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Neural correlates of social motor coordination in autism: A systematic review and meta-analysis of fNIRS studies

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ABSTRACT

This study aimed to provide a comprehensive overview of how individuals with autism spectrum condition (ASC) process social motor coordination, focusing on joint action and its neural correlates, as examined through functional near-infrared spectroscopy (fNIRS) in comparing to their neurotypical (NT) counterparts. Eleven studies were analyzed, with nine included in the meta-analysis. The results identified the inferior parietal lobule (IPL) and superior temporal sulcus (STS) as significant moderators explaining group differences in cortical activation during joint action. Specifically, individuals with ASC showed increased IPL activation and reduced STS activation, indicating a greater reliance on kinematic processing and diminished engagement in encoding and integrating socially relevant information. Although the pooled effect size for inter-brain synchrony (IBS) was not statistically significant, descriptive analyses showed a trend toward reduced reciprocal processing in ASC, particularly in predicting and aligning with a partner's mental states, as supported by decreased IBS in the temporoparietal junction (TPJ). Furthermore, a visual inspection of behavioral and neural outcomes by autism severity exhibited distinct tendencies. Individuals with mild symptoms demonstrated different neural-behavioral associations compared to those with moderate-to-severe symptoms, suggesting that symptom severity influences how neural processing supports joint action. These findings highlight the differential involvement of neural systems in joint actions among individuals with ASC depending on task type and autism severity, and emphasize the distinction between intra- and inter-personal processing. By integrating these findings, this study offers a more integrative perspective on social motor coordination in ASC as a complex, multi-dimensional process.

1. Introduction

With growing attention to the motor aspects in social interactions, extensive research has examined how individuals coordinate their actions in response to others and how movement shapes the dynamics of social engagement (Schmidt et al., 2011). When two or more individuals engage in a specific behavior that temporally and spatially coordinated through mutual influence, such interactions are referred to as joint action (Bieńkiewicz et al., 2021; Sebanz and Knoblich, 2009). This ditinguishes joint action from individual social actions, which may convey social meaning but do not necessarily involve simultaneous engagement between individuals or shared timing constraints. Joint action involves two primary types of motor representations: mirrored identical actions and complementary ones (Sebanz et al., 2006). More specifically, it includes subtypes such as imitation, synchronization, cooperation, and in some cases, competition, depending on the degree to which the actions of each participant are interrelated and mutually aligned (Bieńkiewicz et al., 2021). These behaviors demand varying levels of temporal and spatial coordination between the actions of involved partners. For example, while imitation involves relatively discrete and less continuous adjustment, synchronization highlights sustained temporal alignment, as seen in the continuous matching of tapping with a partner. Whereas imitation and synchronization primarily rely on identically shared spatial representations of movement, cooperation involves complementary actions directed toward a common goal without necessarily requiring identical movements, as seen in jointly carrying an object. Competition may also involve temporal and spatial coordination, but it is driven by opposing goals and conflicting intentions rather than the shared intentionality underlying cooperation. For example, competition may require one individual to achieve a specific gain over their counterpart (Jarrassé et al., 2012).

As such, joint actions involve continuous yet different levels of interdependence in movement coordination between partners, requiring a dynamic interplay between perception and embodied action. This

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makes these joint mutually coordinated actions inherently complex (Sebanz et al., 2006). It involves observing a partner's movements, anticipating both one's own and the partner's actions, and executing them while continuously adjusting based on monitoring and feedback (Keller et al., 2014; Sebanz et al., 2006). Social coordination relies on a tightly coupled interaction between the perceptual and motor systems, and these interactions are continuously shaped through ongoing adaptation in a recurring cycle. Due to the intricate nature and developmental significance of this process in fostering social behaviors, studies have aimed to conceptualize and identify the fundamental mechanisms underlying this coordination skill (Keller et al., 2014; Mayo and Gordon, 2020).

Given the role of social coordination in human interactions, disruptions in these processes can result in significant social challenges, as observed in individuals on the autism spectrum condition (ASC). Research has consistently demonstrated that this population shows impairments in joint action compared to their neurotypical (NT) counterparts, particularly when performing tasks spontaneously without prompts or assistance (Carnevali et al., 2024; Trevisan et al., 2021; Yoo and Yoon, 2019). They demonstrated not only fewer attempts to engage, but also greater difficulty executing coordinated imitative, synchronized, and cooperative behaviors when interacting with partners (Cerullo et al., 2021). While motor control difficulties are frequently observed in individuals on the spectrum, they alone do not explain the deficits observed in joint action, suggesting the involvement of distinct social factors (McNaughton and Redcay, 2020). These social motor skills also engage mechanisms that are independent from purely cognitive processes such as nonsocial information processing (Fitzpatrick et al., 2017). Beyond the general impairments in social motor coordination, multiple factors such as task type, context, and external cues involved in the process interactively influence performance (LaGasse et al., 2024; Yoo and Ha, 2024). From another perspective, successful social motor coordination also requires higher-order cognitive processes, including the evaluation of social contexts and relevance, which impose varying levels of perceptual and cognitive demands (Cerullo et al., 2021). Individuals with ASC have been shown to perform differently depending on the complexity of the social task, such as whether the task involves objects, explicit goals, or socially relevant context. Notably, this population was found to perform better in goal-directed actions or imitations of meaningful gestures than in automatic mimicry or imitation of meaningless gestures (Yates and Hobson, 2020). This complexity underscores the need for a multifaceted analysis of these abilities to foster a broader range of intervention approaches to social development. Understanding the neural processes underlying joint action is essential for identifying how specific brain functions either support or challenge social motor coordination.

Joint actions entail attending to or observing a partner's movements, and thereafter translating them into corresponding actions by forming an internal motor representation aligned with the partner's intentions or goals (Cattaneo et al., 2007). This process typically recruits frontal, temporal, and parietal brain regions (Zhao et al., 2024) that engage the cognitive and motor processes involved in planning, anticipation, and adaptation (Keller et al., 2014). Compared to merely observing a partner or performing similar actions alone, joint actions highlight the complexity of social motor skills, as they require a more dynamic and socially adaptive integration of perceptual input and motor planning. These different conditions elicit distinct patterns of cortical activation in neurotypical children and adults (Bhat et al., 2017; Culotta, 2019). While specific task demands differ, joint actions are generally associated with increased involvement of fronto-parietal and temporo-parietal regions reflecting more complex and integrative neural dynamics. Critical brain regions supporting the neural basis of joint actions include mirror neuron systems (MNS), such as the premotor cortex (PM), inferior frontal gyrus (IFG) and inferior parietal lobule (IPL), in association with superior temporal sulcus (STS; Tognoli et al., 2007; Zhang and Roeyers, 2019). These regions mediate the process of mapping of observed actions onto motor plans. In individuals with ASC, research indicates atypical activation of these structures, whether hyperactive, hypoactive, or altered. However, research has noted that MNS alone does not fully account for the difficulties in joint action observed in individuals on the autism spectrum (Yates and Hobson, 2020). This has led to emphasis on the role of top-down control processes that modulate these sensorimotor mechanisms. The Social Top-Down Response Modulation (STORM) model, proposed by Wang and Hamilton (2012), highlights how social evaluation system in the prefrontal cortex regulate MNS activity based on social context, goals, and task rules. Expanding on this, the Mentalizing Network (MENT) model further explains how social actions, including imitation and cooperation, depend on the coordinated activity of multiple neural systems, such as medial prefrontal cortex (mPFC), dorsolateral prefrontal cortex (DLPFC), and temporoparietal junction (TPJ). These regions are involved in interpreting the intentions and mental states of others, while integrating contextual information to guide goal-directed joint actions (Ciaramidaro et al., 2024). Together, these models support the multilayered nature of joint action, involving the dynamic interaction among sensorimotor and higher-order cognitive systems. indicating disruptions not only in isolated structures but also in the functional connectivity between them. Also, these models support that depending on the contextual conditions, individuals on the autism spectrum showed different performances rather than general limitation in all types of joint actions.

Advances in neuroimaging methods have enabled real-time observation of neural activation during live interactions. Specifically, functional near-infrared spectroscopy (fNIRS), which detects cortical activity by measuring hemodynamic responses in the brain, provides high spatial resolution and is well suited for capturing brain activity during dynamic and naturalistic interactions that may involve motion artifacts (Zhang and Roeyers, 2019). When applied in hyperscanning framework, fNIRS allows the simultaneous measurement of neural activity in interacting social partners, facilitating the study of interpersonal neural synchronization (Holper et al., 2012; Zhao et al., 2024). Given that inter-brain connectivity between partners during social interactions may differ from the neural mechanisms within an individual (i.e., intrapersonal mechanisms), brain-to-brain coupling offers novel insights. In particular, it reflects the fact that intentions and the meaning of the social context are shared between partners. This is because the process of observing, mirroring, or engaging in complementary or mutually adaptive actions reciprocally influences neural responses between individuals (or from the sender to the receiver). Reduced coupling or synchrony indicates disrupted social interactions or weakened social coordination (Hasson and Frith, 2016). Moreover, inter-brain synchrony has been found to correlate with behavioral synchrony. This highlights the neural mechanisms underlying social coordination, the interconnectedness of social behavior, and mutual brain alignment (Kinreich et al., 2017). Similarly, fNIRS offers insights into both the intrapersonal and interpersonal contexts that shape social skills through the interplay between perceptual and motor processes (Liu et al., 2019; Zhang and Roeyers, 2019). Notably, while other brain-imaging techniques have largely focused on observing and processing social information without requiring active engagement, fNIRS enables the investigation of neural correlates associated with active and dynamic participation in social interactions. This facilitates a more multifaceted approach to studying complex social behaviors (McDonald et al., 2019).

