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Atypical Associations Between Emotion Regulation Strategies and Parent-Child Neural Synchronization in Autism Spectrum Disorder: Insights from fNIRS Hyperscanning

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Atypical Associations Between Emotion Regulation Strategies and Parent-Child Neural Synchronization in Autism Spectrum Disorder: Insights from fNIRS Hyperscanning

Running Title: Emotion Regulation and Parent-Child INS in Autism

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Atypical Associations Between Emotion Regulation Strategies and Parent-Child Neural Synchronization in Autism Spectrum Disorder: Insights from fNIRS Hyperscanning

Abstract

Background: Emotion regulation (ER) is critical for mental health in autistic children. Existing studies have shown that autistic children use more maladaptive and fewer adaptive ER strategies, yet the neural mechanisms underlying these ER patterns remain underexplored.

Methods: This study examined the associations between ER strategies and interpersonal neural synchronization (INS) among autistic (n = 30) and neurotypical (n = 30; NT) children during naturalistic parent-child interactions. Brain signals in both parents' and children's prefrontal cortex were assessed while they completed a cooperative puzzle task using functional near-infrared spectroscopy (fNIRS) hyperscanning. Parents reported their children's use of ER strategies across multiple social situations.

Results: INS between autistic children's left dorsolateral prefrontal cortex and their parents' right frontopolar cortex was lower than that in NT dyads. INS-based classification distinguishing autistic from NT children achieved an accuracy of 74.55%. Furthermore, group (autistic versus NT) moderated the associations between INS and specific ER strategies. Specifically, more frequent use of passive reactions was associated with higher INS in NT dyads but not in autistic dyads, whereas more frequent use of venting was linked to lower INS in autistic dyads but not in NT dyads.

Limitations: Findings should be considered preliminary until they are replicated in a larger sample.

Conclusions: Autistic children exhibit reduced INS with their parents during social interactions. This reduction is characterized by atypical associations with maladaptive ER strategies. These findings provide insights for advancing INS-based diagnostic markers and developing family-centred

interventions focusing on emotion co-regulation within parent-child interactions in autism.

Keywords: Autism; emotion regulation strategies; interpersonal neural synchronization; fNIRS hyperscanning; parent-child interactions; machine learning

1. Background

Autism spectrum disorder (ASD) is characterized by deficits in social communication and restricted and repetitive behaviors (American Psychiatric Association, 2013). Approximately one in 100 children worldwide is diagnosed with ASD [59]. Children with ASD exhibit markedly elevated rates of impairments in emotion regulation (ER), four to seven times higher than their neurotypical (NT) counterparts [8]. These impairments are reflected in an atypical ER pattern, indicated by greater reliance on maladaptive ER strategies and fewer adaptive ER strategies [45]. Existing single-brain studies have demonstrated that reduced brain volume (e.g., in the right amygdala and hippocampus) and decreased functional connectivity (e.g., between the amygdala and ventrolateral prefrontal cortex) are associated with ER strategies in autistic children [10,39]. Despite these findings, the neural mechanisms underlying ER strategies from a dual-brain perspective in autistic children remain underexplored.

1.1 ER in Autistic Children

ER is a dynamic process through which individuals monitor, evaluate, and modify their emotional responses to achieve specific goals using socially acceptable strategies [54]. ER strategies are typically categorized as maladaptive or adaptive [2]. Autistic children exhibit developmental delays in ER strategies relative to their NT counterparts [37]. They tend to rely more on maladaptive ER strategies and less on adaptive ER strategies compared to NT peers [45]. Common maladaptive strategies employed by autistic children include venting, avoidance, rumination, and suppression

[21,46,48]. In contrast, adaptive strategies such as cognitive reappraisal and problem solving are less frequently used by autistic children [48,49]. This imbalance in ER strategy use may exacerbate emotion dysregulation across changing environments in autistic children [31].

Family is a crucial environment for developing ER strategies in autistic children, with parents serving as primary caregivers responsible for direct care, coordination, and advocacy [22,28]. In this context, parent-child interactions facilitate the learning and practice of ER strategies, promoting emotional socialization through daily interactions [33]. However, parents of autistic children engage in fewer interactions with their children than parents of NT children, limiting their children's opportunities to develop a broader repertoire of adaptive ER strategies [9]. Given the significance of parent-child interactions, examining the dynamic neural features of this process may provide insights into the atypical ER strategy use in autistic children.

1.2 INS in Autistic Children

Interpersonal neural synchronization (INS) refers to the temporal alignment of neural signals across brains during real-time social interactions [1]. It is a core neural feature associated with social interaction deficits in autistic individuals [50]. Given that social impairments in ASD are pervasive, INS between autistic children and their interactive partners is expected to be lower than that in NT children [63]. However, contrary to this expectation, two studies found no significant differences in INS between autistic and NT parent-child dyads during a cooperative button-pressing task [25,53]. These null results may partly stem from the use of a computerized button-pressing task, which involves relatively simple cognitive processing and limited social complexity. Notably, studies involving adult dyads have found significantly lower INS in autistic adults compared with their NT counterparts when using more naturalistic paradigms, such as eye contact and conversations [17,40].

To the best of our knowledge, no studies have yet compared INS between autistic and NT parent-child dyads during naturalistic interactions.

Moreover, INS has been explored as a potential neural marker for autistic children during social interactions with various interpersonal targets. Specifically, INS between autistic children and their NT peers during cooperative activities (e.g., reading a book, playing a game) predicts children's autistic traits [62]. Additionally, INS between children and experimenters during movement imitation and motor synchrony has demonstrated effectiveness in distinguishing autistic children from NT children [11,26]. Despite these findings, it remains unclear whether INS between children and their parents exhibits similar predictive power for autism.

1.3 Parent-Child INS and ER Strategies

ER is a dynamic interpersonal process in which emotions are transferred from one individual to another, with INS across interacting brains reflecting neural dynamics coevolving over time [3]. A parent-child ER dynamic model suggests that INS during parent-child interactions serves as an underlying neural mechanism shaping children's ER patterns, particularly the development of ER strategies [43]. Empirically, higher levels of parent-child INS have been associated with more adaptive ER strategy development in NT children [44]. Conversely, decreased parent-child INS has been linked to greater irritability in NT children after recovering from frustration [41]. Nevertheless, existing studies are limited to NT samples, leaving it unclear whether similar associations extend to autistic children.

