed below.

Furthermore, the interaction between group and age for two social JA tasks (mirroring walking and complementing corridor) indicated an age effect only for the TD group. Also, on these two tasks, the oldest group with ASD showed coordination abilities resembling the youngest group with TD. Thus, even if JA improves with age in dyads with ASD, they remain far behind the dyads with TD. This gap between groups appeared to remain stable over development and did not diminish with age.

In addition, the significant interaction that emerged between partner and age for the mirroring task indicates clear developmental improvement trends when this task was performed with a peer partner beyond group (62.05 in adolescents and 61.30 in preadolescents, compared to only 51.38 in early childhood), whereas an even pattern of performance levels across the ages emerged when mirroring was performed with a computer-based partner (early childhood: 64.11; preadolescence: 66.67; adolescence: 68.91). To be noted, adolescents did significantly outperform the youngest age group on the latter nonsocial mirroring task, but the similar means for all three age groups on this triangle task suggest maturation of the ability to coordinate mirrored movement with a computer at a relatively early age, younger than that found for socio-motor mirroring ability.

Study Limitations and Implications

Our study has several limitations. Although the sample is quite large and we controlled for shared variability due to dyads' participation, it may be that the dyadic nature of our JA tasks required an even larger number of participants to identify subtler group and age differences. Also, our micro-analysis coding procedure provided one interpretation of the children's coordination abilities, which reflected the shared body movement in relation to each individual child's body movement for each task with regard to the duration or frequency of the behaviors. However, the process of data coding also revealed differences between groups in their quality of body movements, which were not reflected in our coding.

Moreover, despite our comprehensive and rigorous dyadic and group matching criteria, we did not tease out possible differences in children's motor performance (e.g., gross, fine). Hence, part of the explanation of group differences may result from difficulties in motor performance in the ASD group, based on these children's well-documented motor deficiencies (e.g., Bhat, 2020, 2021; Licari et al., 2020; Zampella et al., 2021). We indeed controlled for the dyadic influence on JA performance via our statistical analyses (GLMM, GEE); however, future studies would do well to insert measures of the individual child's motor profile (e.g., Bruininks-Oseretsky Test of Motor Proficiency; Bruininks & Bruininks, 2005) for screening, grouping, and matching procedures, to obtain fuller understanding of these children's deficits in social-motor coordination.

Furthermore, due to progress in the development of human motion computational analytic procedures, it would be interesting to compare our micro-analytic coding with a more objective markerless coding procedure such as "open pose" motion capture (Nakano et al., 2020). Such procedures for analyzing spontaneous dyadic behaviors are still under development, and our future efforts point in that direction. Combinations of more objective data analysis procedures may enable discernment of even more subtle group and age differences in JA.

Lastly, this study focused on peer dyads, but a complete examination of JA coordination abilities in ASD should also include comparisons between child-peer and child–adult JA interactions. Moreover, special efforts were made in the current study to use ecologically valid JA tasks that do not require intensive motor efforts (e.g., walking together or crossing each other in the corridor), but it may be of interest to examine additional tasks representing real-life peer-to-peer activities commonly encountered in school, leisure, or sports activities (e.g., using a real ball in the soccer task).

All in all, our study results hold theoretical and therapeutic implications. Peer dyads with ASD demonstrated relatively more intact JA ability in nonsocial tasks and a larger coordination deficit in social tasks. Moreover, even if we found developmental growth in JA abilities in ASD, they still lag behind their same-age peers with TD. Recent literature emphasizes the motor deficit in ASD (Zampella et al., 2021) and its contribution to the understanding of their interaction deficit (Cheung et al., 2021). Therefore, our comprehensive study results provided important novel support for this link while pinpointing the complexity of the socio-motor skill set needed for joint motor coordination.

Moreover, given that JA is needed in most social interaction activities, incorporation of socio-motor activities into social interventions can be an important innovative channel for facilitating peer engagement. This study supports the importance of addressing JA using an interprofessional team approach, including experts in movement/motor coordination and sensorimotor perception, such as physical therapists and occupational therapists, on the neurodevelopmental team. Integration of JA activities may offer an important novel pathway to change, which may lead to a reduction in their loneliness and social isolation and to an increase in youngsters' social belonging and wellbeing. Former studies indeed found that peer engagement in early childhood is an important index of adaptive functioning in the general population (e.g., Vaughn et al., 2016); likewise, individual variations in peer interaction at early ages predicted later social competence (Rose-Krasnor & Denham, 2009; Sette et al., 2017).

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