Beyond interpersonal interactions, fNIRS has been proven to be promising and increasingly beneficial in autism research. Atypical neural features, particularly in infants at a high risk of developing autism, support its potential as an early screening tool for autism-related symptoms (Conti et al., 2022; McDonald et al., 2019). Furthermore, independent studies have identified the neural mechanisms underlying interpersonal coordination, demonstrating atypical activation in the brain regions responsible for processing social and motor information in individuals on the autism spectrum. Previous reviews on fNIRS studies for this population have provided broad insights into the neural

correlates of social difficulties across a broad spectrum of behaviors (Liu et al., 2019; Zhang and Roeyers, 2019). However, a more focused investigation into the interplay between perceptual and motor aspects specific to social behaviors could help clarify the challenges in social perception, bodily coordination, and integration of these processes in live interactions. Furthermore, while existing studies have highlighted the complex nature of these mechanisms, establishing an integrative model of the neural correlates at play remains inconclusive.

Therefore, this study aims to present a comprehensive overview of research on social motor coordination, particularly focusing on joint action and its neural correlates, as examined through fNIRS methodologies, comparison individuals with ASC and NT individuals. By synthesizing findings across various tasks and brain regions of interest, this study particularly aims to offer insights into the neural mechanisms and potential underlying factors linked to this impaired coordination in this population on the spectrum.

2. Methods

2.1. Search methods and strategy

The literature search followed the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) guidelines. A comprehensive search was conducted to identify studies examining functional brain activation or inter-brain synchrony during joint action tasks involving individuals with ASC and NT individuals using the fNIRS methodology. Electronic databases (i.e., PubMed, Scopus, and Web of Science) were searched between September and October 2024. The search used the following keyword groups: population-related terms ('autism spectrum disorder, autism, autistic, ASD, or Asperger'), task-related terms ('joint action*, synchron*, interpersonal synchron*, social synchron*, social motor synchron*, social motor coordinat*, imitat*, or cooperat*'), and outcome-related terms ('functional near-infrared spectroscopy, near-infrared spectroscopy, fNIRS, NIRS, hyperscanning, inter-brain synchronization, interpersonal neural synchron* and brain-to-brain synchron*').

2.2. Inclusion criteria

The inclusion criteria were as follows: studies must include individuals with ASC, with no age restrictions, thus including both children and adults. Although studies that included both individuals with and without a clinical diagnosis of autism but conducted comparative analyses based on the level of autistic traits were included, studies that recruited only non-diagnosed individuals and compared them by high and low autistic traits were excluded. The primary task must involve both social and motor components, requiring two individuals (one with ASC and another as a partner) to engage jointly in a shared task involving purposeful movements. These movements must be intentional, initiated or adjusted during the task, and influenced by the partner in real time. Accordingly, studies in which participants only passively observed visual stimuli or listened to auditory stimuli without active movement were excluded. Gaze behaviors were also excluded, as they involve limited demands on explicit motor planning and primarily reflect cognitive processes even when eye movements are intentional. Additionally, studies must employ fNIRS to measure oxygenated hemoglobin (HbO2) or inter-brain synchrony (IBS) as the outcome variable. Regarding study design, only controlled studies with a comparison group of NT individuals without neurological disorders, including ASC, were included. Peer-reviewed empirical studies or theses/dissertations published in English were included, provided that full-text access was available.

2.3. Study quality assessment

The National Institutes of Health's (NIH) quality assessment tool for cross-sectional studies was used to evaluate the quality and risk of bias in each included study (National Heart, Lung, and Blood Institute (NHLBI), 2021). Each study was rated on the presented 14 items assessing methodological quality and categorized as "strong" ($\geq$ 80 % of items rated as 'yes'), "good" (70–79 %), "fair" (60–69 %), or "poor" ($<$ 60 %). The primary and second investigators independently reviewed each study, reaching a 98 % agreement on quality ratings. Any discrepancies were addressed through discussion with a third investigator.

A funnel plot was generated and visually examined for asymmetry to evaluate potential publication bias. Egger's regression was used to quantify asymmetry, with a p-value less than .10 indicating potential publication bias (Egger et al., 1997). The intercept value from Egger's test was analyzed to assess the degree and direction of bias, with greater deviation from zero suggesting more pronounced asymmetry, while the inclusion of zero within the confidence interval (CI) suggested limited asymmetry.

2.4. Data extraction and analysis

Descriptive information was extracted from all included studies, including sample sizes, age, and gender ratio. Details regarding the experimental tasks performed during fNIRS measurements, such as specific task types, motor and social aspects of the task, and regions of interest (ROIs) were also collected. Additionally, data on fNIRS measurements were documented, including the systems used, wavelengths, number of channels, and type of measures (e.g., cortical activation or inter-brain synchrony [IBS]).

Joint action tasks were categorized into four subtypes: imitation, synchronization, cooperation, and competition (see Table 1). Additionally, the nature of task was analyzed across two dimensions: motor involvement (involved body parts) and social-motor integration (temporal coordination and movement correspondence, both initiated and adjusted based on the perception of the partner's actions). The operational definitions of these subcategories are presented in Table 2. Regarding motor involvement, each study was classified by the body parts involved: oral motor movements (e.g., verbalization or reading), hand/finger movements, and whole-body movements. For temporal coordination, timing adjustment was categorized as sequenced, alternating, synchronous, and asynchronous, depending on the specific demands for mutual coordination. Sequenced tasks involve distinct and independent turns where precise temporal alignment is unnecessary, with each turn occurring once in succession (e.g., one individual performs a task, followed by the other), while alternating tasks involve repeated turn-taking. Synchronous tasks require individuals to execute movements simultaneously with precise temporal alignment. In contrast, asynchronous tasks involve conditions where individuals intentionally misalign their timing (e.g., moving faster than the other which often reflects a competitive dynamic). With regard to movement correspondence, tasks were classified as identical (where all individuals perform the same movements) or non-identical (where individuals engage in different movements). Non-identical movements were further examined to determine whether the differing movements were random

Table 1
Types of joint action and operational definitions.

Subtype of joint action	Operational definition
Imitation	Replicating the partner's movement with a primary focus on matching the form of the action, regardless of timing
Synchronization	Engaging in the same movement as the partner by continuously aligning the timing of identical actions
Cooperation	Performing the same or complementary actions with the partner to achieve a shared goal, either simultaneously or sequentially
Competition	Performing the same type of task as the partner, but with the intent to achieve a different or opposing goal

Table 2
Dimensions and categories for sub-analysis of joint action tasks.

Dimension	Sub-dimension	Description	Categories
Motor involvement	Involved body parts	The primary region of the body used to execute the movement	Oral motor, hand/finger, and whole-body
Social-motor integration	Level of temporal coordination	The alignment of timing between partners in joint actions	Sequenced, alternating, synchronous, and asynchronous
	Movement correspondence	The degree of interrelation between partners' movements in form or purpose	Identical, non-identical (random), and non-identical (complementary)

or complementary (where the initial movement influenced and determined the subsequent movement of the other individual, even if they were not identical).

With regard to the outcomes of each study, findings on cortical activation and IBS were summarized, with a specific focus on differences between ASC and NT groups. For cortical activation, only regions of interest (ROIs) measuring oxygenated hemoglobin (HbO2) were included if at least two studies compared them between ASC and NT groups. When identical ROIs were measured in both the left and right hemispheres, these data were analyzed separately to account for documented hemispheric asymmetries in this population, specifically during social tasks such as imitation or synchronization (Tamura et al., 2012; Zhu et al., 2014). Each subtype of joint action was analyzed individually: imitation, synchronization, cooperation, and competition. To enhance the robustness of effect size estimation given the small sample sizes, pooled effect sizes were calculated using standardized mean differences (Hedge's *g*). Given that many studies involved multiple task types and repeated measurements across various brain regions within the same sample, a three-level random-effects meta-analysis was conducted using restricted maximum likelihood (REML) to control for the dependency among effect sizes (Fernández-Castilla et al., 2020). This approach accounted for the hierarchical structure of the data, with individual effect sizes (Level 1) nested within studies (Level 3), and within-study variability modelled at Level 2.

For the cortical activation data, two studies (Culotta, 2019; Su et al., 2022) appeared to report overlapping datasets, with the latter study expanding on the former. To present overestimation of effect sizes and violation of statistical independence, only one dataset was included in the analysis. An initial three-level random-effects meta-analysis was conducted using all joint action data. Based on the result, moderator analyses were subsequently conducted with task type, brain region, and hemisphere included as potential moderators. Regarding task type, some studies included non-joint action tasks (i.e., passive observation without intentional action and individual motor task lacking the involvement of others) as comparators. To examine cortical activation during joint action relative to these non-joint action tasks, both were included in the moderator analysis, with observation set as the reference condition. Given that certain joint action subtypes (e.g., synchronization, cooperation, and competition) were reported in only a single study each, all subtypes were grouped into a single joint action category. In contrast, for analyses involving brain region and hemisphere, only joint action data were included, as the activation patterns during non-joint action tasks were conceptually distinct. To visually summarize group differences between ASC and NT groups, forest plots were generated for variables reported in at least two studies, ensuring sufficient data for meaningful comparison.

For IBS, one study (Zhou et al., 2024) was excluded from the meta-analysis because it did not directly compared groups. Instead, that study paired children with high and low autistic traits, focusing primarily on IBS in them as paired partners. For the remaining studies, two used averaged data extracted from multiple channels (Du et al., 2024) or aggregated estimates across ROIs (Kruppa et al., 2021), while one study selected data from the peak channel. As a result, in this meta-analysis, IBS estimates were not analyzed separately for each ROI. Instead, the representative effect size was either selected or calculated. For example, even when individual channel data were shared upon request by the investigator (Tang et al., 2023), the effect sizes was aggregated. Also, random-effect meta-analysis without multilevel structure was studied. Given that this approach did not fully account for task type or ROI-specific differences in IBS data, a descriptive analysis was additionally conducted for each study, considering the type of joint action and ROI.

During meta-analysis, the level of heterogeneity was assessed using the I^2 index (Higgins et al., 2003), with values interpreted as low when I^2 was less than 25%, moderate when between 25% and 50%, substantial when between 50% and 75%, and considerable when greater than 75%. A fixed-effect model was used when heterogeneity was modest to moderate, while a random-effect model was applied when heterogeneity was substantial to considerable. Publication bias was evaluated through visual inspection of funnel plots and tested using Egger's tests. Statistical analyses were conducted using R (version 4.4.2; R Core Team, 2019) and forest plots were generated with RevMan (version 10.1; The Cochrane Collaboration, London, UK).