A developmental model posits that autism-specific challenges (e.g., reduced emotional awareness, ambiguous emotional communication) disrupt parent-child emotion co-regulation, thereby limiting autistic children's development of effective ER strategies [36]. Parent-child INS may

represent an autism-specific neural challenge, reflecting dysfunction in social interactions in autistic children [63]. Since autistic children primarily acquire ER strategies within parent-child interactions, parent-child INS may serve as a potential underlying neural mechanism supporting ER strategy development. However, to date, no direct empirical evidence has examined the potential association between parent-child INS and ER strategies in autistic children.

1.4 The Current Study

This study aimed to investigate ER strategy use and parent-child INS in autistic children by employing fNIRS hyperscanning during a naturalistic puzzle task. Specifically, we examined: (1) group differences in ER strategy use between autistic and NT children; (2) group differences in parent-child INS between autistic and NT dyads; and (3) associations between INS and ER strategy use in autistic and NT groups. Drawing on the developmental model in autism, we hypothesized that (1) autistic children would use more maladaptive and fewer adaptive ER strategies than NT children; (2) INS would be lower in autistic parent-child dyads than in NT dyads; and (3) group (ASD versus NT) would moderate the associations between INS and specific ER strategies.

2. Methods

2.1 Participants

Thirty autistic children (M_{age} = 5.17, SD_{age} = 1.11) and thirty NT children (M_{age} = 5.72, SD_{age} = 1.36), along with their parents, were recruited from local hospitals and schools. Inclusion criteria for autistic children were as follows: (1) aged 3 to 8 years, (2) Childhood Autism Rating Scale (CARS) score >30 [6], and (3) meeting criteria on the Autism Diagnostic Observation Schedule (Second Edition; ADOS-2), total score ≥ 12, communication > 4, social interaction > 7. NT children were

confirmed by a licensed physician to have no history of psychiatric or neurological disorders. A sensitivity analysis using G*Power [15] for mean differences between the autistic and NT groups suggested that a sample size of 60 was sufficient to detect medium-sized effects (d = 0.74, assuming α = 0.05, power = 0.80). The study protocol was approved by the Institutional Review Board of [anonymized for review] University. Written informed consent was obtained from all parents prior to participation.

2.2 Measurement

Demographic Information. Parents completed a demographic questionnaire assessing children's age, gender, and mental health history.

***ER Strategies*.** Parents completed the Children's Emotion Regulation Strategies Inventory (CERSI) to assess children's use of different ER strategies [29]. The CERSI consisted of 36 items across six subscales: problem solving, cognitive reappraisal, displacement activity, self-comfort, passive reactions, and venting. Negative ER strategies contain self-comfort, passive reactions, and venting, whereas positive ER strategies contain problem solving, cognitive reappraisal, and displacement activity. Responses were rated on a 5-point Likert scale ranging from 1 (never) to 5 (almost always). Higher scores on each subscale indicate more frequent use of the respective strategies. Cronbach's α for the subscales ranged from 0.60 to 0.81.

2.3 Cooperative Task

Each parent-child dyad was informed that they would complete a jigsaw puzzle task in a naturalistic setting. During the task, they were seated at adjacent sides of the table and allowed to communicate freely. Each dyad was provided with four target images (e.g., lion, whale) consisting of 77 shuffled pieces. Participants were instructed to complete as many puzzles as possible within five

minutes. Performance was indexed by the ratio of correctly completed puzzles to the total number of puzzles.

2.4 Procedure

Upon arrival, parents provided informed consent after receiving an explanation of the study. They then completed the demographic questionnaire and CERSI. Each parent-child pair was instructed to complete the cooperative task within five minutes (Figure 1). During the task, each dyad wore fNIRS caps to record cerebral blood oxygenation. The entire procedure was video-recorded. The study procedures were conducted in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethics Institute Review Board of Harbin Institute of Technology (Shenzhen; approval No. LLYJ2023-030-023).



Figure 1. Experimental setup for parent-child cooperative puzzle task.

2.5 fNIRS Data Acquisition

Two portable multichannel near-infrared optical imaging systems (NIRSport, NIRx Medical Technologies, NY, USA) were used to acquire fNIRS data. The equipment employed continuous-wave measurements at wavelengths of 760 nm and 850 nm to assess cortical hemodynamic activity, with a

sampling rate of 7.8125 Hz. Each device consisted of eight emitters and eight detectors, with a 3 cm distance between each source-detector pair, forming 21 channels on the frontal cortex of each participant. The channels covered the left and right dorsolateral prefrontal cortex (DLPFC), surrounding AF3 and AF4 (Figure 2). These regions of interest (ROIs) were selected because previous studies using similar experimental paradigms have focused on them [34,35]. To ensure consistency, the positions of the optodes and channels were identical for both parents and children. The spatial positions of all channels were obtained using a three-dimensional digitizer and converted to standard Montreal Neurological Institute (MNI) coordinates (Supplementary Materials). Changes in oxyhemoglobin (HbO), deoxyhemoglobin (HbR), and total hemoglobin (HbT) concentrations were assessed based on the modified Beer-Lambert law. In this study, only HbO concentration changes were used because they have the highest sensitivity to changes in regional cerebral blood flow and signal-to-noise ratio [18].

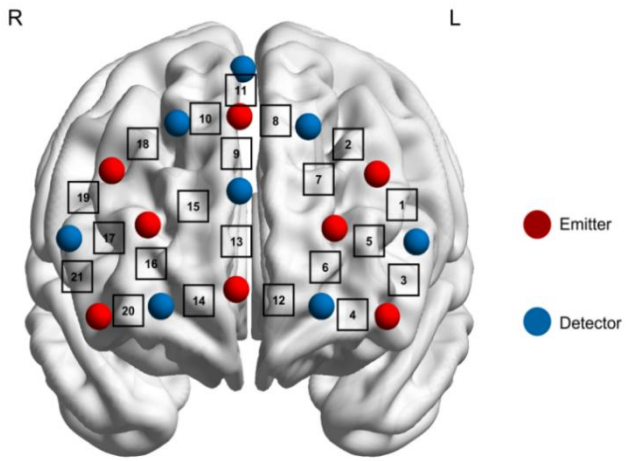


Figure 2. Cap configuration. Functional near-infrared spectroscopy data were recorded in the frontal area for each participant. The emitters and detectors are represented by red and blue circles, respectively, with measured channels labeled using black numbers. L, left; R, right.