Although personal factors such as autism severity (mild vs. moderate to severe) and age group (children vs. adults) could impact neural processes during joint action task types, subgroup or moderator analyses were not conducted due to limited number of studies within certain subgroups (only three studies involving individuals with mild autism symptoms and two studies involving adults with ASC). Instead, differences related to autism severity were descriptively considered when reviewing result trends. Additionally, the association between behavioral data and fNIRS data was examined. Given the limited number of studies, meta-regression was not feasible. Instead, evidence maps were created using matrix plots to visualize qualitative trends, thereby enriching the meta-analysis as a synthesis of quantitative evidence (Yang et al., 2025).

3. Results

3.1. Study selection

In this meta-analysis study, studies were identified to analyze individuals with ASC and NT individuals in comparison during joint action tasks using fNIRS. After initial search, 241 studies were retrieved. After removing duplicates and irrelevant studies, 93 studies were screened based on their titles and abstracts. The remaining 44 studies were then assessed through a full review of the original manuscripts. Following the exclusion of studies that did not meet the inclusion criteria, 11 studies were included in the final analysis. Of these, nine were included in the meta-analysis, as one study did not directly compare the ASC and NT groups for neural data and the other presented overlapping dataset with a study already included. The first and second authors independently evaluated the articles and agreed upon the selected studies. The selection process is summarized in the PRISMA chart (Fig. 1).

3.2. The quality of assessment of the included studies

When the quality of the included studies was systematically reviewed using the NIH Quality Assessment Tool for Cross-Sectional Studies (NHLBI, 2021), of the 11 studies analyzed, two were rated as "strong," five as "good," three as "fair," and one as "poor." The detailed ratings are presented in Table 3. Studies rated as "strong" fully adhered

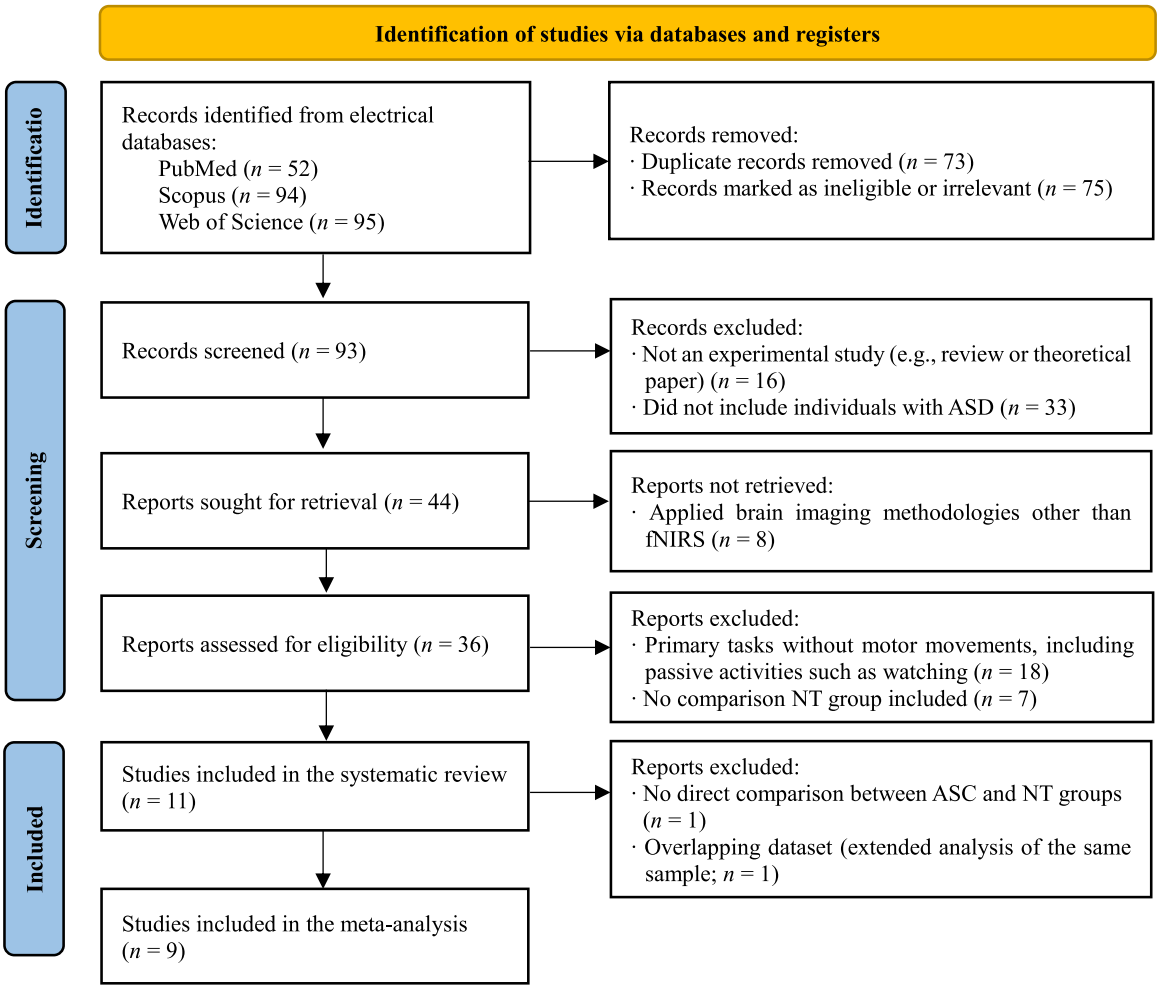


Fig. 1. PRISMA flow diagram of study selection.

to key criteria, including clear research questions, valid measurements, and proper adjustment for confounding variables, ensuring methodological rigor and reliability. Studies categorized as "good" met most criteria but showed limitations, such as insufficient sample size justification or incomplete adjustment for confounders. Studies rated as "fair" demonstrated moderate concerns, such as unclear definitions of the study population or inconsistent sampling methods, potentially affecting their validity and reliability. The single study rated as "poor" displayed significant deficiencies in clearly defining its sampling strategies and reporting outcomes, raising concerns about its validity.

3.3. Characteristics of participants

The included studies involved a total of 208 individuals with ASC, including 162 children and adolescents, and 46 adults. The mean age of the children and adolescents was 10.2 years ($SD = 2.3$), and 29.3 years ($SD = 7.6$) for the adults. In the comparison group of NT individuals, a total of 255 individuals were included, with 207 children and adolescents, and 48 adults. Nine studies involved children and adolescents with a mean age of 10.4 years ($SD = 2.3$), while two studies involved adults with a mean age of 28.1 years ($SD = 7.2$). Regarding autism severity, eight studies involved individuals with moderate to severe autistic symptoms, while three studies involved individuals with relatively mild symptoms. Detailed information is presented in Table 4.

3.4. Publication bias assessment

When studies directly comparing two groups and providing sufficient data for effect sizes were considered ($n = 9$), the results of Egger's test indicated no significant asymmetry in the funnel plot ($Z = 0.40$, $p = .69$). The intercept was estimated at $b = -0.16$ with a 95 % CI ranging from −0.98 to 0.67, which includes zero, suggesting limited evidence of publication bias. The funnel plot is shown in Fig. 2.

3.5. Analyzed social motor coordination tasks

In this study, joint action tasks from the included studies measuring cortical activation or neural synchrony in individuals on the autism spectrum were further analyzed to see which aspects of the task may influence neural mechanism, given their intricate nature. Table 5 presents a task-specific analysis of motor and cognitive aspects of tasks examined in each study.

Firstly, joint action tasks were categorized by subtype. If two different tasks were included in a single study, each was counted separately. Imitation and cooperation tasks were included in six studies, while competition and synchronization tasks were applied in two and one studies, respectively. Four studies incorporated and compared multiple task types: imitation and cooperation in *Culotta, 2019, cooperation and competition in Kruppa et al. (2021), imitation, cooperation, and competition in Su et al. (2022). In addition, Zhou et al. (2024) applied two different cooperation tasks.

Joint action tasks were also analyzed in terms of motor involvement

Table 3
Quality assessment of the included studies.

Assessment criteria	Culotta (2019)	Du et al. (2024)	Krishnan-Barman et al. (2023)	Kruppa et al. (2021)	Quinones-Camacho et al. (2021)	Su et al. (2020)	Su et al. (2021)	Su et al. (2022)	Su et al. (2023)	Tang et al. (2023)	Zhou et al. (2024)
Clearly stated research question	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Clearly defined study population	N	Y	N	Y	N	N	Y	Y	Y	Y	N
Sufficient participation rate	N	Y	Y	Y	Y	N	N	N	N	N	Y
Specified sampling methods	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Sample size justification	N	Y	Y	N	N	N	N	N	N	N	Y
Exposure measured prior to outcome	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Sufficient timeframe	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Examination of different levels of exposure	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Valid exposure measurement	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Repeated assessment of exposure	N	N	N	N	N	N	N	N	N	N	N
Valid outcome Measurement	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Blinding of outcome assessors	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Low loss to follow-up	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Adjustment for confounding variables	Y	N	N	Y	Y	Y	Y	Y	N	N	Y

and social-motor integration. For motor involvement, tasks were categorized based on the body parts involved: oral motor movement ($n = 2$), hand/finger movement ($n = 13$), and whole-body movements ($n = 1$). Notably, nine studies (82 %) involved hand/finger movements, such as manipulating objects (building blocks or key/button pressing). Regarding social-motor integration (i.e., the level of temporal coordination and social-motor integration), tasks that requires synchronous movement comprised the largest portion ($n = 9$), followed by alternating ($n = 4$), asynchronous ($n = 2$) and sequenced tasks ($n = 1$). Among these, 11 out of 16 trials involved tasks that required participants to execute movements identical to those of their partner.

Considering all aspects, imitation tasks primarily involved hand/fingers movements. Participants were often asked to replicate small, simple movements, by observing and replicating simultaneously, or by observing and replicating them later. Synchronization tasks were observed in only one study, involving continuous whole-body movements that were temporally coordinated with a partner. Cooperation tasks also predominantly involved hand/finger movements, either synchronously or in an alternating way. Participants were required to complete the joint task together, either simultaneously or by taking turns to build on their partner's efforts and contribute to the shared goal. Competition tasks were included in parallel with cooperation tasks, using the same structure but adding a competitive element, typically requiring faster performance than the partner (see Fig. 3).

3.6. fNIRS measurement

Tables 6 and 7 summarize the results of fNIRS measurement during joint action tasks comparing the ASC and NT groups. Table 6 presents findings from studies measuring cortical activation, while Table 7 displays findings from studies measuring inter-brain synchrony between participants and their partners in each group.

For three-level random-effects meta-analysis, when data from joint action tasks were pooled across all conditions without differentiating task subtypes ($k = 54$), the pooled effect size was not statistically significant, Hedges' $g = -0.002$, $SE = 0.20$, 95 % CI [-0.39, 0.39], $p = .99$. Analysis of the variance components indicated that 34.1 % of the heterogeneity was attributed to between-study differences at Level 3 ($\sigma^2 = 0.14$), while 65.9 % was due to within-study variability at Level 2 ($\sigma^2 = 0.26$). A substantial level of heterogeneity was also observed across effect sizes, $Q(53) = 171.22$, $p < .0001$, supporting the need for moderator analyses.

Regarding task type, when non-joint action tasks were included and observation condition was set as the reference, the overall test of moderators was not statistically significant, $Q_M(2) = 5.08$, $p = .08$, indicating that task type accounted for the heterogeneity at a marginal level. However, individual comparisons showed notable trends. Compared to observation, joint action tasks showed a significantly smaller and negative effect size, Hedges' $g = -0.38$, $p = .03$, indicating greater cortical activation in the NT group than in the ASC group. In contrast, individual motor tasks did not yield statistically significant differences relative to observation.

Table 4
Characteristics of the studies included in the meta-analysis.

Study	ASC Group				NT Group			fNIRS Measurement			Task*	ROI
	N	M: F	Autism severity (screening)	Age (yrs)	*n*	M: F	Age (yrs)	System	Wave length (nm)	Channel		
Culotta (2019)	15	12: 3	M-S (VABS 65.9/ 71.1; SS 78.9/ 75.5)	11.5	15	8: 7	12.2	ETG−4000, Hitachi	695, 830	38	To build logs individually, by leading or imitating* a partner synchronously, or by alternating turns* to construct a configuration cooperatively prompted by cards	MFG, IFG, PCG, STS, IPL
Du et al. (2024)	20	15: 5	M-S (SRS 90.5)	6.1	20	16: 4	5.1	NirSmart, Danyang Huichuang	730, 850	20	To imitate meaningful and meaningless gestures simultaneously	IFG, IPL, TPJ
Krishnan-Barman et al. (2023)	22	17: 5	Mi (AQ 32.2; IQ 115)	33.8	22	16: 6	30.2	LabNIRS, Shimadzu	780, 805, 830	44	To imitate a partner's movements (moving blocks) in sequence while either being watched* or unwatched	IPL, TPJ, STS, MTG, LO
Kruppa et al. (2021)	18	18: 0	M-S (SRS 84.5)	13.5	41 (18[a])	41: 0	12.7	ETG−4000, Hitachi	NR	22	To press the button to complete the game simultaneously* or faster than the partner*	lFPC, lDLPFC, mFPC, BA 8, rFPC, rDLPFC
Quinones-Camacho et al. (2021)	24	11:4	Mi (SRS 74.1; IQ 110)	25.1	26	11:6	26.3	ETG−4000, Hitachi	760, 850	8	To speak with a partner by taking turns about the presented topic	PFC, TPJ
Su et al. (2020)	14	9: 5	M-S (SCQ 25.6; VABS 70.6; IQ 79.6)	11.3	17	11: 6	10.8	ETG−4000, Hitachi	695, 830	22	To observe a partner performing a clean-up action, perform it individually, or imitate the partner simultaneously*	MIFG, IPL, MSTG
Su et al. (2021)	15	12: 3	M-S (SRS T77.7)	12.7	15	10: 5	12.5	ETG−4000, Hitachi	695, 830	32	To observe a partner's swaying movements, sway individually, or sway synchronously with the partner while either facing each other or touching fingertips*	MFG, IFG, PCG, STS, IPL
Su et al. (2022)	15	12: 3	M-S (SCQ 24.5; VABS 71.1; SRS 78.7)	11.5	15	8: 7	12.2	ETG−4000, Hitachi	695, 830	38	To build logs by leading or imitating a partner synchronously*, alternating turns* to construct a configuration cooperatively prompted by cards, or competing to complete the task faster than the partner*	MFG, IFG, PCG, STS, IPL
Su et al. (2023)	15	11: 4	M-S (SCQ 24.5; VABS 71.1; SRS 78.7)	11.1	17	11: 6	10.8	ETG−4000, Hitachi	695, 830	24	To observe a partner performing communicative gestures, perform the gestures depicted in pictures individually, and imitate the partner's gestures simultaneously*	MIFG, MSTG, IPL
Tang et al. (2023)	36	30: 6	Mi (CARS 32.2)	8.0	35	21: 14	8.2	ETG−4000, Hitachi	695, 830	22	To press a key simultaneously with a partner, following the previously discussed cooperation strategy	Right frontal–parietal region
Zhou et al. (2024)	14	11: 3	M-S (BAPQ 115.1)	10.4	32	24: 8	9.9	NIRScout, NIRx	760–850	16.6 (regular), 6.7 (short)	To watch a video alone or together (Study 1), read a book jointly with a partner* (Study 2), and either play a Jenga game with a partner* or pretend to do so (Study 3)	lFC, rFC, lTP, rTP

a. Number of NT group members included in the matched comparison.
*Indicating the joint action task considered for inclusion in the meta-analysis when multiple tasks or conditions were used.
Note. ASC = autism spectrum condition; NT = neurotypical; M = male; F = female; ROI = region of interest; M-S = moderate to severe; VABS = Vineland Adaptive Behavior Scales; SS = Socialization Subscale; MFG = middle frontal gyrus; IFG = inferior frontal gyrus; PCG = pre- and post-central gyrus; STS = Superior temporal sulcus; IPL = inferior parietal lobule; SRS = Social Responsiveness Scale; TPJ = temporo-parietal junction; Mi = mild; AQ = Autism-Spectrum Quotient; IQ = Intelligence Quotient; MTG = middle temporal gyrus; LO = lateral occipital cortex; NR = not reported; l = left; FPC = frontopolar cortex; DLPFC = dorsolateral prefrontal cortex; m = medial; BA = Brodmann area; r = right; PFC = prefrontal cortex; SCQ = Social Communication Questionnaire; MIFG = middle and inferior frontal gyri; MSTG = middle and superior temporal gyri; CARS = Childhood Autism Rating Scale; BAPQ = Broad Autism Phenotype Questionnaire; FC = frontal cortex; TP = temporoparietal area.

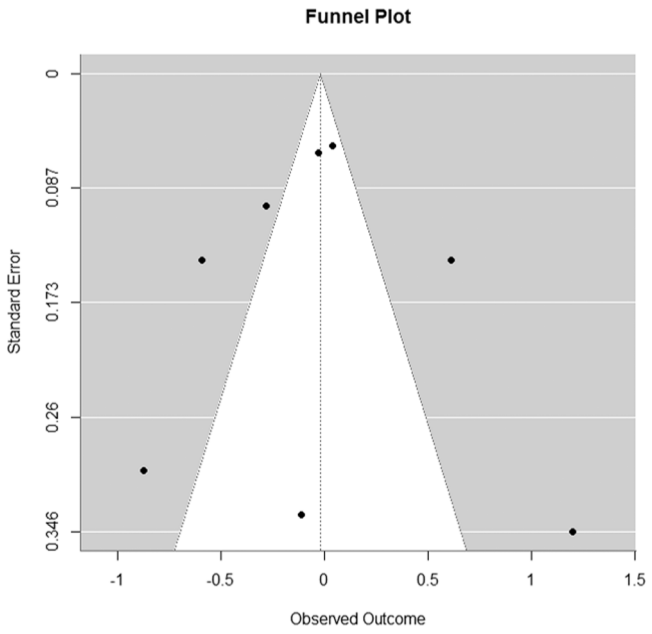


Fig. 2. Funnel plot results for publication bias assessment.

Regarding brain region, the overall test of moderators was significant, $Q_M(4) = 27.25$, $p < .001$, indicating that brain region accounted for a significant portion of the heterogeneity. Using IFG as the reference, IPL showed a significantly larger group difference compared to the IFG, Hedges' $g = 0.63$, $p = .003$, indicating relatively stronger activation in the ASC than in the NT group. In contrast, the STS showed a significantly smaller group difference compared to the IFG, with a negative effect size, Hedges' $g = -0.42$, $p = .04$, indicating greater activation in the NT group specifically in this region. For hemisphere, using only joint action data, the overall moderator test was not significant, $Q_M(1) = 0.005$, $p = .943$. No significant differences were observed between the left and right hemispheres, Hedges' $g = -0.01$, $p = .96$, indicating that hemispheric lateralization did not moderate the group differences in cortical activation. Table 8 summarizes the results of moderator analyses.

For IBS, the pooled effect size was small and not statistically significant, indicating no substantial differences in brain synchrony patterns between the ASC and NT groups, Hedges' $g = 0.05$, $SE = 0.41$, 95 % CI [-0.75, 0.86], $p = .90$. Significant heterogeneity was observed across studies, $Q(3) = 20.61$, $p < .001$, $I^2 = 91.3$ %.