2.6 Data Analysis

2.6.1 Behavioral Data Analysis

Descriptive statistics were performed on the demographic characteristics of autistic and NT children. Independent-samples *t* tests were also conducted to examine group differences in ER strategies and puzzle performance between the autistic and NT groups.

2.6.2 fNIRS Data Analysis

Quality Check. Raw data from one parent-child dyad in the NT group and two dyads in the ASD group could not be recorded due to equipment failure. During preprocessing, noisy channels were identified based on the signal-to-noise ratio (SNR) of the heartbeat component; channels with an SNR below three dB were classified as bad [52]. Two additional dyads (one from each group) were excluded because at least 11 channels (≥50%) from either the parent or the child were identified as bad [25]. The final sample included 27 ASD and 28 NT dyads. Descriptive information for valid children by group is provided in the Supplementary Materials. Remaining bad channels were interpolated with the average signals of neighboring channels [60].

Preprocessing. The first and last 15 seconds of data were removed to retain the steady-state period. Data were preprocessed using functions in Homer3 [19] in MATLAB R2021a (MathWorks, Inc., Natick, MA, USA). A discrete wavelet transform filter was applied to detect and correct motion artifacts [32]. Principal component analysis was then used to remove global physiological noise with a variance threshold of 80% [61]. Finally, data above 0.8 Hz or below 0.01 Hz were excluded to eliminate high- and low-frequency physiological noise.

Pair-Level Analysis. The wavelet transform coherence (WTC) algorithm was used to compute the INS for the two fNIRS time series of each parent-child pair [16]. This procedure generated a two-dimensional matrix of coherence values, with columns and rows representing specific frequencies and

time points. All possible channel combinations within the parent-child pair were calculated (i.e., 21 × 21 = 441 in total). The coherence values were converted into Fisher *z*-values and time-averaged across the task period.

Frequency Ranges of Interest. To identify the frequency of interest (FOI) for INS, the band-by-band analysis was conducted within the 0.01-0.5 Hz range, comprising a total of 68 frequency bands [38,62]. For each band, INS values (averaged across all channels in each dyad) were compared between the ASD and NT groups using independent-samples *t* tests. The resulting *p* values were adjusted for multiple comparisons using the false discovery rate (FDR), with a significance threshold set at 0.05 [5]. FOIs were defined as frequency ranges containing at least three consecutive significant bands ($p < 0.05$). Accordingly, two FOIs were identified: 0.010-0.012 Hz and 0.162-0.216 Hz (Figure 3). These FOIs also excluded high- and low-frequency physiological noise, such as cardiac pulsation (~ 1 Hz) and respiration (~ 0.2-0.3 Hz). Coherence values within each selected frequency range were averaged.

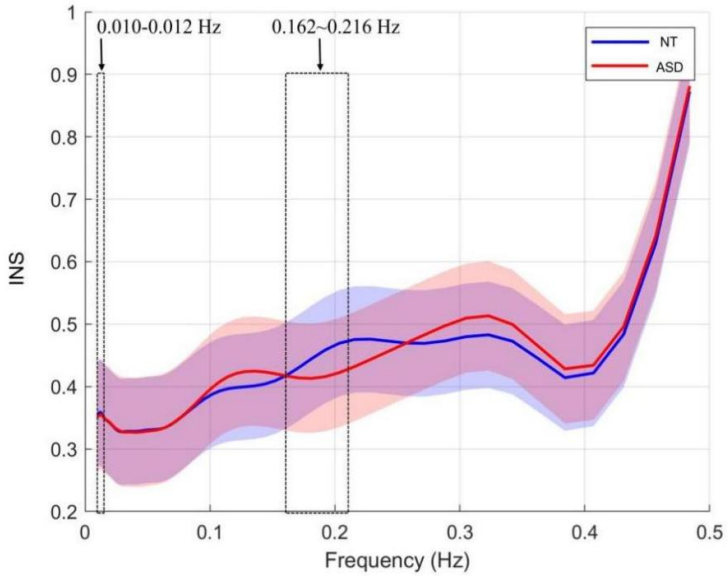


Figure 3. Band-by-band analysis of INS between ASD and NT groups. The gray dotted frame indicates the frequencies of interest that are associated with significant group differences (ASD vs. NT), specifically 0.010-0.012 Hz and 0.162-0.216 Hz. Shaded area around the line represents ±1 *SD*.

Group Comparison of INS. Independent-samples *t* tests were conducted to compare group differences (ASD vs. NT) in INS across all channel combinations, with resulting *p* values corrected using the FDR. To confirm that the observed group differences in INS were due to real dyads interacting rather than by chance, a permutation test was implemented on random dyads. Coherence values were calculated for randomly paired parent-child dyads who did not participate in the puzzle task together within each group. For each random pair, coherence values in the corresponding channel combinations were selected, and INS values were averaged within the ROIs. An independent-samples *t* test was then conducted to compare INS between the random pairs in the ASD and NT groups, generating a single *t* value. This procedure was repeated 1000 times to generate a distribution of *t* values, which was compared with the *t* value from real pairs to determine statistical significance.

INS Directionality. Granger causality analysis (GCA) was employed to assess the directionality of brain signal coupling using the HERMES toolbox in MATLAB. For each dyad, G-causality values were estimated in both directions (parent→child and child→parent). As these values exhibited a skewed distribution, the Box-Cox transformation was applied before statistical analysis. Subsequently, a repeated measures ANOVA was conducted to examine the effects of group (ASD vs. NT) and direction (parent→child vs. child→parent) on G-causality.

INS-based Classification of Autistic and NT Children. A logistic regression analysis was conducted to assess whether INS distinguishes between the ASD and NT groups. To evaluate classification accuracy and performance with a small sample size, we employed a linear support vector machine (SVM) with leave-one-out cross-validation (LOOCV). In the SVM models, INS was used as input feature, with groups as the binary outcome. In LOOCV, one sample was iteratively held out as the test set, while the remaining *N*-1samples formed the training set. Classification accuracy

was calculated after testing all samples. The area under the curve (AUC) of the receiver operating characteristic (ROC) curve was also calculated, which plots the true positive rate against the false positive rate to assess classification performance. Furthermore, 5,000 permutation tests were used to evaluate the statistical significance of the classification.

2.6.3 Moderation Analyses

To examine whether group (ASD versus NT) moderated the association between various ER strategies and INS, we conducted six separate moderation models. In each model, one of the six ER strategies (e.g., cognitive reappraisal, problem solving, displacement activity, venting, passive reactions, self-comfort) served as the independent variable, INS as the dependent variable, group as the moderator, with age as a covariate. Moreover, simple slope analyses were performed to probe the interaction effects.

3. Results

3.1 Behavioral Results

In terms of puzzle performance (Figure 4a), the ASD group obtained lower puzzle scores than the NT group, $t(52) = 2.61$, $p = 0.012$, 95% CI [0.16, 1.26], Cohen's $d = 0.71$, indicating poorer performance in the ASD group. Regarding the ER strategies (Figure 4b), autistic children exhibited less frequent use of cognitive reappraisal than NT children, $t(50) = 2.58$, $p = 0.007$, 95% CI [0.47, 2.73], Cohen's $d = 0.79$. Furthermore, autistic children showed less frequent use of problem solving than NT children, $t(50) = 4.49$, $p < 0.001$, 95% CI [3.77, 9.86], Cohen's $d = 1.25$.

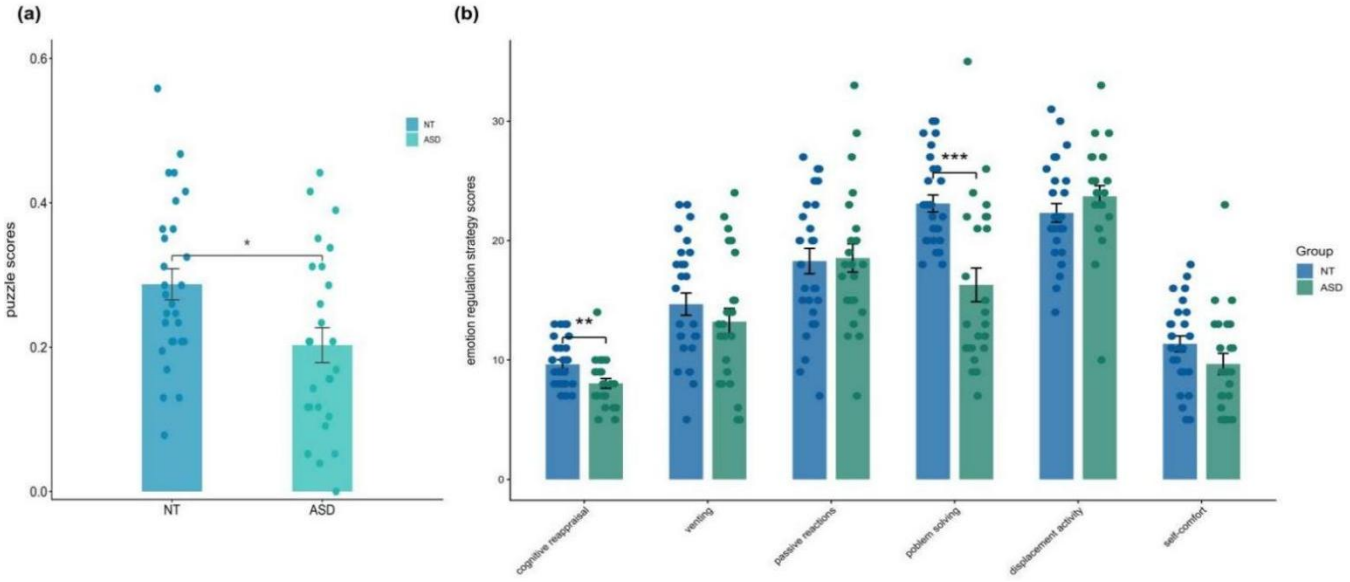


Figure 4. Behavioral results. (a) Puzzle task performance in ASD and NT groups. (b) Emotion regulation strategy scores in ASD and NT groups. Error bars represent standard errors. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

3.2 Neural Results

Group Comparison of INS. A significant group difference in INS was observed within the frequency range of 0.1615–0.2156 Hz in the left dorsolateral prefrontal cortex (l-DLPFC, CH8) of children and the right frontopolar cortex (r-FPC, CH13) of parents (Figure 5a and 5b). Specifically, INS for the channel combination of $CH8_{children}$–$CH13_{parents}$ was significantly lower in the ASD group than in the NT group, $t(53) = 4.20$, $p_{corr} = 0.045$, 95% CI [0.03, 0.07], Cohen's $d = 1.15$ (Figure 5c).

Permutation Test. Validation results indicated that the group difference in INS for the $CH8_{children}$–$CH13_{parents}$ channel combination was specific to the real interacting dyad, as the t-value for the actual dyads exceeded the upper 95% of the permutation distribution (Figure 5d). Specifically, INS in the l-DLPFC of children and the r-FPC of parents was significantly lower in the ASD group than in the NT group, suggesting that this group effect was robust and unlikely to have occurred by

chance.