Forest plots were then generated for variables reported in at least two independent studies. For cortical activation, plots were created for the IFG, IPL, and STS regions during imitation tasks. For IBS, pooled effect sizes from four included studies were visualized (see Fig. 4). Among the cortical regions, a significant effect size was observed only in the IPL. The IPL showed a small-to-moderate effect, indicating significantly higher activation in the ASC group compared to the NT group, Hedges' $g = 0.34$, 95 % CI [0.05, 0.64], $Z = 2.27$, $p = .02$, $I^2 = 57$ %. The pooled effect size for IBS was small, Hedges' $g = -0.34$, 95 % CI [-0.73, 0.05], $Z = 1.71$, $p = .09$, $I^2 = 77$ %. Although it did not reach significance, this marginal trend suggests a possible decrease in brain synchrony in the ASC group, compared to the NT group.

Fig. 5 presents a visual summary of the meta-analysis findings, incorporating results from the moderator analysis for cortical activation studies and random-effect analysis for studies measuring IBS, highlighting significant differences between the ASC and NT groups. For cortical activation, the moderator analysis indicated that during joint action tasks, the ASC group showed significantly increased IPL activation and decreased STS activation compared to the NT group. Greater IPL activation was further supported by a separate meta-analysis for studies including imitation tasks, which yielded a significant effect size in the same direction. For IBS, due to small number of studies and high heterogeneity, moderator analysis and pooled effect estimates were not conducted. Instead, descriptive summaries of individual studies are presented. Notably, two studies with significant effect sizes reported reduced IBS in the ASC group: one in the IPL during imitation and another in the TPJ during cooperation tasks.

The current study further investigated whether behavioral and fNIRS outcomes are associated, and whether this association varies by autism

Table 5
Motor and cognitive aspects of interpersonal synchronization tasks in the included studies.

Study	Partner	Type of joint action	Motor involvement		Social-motor integration	
			Movement type	Involved body parts	Temporal coordination	Movement correspondence
Culotta (2019)	Adult stranger	• Imitation • Cooperation	Manipulating object positions (building blocks)	• Hand/finger • Hand/finger	• Synchronous • Alternating	• Identical • Non-identical (compl)
Du et al. (2024)	Adult stranger	Imitation	Manipulating objects while holding them (e.g., shaking a bell)	Hand/finger	Synchronous	Identical
Krishnan-Barman et al. (2023)	Adult stranger	Imitation	Manipulating object positions (moving blocks)	Hand/finger	Sequenced	Identical
Kruppa et al. (2021)	Parents and adult stranger	• Cooperation • Competition	Button pressing	• Hand/finger • Hand/finger	• Synchronous • Asynchronous	• Identical • Identical
Quinones-Camacho et al. (2021)	Adult stranger	Cooperation	Articulating words during a conversation	Oral motor	Alternating	Non-identical (compl)
Su et al. (2020)	Adult stranger	Imitation	Manipulating object positions (clean-up action)	Hand/finger	Synchronous	Identical
Su et al. (2021)	Adult stranger	Synchronization	Swaying	Whole-body	Synchronous	Identical
Su et al. (2022)	Adult stranger	• Imitation • Cooperation • Competition	Manipulating object positions (building blocks)	• Hand/finger • Hand/finger • Hand/finger	• Synchronous • Alternating • Asynchronous	• Identical • Non-identical (compl) • Non-identical (random)
Su et al. (2023)	Adult stranger	Imitation	Simple gestures (e.g., waving and thumbs-up gesture)	Hand/finger	Synchronous	Identical
Tang et al. (2023)	Parents	Cooperation	Key pressing	Hand/finger	Synchronous	Identical
Zhou et al. (2024)	Age-matched peer (a peer with a low level of autistic traits)	• Cooperation • Cooperation	• Reading books • Manipulating object positions (playing a Jenga game)	• Oral motor • Hand/finger	• Synchronous • Alternating	• Identical • Non-identical (compl)

Note. Compl = complementary.

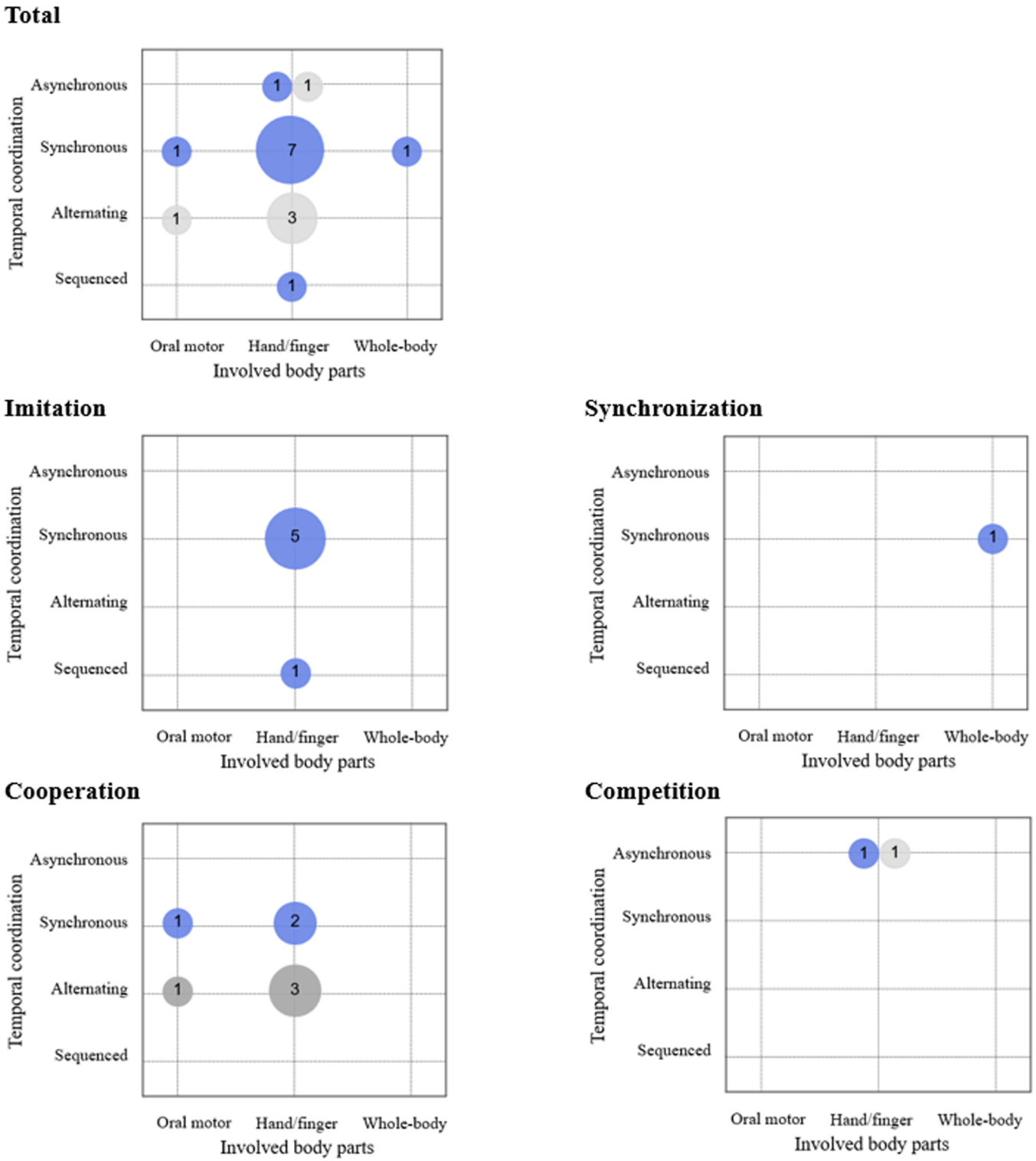


Fig. 3. Evidence maps illustrating the dimensions of social motor tasks applied in the included studies, based on the body parts involved (x-axis) and level of temporal coordination (y-axis). With regard to movement correspondence, blue bubbles indicate identical movements between partners, while gray bubbles represent non-identical movements. The bubble sizes reflect the number of studies, with the number indicating the exact count.

severity. For this analysis, a single pooled effect size was calculated per study for both behavioral and neural data, integrating repeated measures across multiple tasks and brain regions. Each effect size was used to indicate the magnitude of group differences (i.e., whether outcomes were greater in the ASC group or the NT group, or showed no significant differences). Table 9 summarizes the task characteristics and measurement details of each study, and Fig. 6 illustrates the integrated group differences in behavioral and neural outcomes across studies.

Subgroups with mild versus moderate-to-severe autism symptoms demonstrated distinct patterns in behavioral performance and corresponding neural outcomes (i.e., cortical activation and IBS). Individuals with mild autism symptoms showed no significant behavioral differences with the NT group, while those with more severe symptoms exhibited significantly reduced behavioral performance. Interestingly,

Table 6
The fNIRS results from the group comparisons in each included study assessing cortical activation.

Study	Main findings from group comparison
Krishnan-Barman et al. (2023)	Significantly greater activation of the STG in the ASC group compared to the NT group when imitating movements while being watched by a partner
Su et al. (2020)	Significantly lower activation of the right MIFG and the left MSTG and greater activation of the IPL in the ASC group compared to the NT group when imitating the sequenced motor task simultaneously with a partner
Su et al. (2021)	Significantly lower activation of the IFG and STS and greater activation of IPL when swaying simultaneously in time with a partner, either while facing each other or touching
Su et al. (2022)	• Significantly lower activation of the left STS when imitating the partner's movement simultaneously • Significantly lower activation of both the left and right STS and greater activation of the left IPL when cooperatively performing the motor task while alternating turns with a partner
Su et al. (2023)	Significantly lower activation of the MSTG and greater activation of the MIFG and IPL when imitating a partner's gestures simultaneously

Note. STG = superior temporal gyrus; ASC = autism spectrum condition; NT = neurotypical; MIFG = middle and inferior frontal gyrus; MSTG = middle and superior temporal gyrus; IPL = inferior parietal lobule; IFG = inferior frontal gyrus; STS = superior temporal sulcus.

Table 7
The fNIRS results from the group comparison in each included study assessing inter-brain synchrony.