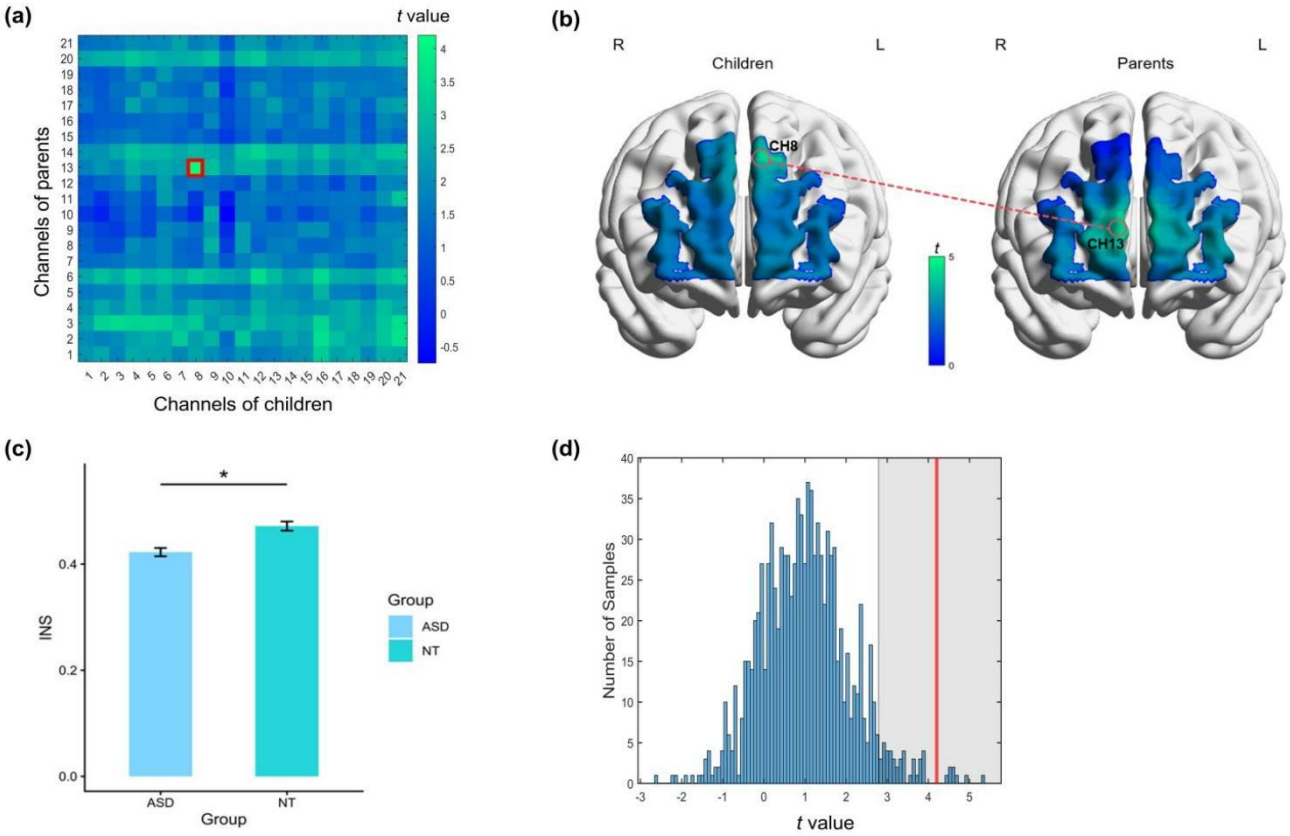


Figure 5. INS comparison between ASD and NT groups. (a) Group differences across all channel combinations. The red solid frame indicates *t* values after FDR correction ($p < 0.05$). (b) Anatomical locations of the left dorsolateral prefrontal cortex ($CH8_{children}$) and right frontopolar cortex ($CH13_{parents}$). (c) Group difference in INS at the $CH8_{children}$–$CH13_{parents}$. (d) Pseudo-dyad permutation distributions. The group difference in INS at the $CH8_{children}$–$CH13_{parents}$ in real pairs (red line) was significant at the 5% chance level (gray shading). L, left; R, right. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

INS Directionality. A marginally significant interaction between group and direction was observed, $F(1,53) = 3.14$, $p = 0.082$, $\eta_p^2 = 0.06$. Simple effects analysis further indicated that, for the NT group, G-causality from parents to children was significantly greater than that from children to parents (Figure 6a and 6b), $t(53) = 2.16$, $p = 0.036$, Cohen's $d = 0.41$, indicating that parents led their children in completing the puzzle task. However, in the ASD group, the difference between G-

causality from parents to children and from children to parents did not reach significance, $t(53) = -0.37$, $p = 0.717$, Cohen's $d = -0.07$, indicating no significant trend for either autistic children or their parents in leading the puzzle task completion.

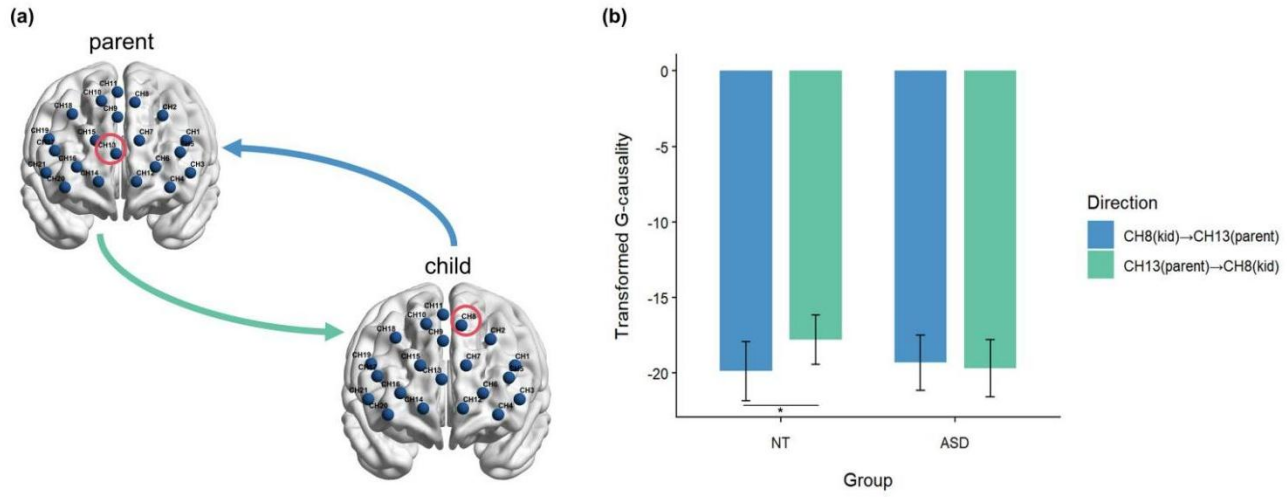


Figure 6. Granger causality results for INS. (a) G-causality was analyzed in two directions: parent-to-child (green solid line) and child-to-parent (blue solid line). (b) Mean G-causality values (Box-Cox transformed) in parent-to-child direction were significantly greater than in child-to-parent direction in the NT group. Error bars represent standard errors. *$p < 0.05$.

INS-Based Classification. A logistic regression model revealed that INS significantly predicted the probability of autism ($B = -28.21$, $SE = 8.62$, $z = -3.27$, $OR = 5.63 \times 10^{-13}$, $p = 0.001$), indicating that lower INS in the l-DLPFC of children and the r-FPC of parents was associated with higher odds of ASD (Figure 7a). In addition, the SVM model showed a classification accuracy of 74.55%, with an AUC of 0.82 (Figure 7b), suggesting relatively good classification performance. Furthermore, the 5,000 permutation test yielded a p-value of 0.0002, indicating that the classification results were significant.

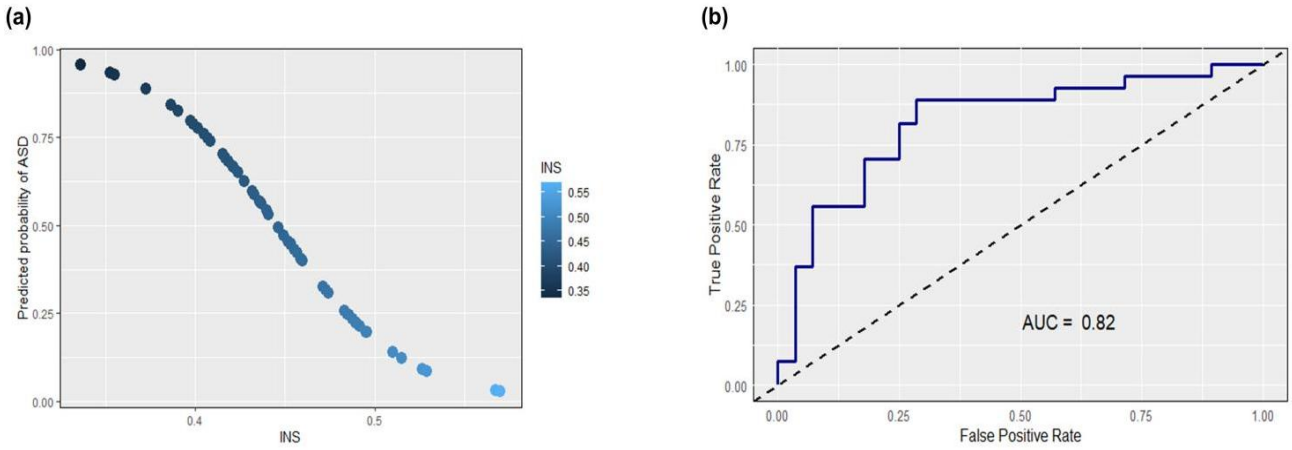


Figure 7. INS-based prediction of ASD and NT children. (A) Prediction of ASD probability based on INS using a logistic regression model. (B) Receiver operating characteristic (ROC) curve for the support vector machine (SVM) model. The 45-degree diagonal ROC line (black dotted line) represents random classification. As the ROC curve approaches the diagonal line, the performance of the SVM model deteriorates. The area under the ROC curve (AUC) measures the model's ability to distinguish between positive and negative classes. A higher AUC score indicates better classification performance.

3.3 Moderating Models

Passive Reactions Affect INS in the NT Group but Not in the ASD Group. Results indicated a significant interaction effect of group and passive reaction on INS, $b = 0.005$, $p = 0.020$. Simple slopes analysis further revealed that passive reaction positively predicted INS in the NT group (Figure 8a), $b_{NT} = 0.004$, $SE = 0.001$, $t(46) = 2.41$, $p = 0.020$, indicating that more frequent use of passive reaction to regulate emotion was associated with higher INS. However, no significant association was found between passive reactions and INS in the ASD group, $b_{ASD} = -0.002$, $SE = 0.002$, $t(46) = -1.01$, $p = 0.319$.

Venting Affects INS in the ASD Group but Not in the NT Group. A significant interaction effect of group and venting on INS was observed, $b = 0.006$, $p = 0.020$. Simple slopes analysis further revealed that venting marginally predicted INS in the ASD group (Figure 8b), $b_{ASD} = -0.003$, $SE =$

0.002, $t(46) = -1.76$, $p = 0.086$, indicating that more frequent use of venting to regulate emotion was associated with lower INS. However, no significant association was found between venting and INS in the NT group, $b_{NT} = 0.003$, $SE = 0.002$, $t(46) = 0.11$, $p = 0.107$.

No Additional Significant Interaction Effects. No significant interaction effects between group and several ER strategies on INS was found (Table 1). Specifically, the interaction between group and cognitive reappraisal on INS was non-significant (Figure 8c), $b = -0.001$, $p = 0.914$. Similarly, no significant interaction was observed between group and problem solving on INS (Figure 8d), $b = 0.001$, $p = 0.837$, or between group and displacement activity on INS (Figure 8e), $b = 0.000$, $p = 0.970$. Finally, the interaction effect between group and self-comfort on INS was also non-significant (Figure 8f), $b = 0.005$, $p = 0.150$.