Study	Partner	Type of joint action	ROI	Main findings from group comparison
Du et al. (2024)	Adult stranger	Imitation	rIPL	• IBS in meaningless gesture condition: ASC < NT • IBS in meaningful gesture condition: ASC > NT
Kruppa et al. (2021)	Parents and adult stranger	Cooperation	FP	No significant group differences
Quinones-Camacho et al. (2021)	Adult stranger	Cooperation	lTPJ, rTPJ	IBS in a conversation task condition: ASC < NT
Tang et al. (2023)	Parent	Cooperation	FP (SFC)	No significant group differences
Zhou et al. (2024)	Age-matched peer (a peer with a low level of autistic traits)	Cooperation	FC, TP	• Increased IBS between the FC in the group with high autistic traits and TP in the group with low autistic groups, as well as between the TPs in both partners during joint book reading, negatively correlating with the autism quotient

Note. ROI = region of interest; r = right; IPL = inferior parietal lobule; IBS = Inter-brain synchrony; ASC = autism spectrum condition; NT = neurotypical; FP = frontal-parietal region; l = left; TPJ = temporo-parietal junction; r = right; SFC = superior frontal cortex; FC = frontal cortex; TP = temporoparietal area.

even when behavioral performances were comparable to that of the NT group as seen in the mild subgroups, the ASC group tended to show distinct patterns of neural activation and coupling.

Specifically, for cortical activation, individuals in the ASC group who showed significantly more behavioral errors and less accurate or synchronized movements also exhibited reduced activation in brain regions associated with the mirror neurons system, such as the IFG, IPL, and STS. For IBS, neural outcomes varied across the four studies. Two studies reported no group differences in IBS, while the other two demonstrated inconsistent patterns, with one indicating increased synchrony in the IPL for the ASC group and the other showing decreased synchrony in the TPJ. These contrasting results may be due to context-dependent effects on neural coupling, likely linked to greater heterogeneity in task design among IBS studies. While cortical activation was primarily measured during imitation tasks involving relatively homogeneous processes of replicating simple movements, IBS was examined in cooperation tasks involving broader and more varied forms of mutual adjustments.

Table 8
Moderator effects of task type, brain region, and hemisphere on cortical activation differences between ASC and NT groups.

Moderator	Hedges' *g*	*SE*	*Z*	95 % CI	*p*
Task type					
Intercept (Observation)	0.31	0.17	1.85	[−0.02, 0.63]	.07
Individual movement	−0.28	0.17	−1.61	[−0.62, 0.06]	.11
Joint action tasks	−0.38	0.17	−2.25	[−0.71, −0.05]	.03*
Brain region					
Intercept (IFG)	0.05	0.33	0.16	[−0.60, 0.71]	.87
IPL	0.63	0.21	3.03	[0.22, 1.04]	.002**
MFG	0.03	0.24	0.11	[−0.44, 0.50]	.91
PCG	0.28	0.24	1.19	[−0.19, 0.75]	.24
STS	−0.42	0.21	−2.03	[−0.83, −0.01]	.04*
Hemisphere					
Intercept (Left)	−0.01	0.22	−0.05	[−0.43, 0.41]	.96
Right	0.01	0.17	0.07	[−0.33, 0.35]	.94

Note. IFG = inferior frontal gyrus; IPL = inferior parietal lobule; MFG = middle frontal gyrus; PCG = pre- and post-central gyrus; STS = superior temporal sulcus.

4. Discussion

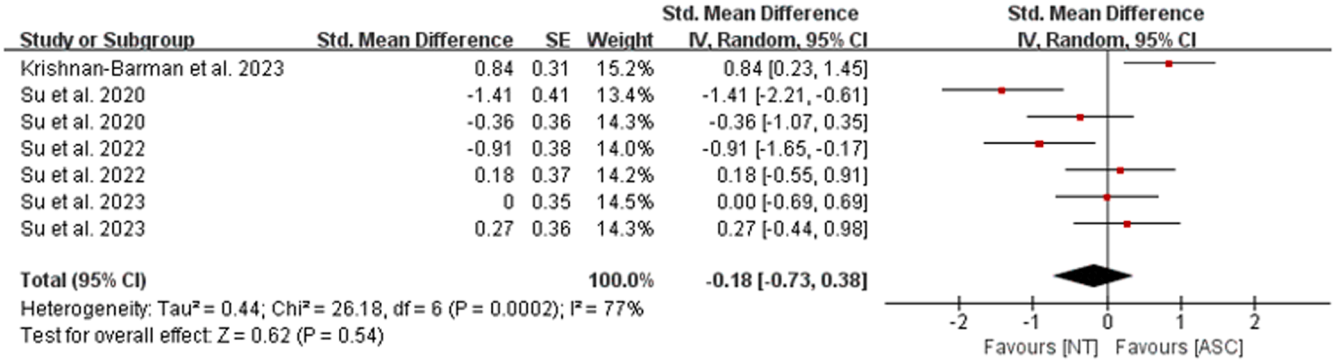
This study systematically reviewed research on joint action tasks in which individuals with ASC engaged in live, real-time interactions with partners, examining neural patterns such as cortical activation and IBS using fNIRS. A meta-analysis was conducted to synthesize findings regarding differences in neural substrates between the ASC group and their neurotypical counterparts across these tasks. To further explore factors influencing these neural mechanisms, additional analyses examined associations with individual characteristics, specifically autism severity, and behavioral performance, supported by descriptive and visual inspection. A total of 11 studies were included in the review, with 9 included in the meta-analysis after excluding two studies: one that lacked a direct comparison between the ASC and NT groups and another that involved an overlapping dataset as an extended analysis of a previously included sample. For the visual inspection of the relationship between fNIRS and behavioral data, one study was excluded due to the absence of behavioral measures, resulting in 10 studies being considered for that analysis.

4.1. Scope of joint action tasks

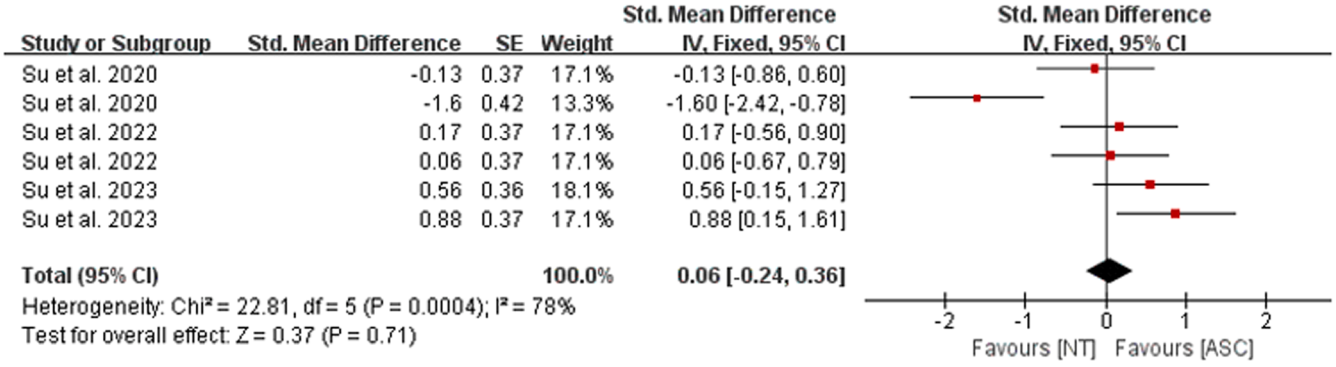
An examination of the joint action task types in the included studies demonstrated that imitation and cooperation tasks were most commonly

A. Cortical activation (Imitation task)

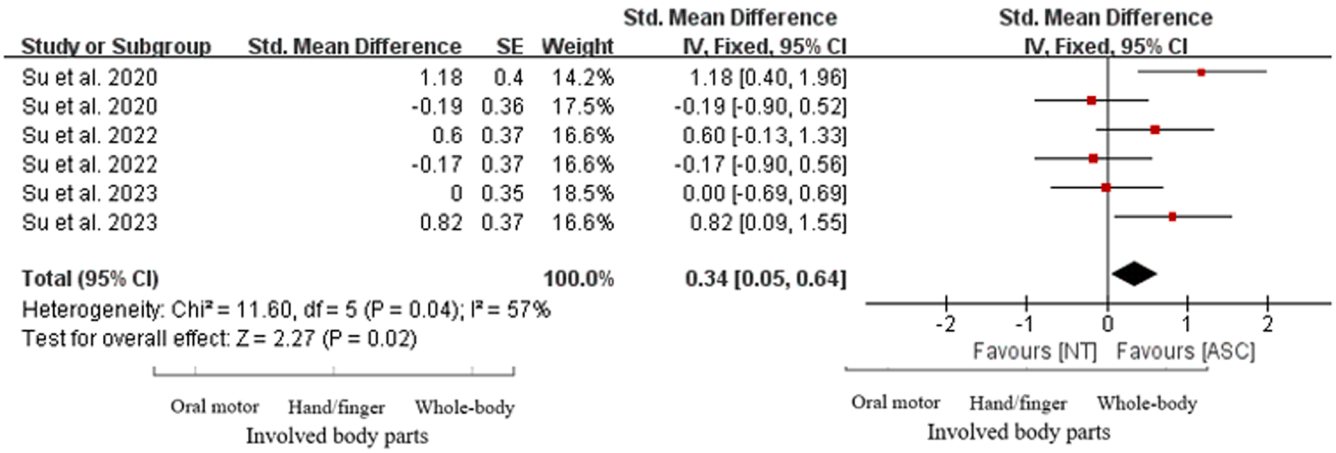
STS



IFG



IPL



B. Inter-brain synchrony

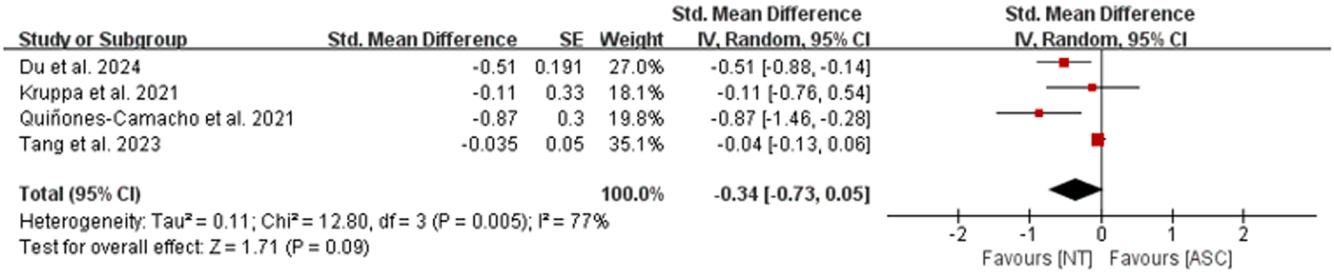


Fig. 4. Forest plots of effect sizes comparing ASC and NT groups in cortical activation during imitation tasks (Panel A) and IBS (Panel B). For cortical activation, data from left and right hemisphere of each brain region are presented in sequential order within each study.