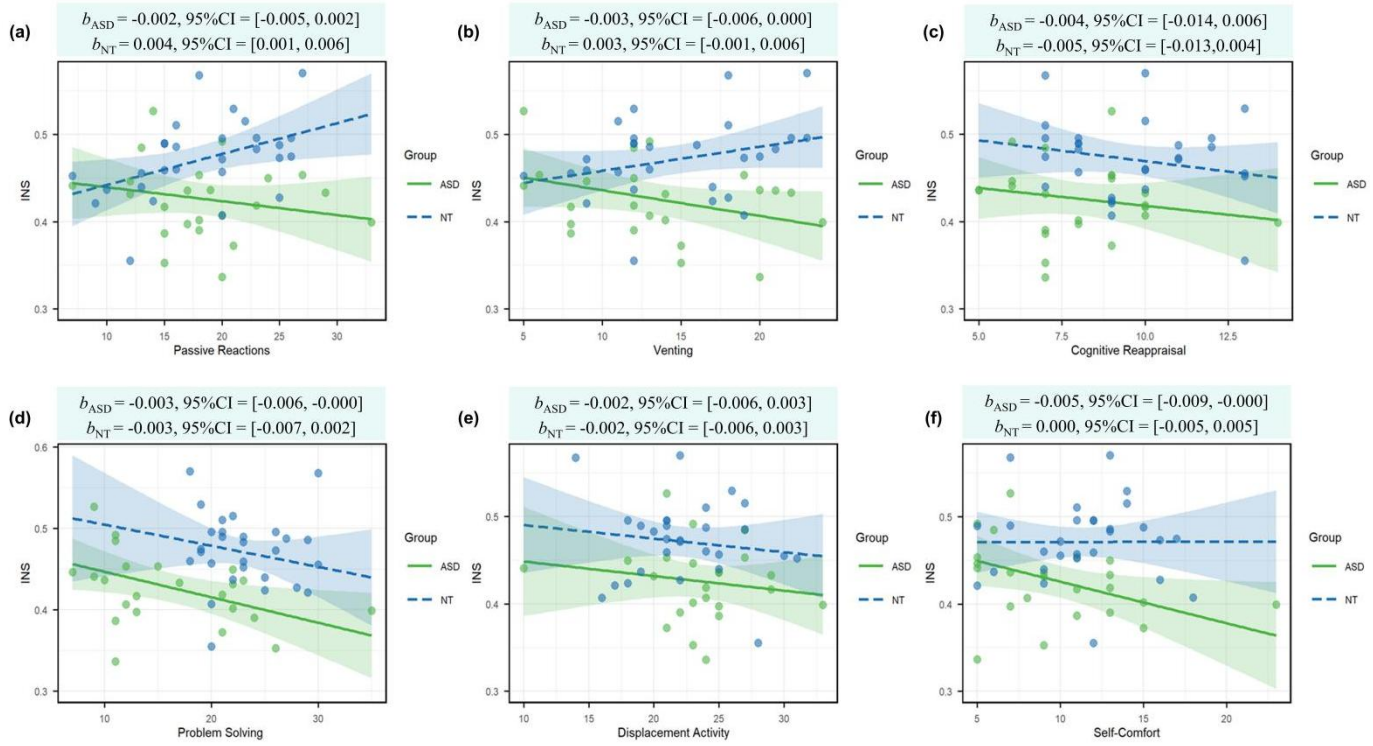


Figure 8. Simple slopes plots for interaction effects of group (ASD vs. NT) and various emotion regulation strategies on INS. (a) Passive reactions. (b) Venting. (c) Cognitive reappraisal. (d) Problem solving. (e) Displacement activity. (f) Self-comfort.

Table 1. Moderating models of group on the associations between ER strategies and INS.

Models	Predictors	*b*	*SE*	*t*	*p*	R^2	*F*
Model 1	age	0.009	0.005	1.661	0.104	0.288	4.658**
	group	**0.052**	0.014	3.840	< 0.001		
	cognitive reappraisal	-0.004	0.005	-0.852	0.399		
	group × cognitive reappraisal	-0.001	0.006	-0.109	0.914		
Model 2	age	**0.012**	0.005	2.200	0.033	0.348	6.150***
	group	**0.063**	0.015	4.327	< 0.001		
	problem solving	**-0.003**	0.001	-2.366	0.022		
	group × problem solving	0.001	0.003	0.208	0.837		
Model 3	age	0.008	0.005	1.515	0.137	0.276	4.374**
	group	**0.043**	0.013	3.339	0.002		
	displacement activity	-0.002	0.002	-0.768	0.446		
	group × displacement activity	0.000	0.003	0.038	0.970		
Model 4	age	0.009	0.005	1.747	0.087	0.341	5.939***
	group	**0.045**	0.012	3.705	< 0.001		
	venting	-0.003	0.002	-1.757	0.086		
	group × venting	**0.006**	0.002	2.402	0.020		
Model 5	age	0.007	0.005	1.332	0.190	0.356	6.347***
	group	**0.046**	0.012	3.797	< 0.001		
	passive reactions	-0.002	0.002	-1.008	0.319		
	group × passive reactions	**0.005**	0.002	2.420	0.020		
Model 6	age	**0.011**	0.005	2.081	0.043	0.325	5.545***
	group	**0.048**	0.013	3.854	< 0.001		
	self-comfort	**-0.005**	0.002	-2.146	0.037		
	group × self-comfort	0.005	0.003	1.463	0.150		

Note. Coefficients in bold are significant, $p < 0.05$.

4. Discussion

This study investigated the associations between ER strategies and INS during parent-child interactions in autism. Autistic children used fewer adaptive ER strategies (i.e., cognitive reappraisal, problem solving) than NT children (partly supporting H1). At the neural level, parent-child INS in autistic dyads was lower than that in NT dyads (supporting H2). Furthermore, group moderated the associations between specific ER strategies (i.e., passive reaction, venting) and INS (supporting H3). Specifically, greater use of passive reaction strategies was linked to higher INS in NT dyads, whereas this association was not observed in autistic dyads. In contrast, greater use of venting strategies was linked to lower INS in autistic dyads, whereas no such association was found in NT dyads. These findings indicate the presence of atypical associations between specific maladaptive ER strategies and parent-child INS in autism.

4.1 Fewer Adaptive ER Strategies in Autistic Children

Our behavioral findings indicated that autistic children use cognitive reappraisal and problem-solving strategies less frequently than NT children, consistent with previous research showing that autistic children employ fewer adaptive ER strategies than their peers [49]. ASD-related predispositions, such as cognitive deficits and biological risks, may contribute to challenges in developing adaptive ER strategies [4]. Despite these challenges, no significant differences were found in maladaptive strategies between autistic and NT children. This may be because both autistic and NT children in this age range rely on maladaptive ER strategies (e.g., venting, passive reactions) that place low demands on verbal skills, nonverbal intelligence, and emotion comprehension [7,47]. Overall, this study identified a distinct ER profile, in which differences between autistic and NT children were more pronounced in adaptive rather than maladaptive strategies.

4.2 Dysfunction in Parent-Child INS in ASD

Neural findings indicated that autistic children exhibited lower INS with their parents than NT children during parent-child interactions. Specifically, INS between the left DLPFC of autistic children and the right FPC of their parents was lower than that in NT child-parent dyads, consistent with previous findings on collaborative interactions [56]. This reduction in localized neural synchronization may reflect impaired socio-cognitive processes involved in parent-child interactions, which are characterized by a common goal, shared attention, and interactive processes [25,44]. Notably, the DLPFC supports executive control for selecting goal-directed actions or thoughts [24,27], whereas the FPC supports goal management and cognitive-control resource reallocation [30]. Given that the cooperative puzzle task places demands on shared attention and goal alignment, this reduced DLPFC-FPC INS likely reflects weaker interbrain coupling in executive control and goal management in autistic child-parent dyads relative to NT dyads.

Furthermore, our findings revealed that reduced INS during parent-child interactions can distinguish between autistic and NT children, with high classification accuracy. This finding aligns with previous research demonstrating that reduced INS during experimenter-child interactions similarly differentiates autistic from NT children [12,26]. These findings collectively suggest that reduced INS may constitute a core feature of autism and may holds promise as a potential biomarker for social deficits in autistic children [50,63]. However, caution is warranted when interpreting reduced INS as an autism biomarker, given that the small sample size may have inflated classification accuracy and limited generalizability [51]. Validation in larger, more diverse samples is therefore necessary to establish the diagnostic utility of INS measures across various social contexts.

4.3 Atypical INS-ER Strategy Associations in ASD

An atypical pattern was identified whereby greater use of passive reaction strategies was linked

to higher parent-child INS in NT dyads but not in autistic dyads. Passive reactions are characterized by avoidance of emotion-triggering situations and inaction in response to problems [29]. In NT dyads, these reactions serve as salient signals that elicit parental emotional responses, including shared attention, goal alignment, and affective matching—processes that foster social alignment and INS [13,23]. However, this pattern was absent in autistic dyads, possibly because parents may misinterpret passive reactions as mere social difficulties rather than cues for emotion co-regulation, thereby limiting social alignment opportunities.

Moreover, greater use of venting strategies was linked to lower INS in autistic dyads but not in NT dyads. Venting strategies involve destructive expression of negative emotions. Autistic children deployed more venting strategies, such as vocal or physical venting, than NT children, and these behaviors were associated with language impairments [20,58]. While NT parents typically respond to venting with goal recognition and co-regulation that facilitates INS [57], autistic children's venting may produce more salient yet ambiguous emotional expressions. These expressions challenge parental understanding and appropriate co-regulation [36], disrupting social alignment in emotional states and resulting in lower INS. Collectively, these findings suggest that different parental responses to children's ER strategies may critically shape parent-child neural synchronization patterns in autism versus typical development.

4.4 Clinical Implications

These findings have several pivotal clinical implications. First, INS in the prefrontal cortex during parent-child interaction could serve as objective biomarkers for autism, complementing subjective diagnostic measures. Second, family-centred interventions should focus on enhancing emotion co-regulation between autistic children and their parents during daily interactions, thereby

creating naturalistic opportunities for learning and internalizing ER strategies. Specifically, autistic children may elicit different responses from their parents depending on the ER strategies they use (e.g., passive reactions, venting), and guiding parents to identify and respond to these emotional cues is a critical aspect of the intervention. Third, given that emotion regulation involves multi-brain dynamics [3], neuromodulation approaches targeting INS (e.g., hypertranscranial electrical stimulation and transcranial magnetic stimulation) may provide a novel avenue for reducing emotional dysregulation in autistic individuals. Finally, since current autism diagnoses rely heavily on subjective assessments that are susceptible to observer bias and may overlook early or subtle symptoms [42], an INS-based machine learning approach may serve as an objective decision-support system, pending further clinical validation.

5. Limitations

This study has several limitations that should be addressed in future research. First, while this study is the first to identify the correlations between ER strategies and parent-child INS in autism, experimental or longitudinal designs are needed to further explore the causal associations between ER strategies and parent-child INS in autism. Second, the small sample size and exclusive use of SVM may have constrained classification performance and generalizability. Larger and more diverse datasets, along with alternative machine learning approaches (e.g., GaussianNB, neural networks, random forests), may improve robustness and clinical utility. Third, the present study did not include a replication sample to validate the findings. The specific inclusion criteria for children with autism made it challenging to recruit a separate cohort within the limited time and resources available. Specifically, collecting dual-brain data from children with autism and their parents was challenging,

as the optodes placed on the frontal cortex caused discomfort, making it difficult for young children to sustain participation during the experiment. Future studies should prioritize replication samples and explore methods to minimize discomfort (e.g., using lighter optodes) during fNIRS data collection. Finally, the current study assessed INS only in frontal regions; other cortical areas associated with emotion regulation (e.g., parietal and temporal cortices) were not examined [14,55]. Future research should examine broader cortical regions to provide more comprehensive understanding of neural synchrony in autism.

6. Conclusions

The present study investigated the INS in autistic and NT child-parent dyads during a cooperative puzzle task and its associations with children's use of ER strategies using fNIRS hyperscanning techniques. The findings demonstrate an atypical INS pattern in autism, with lower INS in the frontal cortex in autistic children and their parents compared to NT dyads during parent-child interaction. Additionally, this reduced INS could distinguish autistic from NT children with high classification accuracy, highlighting its potential as a biomarker for diagnosing autism. Furthermore, the study revealed atypical associations between parent-child INS and specific ER strategies. Specifically, greater use of passive reaction strategies was associated with higher INS in NT child-parent dyads but not in autistic dyads, while greater use of venting strategies was linked to lower INS in autistic dyads but not in NT dyads. These findings underscore the neural underpinnings of maladaptive ER strategies in ASD and offer implications for individualized interventions focusing on emotion co-regulation in parent-child dyads.

List of abbreviations

ASD: Autism spectrum disorder

NT: Neurotypical

ER: Emotion regulation

fNIRS: Functional near-infrared spectroscopy

INS: Interpersonal neural synchronization

CARS: Childhood autism rating scale

ADOS: Autism diagnostic observation schedule

CERSI: Children's emotion regulation strategies inventory

ROIs: Regions of interest

HbO: Oxyhemoglobin

HbR: Deoxyhemoglobin

HbT: Total hemoglobin

SNR: Signal-to-noise ratio

WTC: Wavelet transform coherence

FOI: Frequency of interest

FDR: False discovery rate

GCA: Granger causality analysis

SVM: Support vector machine

LOOCV: Leave-one-out cross-validation

DLPFC: Dorsolateral prefrontal cortex

FPC: Frontopolar cortex

Declarations

Ethics approval and consent to participate

All experimental protocols were approved by the Ethics Institute Review Board of Harbin Institute of Technology (Shenzhen), No. LLYJ2023-030-023.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available due to privacy or ethical restrictions, but are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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Authors' contributions

Dongming Qin: data analysis, writing the original draft

Peilian Chi: editing and supervision.

Zhen Wei: clinical diagnosis, resources and supervision.

Liying Long & Di Cui: investigation and data collection

Shumeng Hou: conceptualization, supervision, editing and funding acquisition.

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