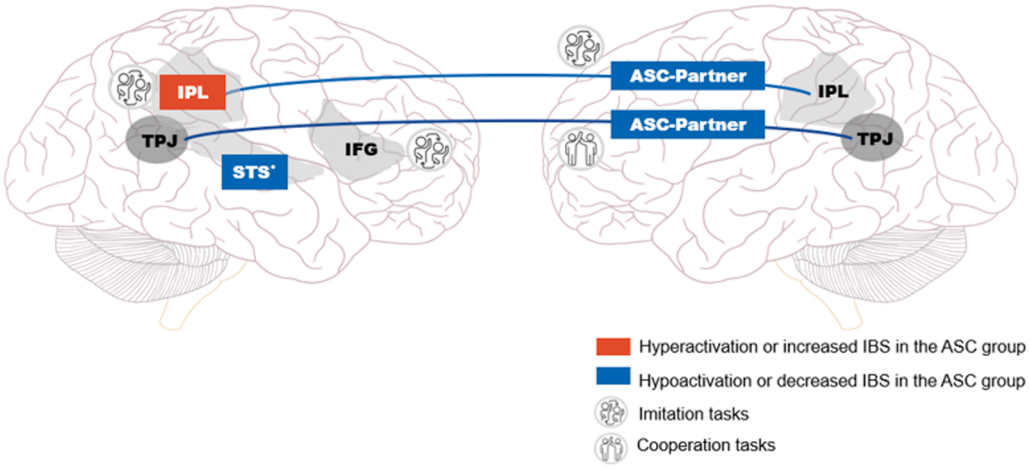


Fig. 5. Summary of meta-analysis results illustrating cortical activation and IBS differences between the ASC and NT groups during joint action tasks. Brain regions shaded in red or blue indicate areas with significant pooled effect sizes. ASC = autism spectrum condition; NT = neurotypical individuals; IPL = inferior parietal lobe; STS = superior temporal sulcus; IFG = inferior frontal gyrus; TPJ = temporoparietal junction.
*Since the STS result are derived from a moderator analysis that integrates all type of joint action tasks, specific task types are not indicated in this diagram.

Table 9
Pattern of group differences in behavioral and fNIRS data.

Measurement	Author	Autism severity	Joint action task type	Behavioral data		fNIRS data	
				Measures	Pooled ES	ROI[a]	Pooled ES
Cortical Activation	Krishnan-Barman et al. (2023)	Mi	Imit	Peak height of motion	ASC ≈ NT	STG	**ASC** > NT
	Su et al. (2020)	M-S	Imit	Behavioral coding for synchrony	ASC < **NT**	IPL, MIFG, MSTG	ASC < **NT**
	Su et al. (2021)	M-S	Sync	Motion synchrony	ASC < **NT**	IFG, STS	ASC < **NT**
	Su et al. (2022)	M-S	Imit	Movement errors	ASC < **NT**	IPL, STS	ASC < **NT**
	Su et al. (2023)	M-S	Imit	Movement errors	ASC < **NT**	IPL, MIFG	ASC < **NT**
IBS	Quinones-Camacho et al. (2021)	Mi	Coop	Frequency of utterance	ASC ≈ NT	TPJ	ASC < **NT**
	Tang et al. (2023)	Mi	Coop	Winning ratio	ASC ≈ NT	NS	ASC ≈ NT
	Du et al. (2024)	M-S	Imit	Movement accuracy and synchrony	ASC < **NT**	IPL	**ASC** > NT
	Kruppa et al. (2021)	M-S	Coop	Reaction time	ASC < **NT**	NS	ASC ≈ NT

Note. ES = effect size; Mi = mild; Imit = imitation; ASC = autism spectrum condition; NT = neurotypical; STG = superior temporal gyrus; M-S = moderate to severe; IPL = inferior parietal lobule; MIFG = middle and inferior frontal gyri; MSTG = middle and superior temporal gyri; Sync = synchronization; IFG = inferior frontal gyrus; STS = superior temporal sulcus; Coop = cooperation; TPJ = temporo-parietal junction.
[a]Brain regions of interest showing significant group differences.

used, whereas synchronization and competition tasks were applied in only one and two studies, respectively. Regarding the dimensions of joint action tasks, those involving fine motor skills (i.e., hand and finger movements) were most frequently applied, either during imitation or cooperation with partners. In terms of motor involvement, these tasks often required object manipulation, which tend to constrain movement options due to the physical properties of objects. Such goal-directed actions may simplify motor demands, and, in turn, facilitate imitation in individuals with ASC (Vivanti et al., 2008). Studies have shown that individuals with ASC make more frequent attempts at imitation and demonstrate improved task performance when engaging in meaningful and purposeful movements such as tool use. This is particularly evident when compared to meaningless sequences of finger movements, even when the latter are motorically simpler (Rogers et al., 2010; Williams et al., 2004). This suggests that both the cognitive and motor demands of jointly engaged movements are significantly influenced by the semantic relevance of the movement, which, in turn, affects task performance in this population.

Regarding the demands for social-motor integration, the included studies identified various combinations of temporal coordination and movement correspondence that can be structured to elicit different levels of social coordination. Synchronous coordination was the most frequently applied form of joint action. It commonly required identical movements, necessitating participants to replicate the movements initiated by their partner. Such tasks required ongoing engagement in joint action and continuous observation and perception of the partner's movements, which are then incorporated into one's movement plans (Vivanti et al., 2008). These findings illustrate the extent to which movement-based tasks are inherently social and extend beyond motor execution. This suggests that social tasks for this population can be systematically designed to integrate both perceptual and motor components. This, in turn, provides a more structured framework for understanding social coordination rather than treating it as a singular construct.

The synchronization task was minimally applied in the included fNIRS studies, despite increasing research interest in this area. This is especially notable given the role of timing information in social actions and joint action (LaGasse et al., 2024; Sebanz et al., 2006). This gap may limit the development of a more comprehensive understanding of the neural mechanisms underlying joint actions in this population. One possible explanation is that many of the tasks in the reviewed studies implicitly incorporated synchronous coordination but placed greater emphasis on the immediate mirroring of movement patterns or cooperative goal-directed actions, rather than isolating synchronization as a distinct feature. Thus, they aligned more closely with imitation or cooperation. In contrast, general interpersonal synchronization tasks focus on maintaining identical movements, in which timing precision is prioritized over specific goals or potentially adaptable motor sequences

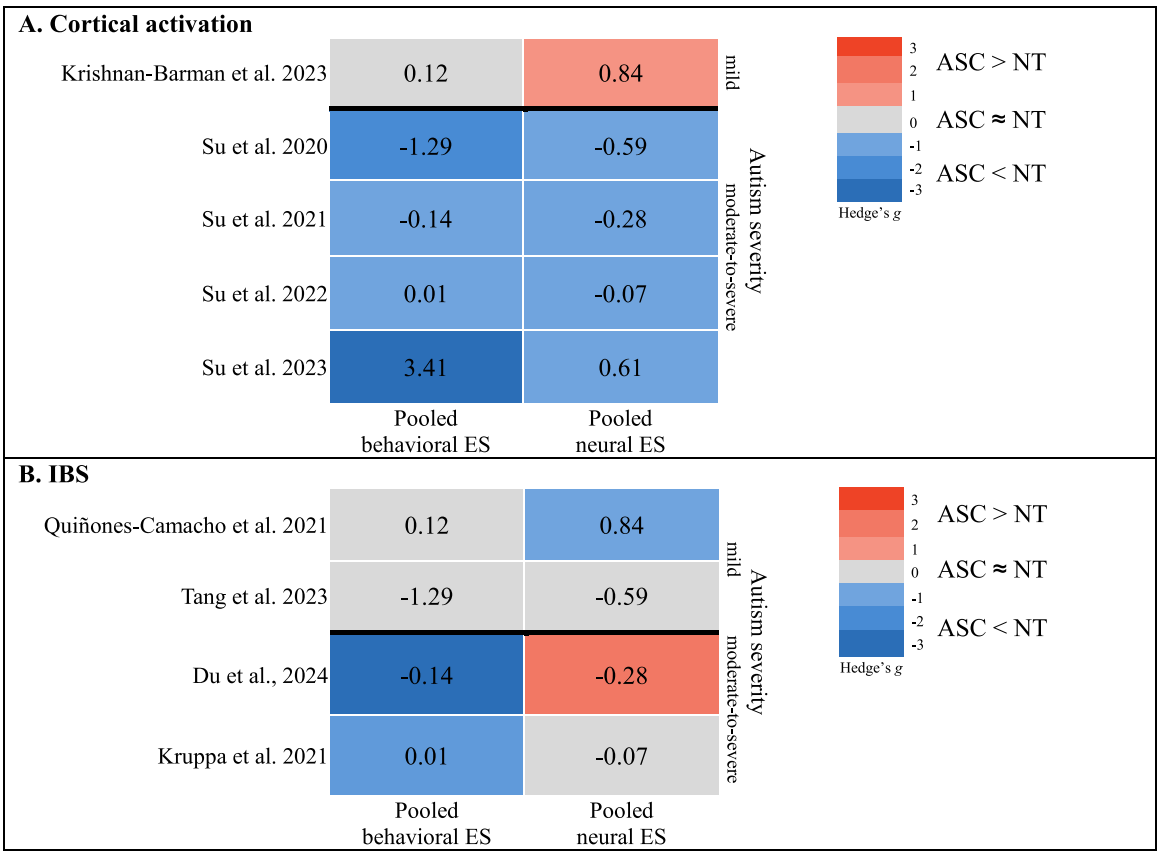


Fig. 6. Matrix plot showing pooled behavioral and neural effect sizes (Hedge's *g*) for ASC versus NT groups, with the color scale denoting the magnitude of the effect. Red shades represent greater values in the ASC group, while blue shades indicate greater values in the NT group. Each panel corresponds to a different measurement type. Within each panel, studies are further categorized by autism severity, with the bold horizontal line separating studies involving individuals with mild symptoms (above) from those with moderate to severe symptoms (below).

(Tognoli et al., 2007). Although the findings of this study may be relevant to synchronization tasks, further research is needed to systematically determine whether synchronization relies on similar neural substrates, or if imitation or cooperation imposes additional cognitive demands related to understanding joint goals and executing more precise motor actions.

4.2. *Meta-analysis results for fNIRS measurement*

This meta-analysis highlighted distinct neural substrates, showing that the differences between the ASC and NT groups varied depending on specific brain regions measured by fNIRS. Atypical social processing in individuals with ASC is widely documented. However, the current findings extend this discussion by integrating differential neural engagement across various social tasks, each involving the processing of the temporal and spatial aspects of movement control at different levels.

Moderator analyses demonstrated that group differences in cortical activation during observation and individual movement tasks were not significantly different. In contrast, joint action tasks resulted in a significantly smaller effect size compared to observation, indicating decreased activation in the ASC group relative to their NT counterparts. Although observation is consistently considered a weakness in individuals with ASC, commonly attributed to reduced motivation to share gazes and process socially relevant attentional cues, the degree of group differences in neural activation during observation did not differ significantly from that during individual movement tasks. This suggests that the reduced activation in the ASC group cannot be explained solely by deficits in perceptual or motor processing. Instead, it may reflect difficulties in more complex integrative processes that require dynamic coordination of perceptual and motor systems.

These findings are further supported by moderator analysis of brain regions and the corresponding forest plot, which identified the IPL and STS as significant moderators. Specifically, the ASC group showed greater IPL activation and reduced STS activation compared to the NT group. When the imitation tasks were analyzed separately, the IPL was the only region that showed a significant group difference, with the ASC group exhibiting significantly increased activation. This pattern of hyperactivation aligns with previous findings (Yang and Hofmann, 2016) and reflects atypical functioning in the IPL, a region critical for mapping observed actions onto motor representations and coding action goals. According to the emulation-planning and mimicry (EP-M) model, the IPL plays a central role in goal-directed imitation via the emulation pathway (STS-IPL-IFG), supporting the extraction and representation of action goals (Kana et al., 2011; Williams et al., 2006). Notably, the IPL is usually inactive when actions are externally guided by explicit goals, instructions, or social cues (Ogawa and Inui, 2007). It becomes more active when individuals need to construct movement goals internally. This increased activity occurs, for example, when imitating meaningless or unfamiliar intransitive gestures. In these situations, individuals rely on processing the kinematic and spatial information of the observed action without any contextual cues (Reader et al., 2018). The IPL hyperactivation identified in this meta-analysis, which synthesizes findings across multiple studies on joint action, indicates that individuals with ASC rely more on low-level kinematic information and self-generated motor plans than on integrating observed actions with socially grounded motor representations. This pattern also suggests the use of a compensatory strategy during joint actions, in which actions are processed as abstract sequences rather than socially meaningful cues (Daniel et al., 2022). This interpretation aligns with the previous study (Boria et al., 2009), which demonstrated that children with ASC exhibit

difficulties in understanding "why" (i.e., the underlying intention), while their ability to identify "what" (i.e., the goal of the motor act) remains intact.

In contrast, the STG is essential for detecting biological motion and interpreting semantic information, including eye gaze, facial expressions, and bodily movements (Redcay, 2008; Vander Wyk et al., 2009). It engages in temporal processing by monitoring dynamic sequences of inputs and automatically extracting socially relevant meanings, which is critical for social perception and cognition (Redcay, 2008). Through its connections with both the MNS (e.g., IFG and IPL) and MENT (e.g., mPFC and TPJ), the STG provides sensory input that supports bottom-up perception-action integration and top-down cognitive control involved in social information processing (Alaerts et al., 2017). Impaired STS functioning has been consistently associated with social-cognitive challenges in individuals with ASC. The findings indicate that reduced STS activation or atypical connectivity with other brain regions in ASC may contribute to difficulties in adequately orienting to social cues or effectively recruiting neural resources. This can affect their ability to interpret socially meaningful information, especially in response to varying task demands and social contexts. Similarly, the current meta-analysis found decreased STS activation in the ASC group, particularly during meaningful, goal-directed actions such as building with blocks or cleaning. This finding indicates that individuals with ASC may have difficulty in recruiting sufficient neural resources via the STS when processing explicit social cues embedded in the biological motions of others.

Regarding IBS, the pooled effect size indicated a trend toward decreased neural synchrony in ASC-partner pairs, although this difference was not statistically significant. However, descriptive analyses of individual studies have highlighted reduced inter-brain coupling between partners, specifically in the IPL and TPJ. These findings are consistent with previous studies demonstrating decreased synchrony in the same regions among adult pairs with higher and lower autistic traits (Feng et al., 2024; Li et al., 2024). As indicators of mutual interaction quality, such decreased neural coupling suggests diminished cognitive and social alignments between partners, with impairments potentially attributable to individuals, with and without ASC. Disrupted synchrony may stem not only from atypical neural functioning in individuals with ASC, but also from neurotypical partners or partners with lower autistic traits with limited ability to attune to their ASC counterpart.

In particular, decreased IBS in the IPL, a core region of the MNS, may reflect impairments in the shared understanding of actions necessary for social alignment. Reduced synchrony in the TPJ further indicate potential disruptions in the higher-order modulation of joint action. Research suggests that MNS processes are regulated by top-down control systems that predict others' actions, monitor discrepancies between expected and actual outcomes, and continuously update predictions and action plans. These processes operate in a dynamic, reciprocal feedback loop (Ciaramidaro et al., 2024; Shamay-Tsoory et al., 2019). Within this framework, the TPJ plays a key role in distinguishing oneself from others, adjusting behaviors based on prediction errors, and intentionally inhibiting automatic tendencies. It enables flexible responses that go beyond the mere replication of the observed action, particularly when self-other boundaries are less distinct and predictive demands are high (Era et al., 2020; Bitsch et al., 2018). Accordingly, the observed reduction in IBS within the TPJ indicates that individuals with ASC, and potentially their NT partners, mutually influence each other's ability to align their internal expectations with a partner's intentions and behavior in real time, due to disruptions in predictive and adaptive mechanisms (Ciaramidaro et al., 2024). However, these findings should be interpreted with caution given the high heterogeneity among the studies. This variability may obscure significant group-level effects. Further research with larger sample sizes and improved methodological consistency is needed to obtain a more conclusive understanding of disrupted brain-to-brain synchrony in dyadic interactions and to clarify the roles of both ASC and NT individuals in contributing to this interactional disruption.

Additionally, this study explored how the relationship between neural and behavioral patterns varies depending on the severity of autism symptoms. The findings showed that individuals with relatively mild symptoms exhibited behavioral performance similar to the NT group, yet displayed distinct neural patterns that may reflect the use of compensatory or alternative strategies. In contrast, individuals with moderate to severe symptoms demonstrated significant deficits in behavioral performance, accompanied by atypical neural activity. Furthermore, although cortical activation findings were relatively consistent across studies, IBS results were more variable. This discrepancy likely reflects the differences in task types. Cortical activation was primarily measured during imitation tasks involving a uniform task paradigm, whereas IBS was assessed during cooperative tasks that require more diverse cognitive and motor adjustments. Cooperative tasks demanding complementary rather than identical actions are more sensitive to individual differences in autism symptom severity and cognitive control. Due to the limited sample size, the current study could not systematically explore how these varying task demands interact with symptom severity and neural-behavioral coupling. Future studies are needed to develop a more systematic framework for categorizing task demands and to examine how these factors affect both neural and behavioral responses and their interrelations.

5. Conclusion

This study systematically examined the neural correlates of social coordination in individuals with ASC by integrating the findings of real-time engagement in diverse social actions. The integrated results of cortical activation and IBS analyses highlight the distinction between the neural mechanisms underlying individual action planning (single-brain MNS activation) and those supporting real-time, adaptive coordination (IBS across interacting dyads). Individuals with ASC may exhibit atypical prediction and planning of motor responses in response to social stimuli at the intrapersonal level, along with challenges in mutual adaptation to complex, real-time interactions at an interpersonal level. In particular, reduced STS input may fail to sufficiently modulate IPL activity, resulting in over-reliance on internally generated motor plans and a diminished ability to encode and integrate socially meaningful information into contextually appropriate responses. This, in turn, may impair the reciprocal processes of prediction, monitoring, and adaptation necessary for maintaining neural coupling and behavioral alignment in social contexts. Moreover, these patterns appear to vary depending on autism severity, with mild cases showing subtle neural alterations despite preserved behavioral performance, and more severe cases showing concurrent behavioral and neural deficits. It is important to note, however, that these interpretations are based on general trends rather than direct meta-analytic comparisons. Therefore, definitive conclusions should remain tentative. Future research employing more rigorous and systematic approaches is essential to validate these interpretations and further delineate the distinct or potentially synergistic roles of these neural systems in social motor coordination among individuals with ASC.

Social motor coordination in ASC is a complex and multidimensional process that extends beyond movement execution and requires action planning, perceptual interpretation, and real-time social adaptation. Rather than treating joint action as a singular construct, it is essential to consider its varying demands, which range from shared intentionality and movement replication to cooperative goal sharing and complementary actions. Investigating how individuals with ASC integrate social, temporal, and spatial cues in real-world interactions will be critical for developing interventions that address both motor execution and higher-level cognitive aspects of social coordination.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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An asterisk (*) indicates studies included in the analysis

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