126 (2025) 202656

Contents lists available at ScienceDirect

Research in Autism

journal homepage: www.elsevier.com/locate/rasd

The effects of naturalistic developmental behavioral interventions in young children with autism spectrum disorder: A systematic review and network meta-analysis

LI Dan [a,1], HUANG Yaping [a,1], CUI Xiaobing [b], BING jiaojiao [a], SHEN Youhong [d,*], YIN huazhan [c,**]

[a] Department of special education, Hunan Normal University, Changsha, China
[b] Institute of psychology, Chinese Academy of Sciences, Beijing, China
[c] Department of psychology, Hunan Normal University, Changsha, China
[d] School of educational science, Hunan Normal University, Changsha, China

ARTICLE INFO

Keywords:
Natural developmental behavioral intervention·Children·Autism spectrum disorder·Network meta-analysis·Systematic review

ABSTRACT

The Naturalistic Developmental Behavioral Interventions (NDBIs) have been widely regarded as the gold standard for early intervention in children with autism. However, there is still ongoing debate regarding the effectiveness of different NDBIs based on current research evidence. Furthermore, limited knowledge exists regarding which interventions are most suitable for children with Autism Spectrum Disorder (ASD). In order to address these gaps, we conducted a comprehensive systematic review using network meta-analysis to evaluate the impact of NDBIs on children aged up to 8 years old who have ASD. Ultimately, forty-one papers involving 2781 participants and six distinct intervention methods were included in our analysis. This study assessed the efficacy of interventions across five domains: receptive language skills, expressive language skills, cognitive development, reduction in symptoms associated with ASD, and social skills enhancement. The findings from our analysis suggest that ESDM may be considered as the most effective intervention for improving receptive language, expressive language and cognitive development. LEAP most likely the most effective intervention to alleviate symptoms related to ASD. Additionally, ESI appears to be the optimal intervention method for enhancing social skills among this population group. Overall, this study fills an important gap in previous literature reviews by providing valuable insights into early NDBIs specifically tailored for children diagnosed with ASD.

1. Introduction

Autism Spectrum Disorder (ASD) is a pervasive neurodevelopmental disorder characterized by impairments in social interaction and repetitive stereotyped behaviors (American Psychiatric Association & Association, 2013). The prevalence of ASD is increasing. According to the weekly report released by the Centers for Disease Control and Prevention (CDC) in April 2023, by 2020, the overall

* Correspondence to: School of Educational Science, Hunan Normal University, Road Lushan, Yuelu District, Changsha 410081, China.
** Correspondence to: Department of Psychology, Hunan Normal University, Road Lushan, Yuelu District, Changsha 410081, China.
E-mail addresses: 64037325@qq.com (S. Youhong), yhz1979@sina.com (Y. huazhan).
[1] LI Dan** and HUANG Yaping** contributed equally to this paper

https://doi.org/10.1016/j.reia.2025.202656

Available online 28 June 2025

prevalence of ASD among 8-year-olds reached 2.76 % by 2020, indicating that approximately one in every thirty-six 8-year-olds has autism(Maenner et al., 2021; Maenner et al., 2023). The pathogenesis of ASD remains unclear, and effective pharmacological treatments are currently lacking. However, appropriate early interventions can enhance the overall functioning of children with ASD, improving their social skills, language abilities, cognitive development and adaptive behaviors. These interventions have the potential for positive long-term outcomes (Magiati et al., 2014; Vivanti & Zhong, 2020). Nevertheless, questions regarding the active components persist as research indicates variability in effectiveness based on specific intervention approaches and individual characteristics of children with ASD (Trembath et al., 2023). Therefore, effective early interventions for ASD play a critical role in clinical practice and public health.

Traditional behavioral approaches, such as discrete trial learning (DTT), have been shown to possess several deficiencies, including limited generalizability of learning outcomes, lack of spontaneity and flexibility in children's responses, and excessive reliance on prompts (Schreibman, 2005). Additionally, these approaches can elicit negative emotional responses in children with autism, such as anxiety, frustration, and difficulties in adapting (Kupferstein, 2018). Research has demonstrated that children with autism follow similar developmental pathways to typically developing children across various domains (Lifter et al., 1993; Mundy et al., 1987; Tager-Flusberg et al., 1990), emphasizing the importance of incorporating a combination of developmental principles and developmental sequencing in early intervention. Schreibman et al. (2015) proposed a framework for categorizing intervention models that integrate both behavioral and developmental strategies called naturalistic developmental and behavioral interventions (NDBIs), which is considered best practice for early intervention for children with autism (Zwaigenbaum et al., 2015). The teaching targets of NDBIs encompass various developmental domains, including language and communication, play, social interaction, cognition, and motor skills. Previous meta-analyses have consistently demonstrated the significant role NDBIs have in enhancing language skills (Jenna E Crank et al., 2021; Song et al., 2024; Tiede & Walton, 2019), cognitive development (Jenna E Crank et al., 2021; Song et al., 2024; Tiede & Walton, 2019), social skills (Tiede & Walton, 2019), adaptive behaviors (Fulton et al., 2014; Song et al., 2024), as well as reducing symptoms associated with ASD (Tiede & Walton, 2019). However, certain studies have also suggested that the impact of NDBIs on joint attention may be less pronounced (Tiede & Walton, 2019), and they may not significantly contribute to the reduction of autism symptoms (Jenna E Crank et al., 2021; Elizabeth A Fuller et al., 2020).

While there exist various NDBIs, the more common approaches commonly employed approaches include Pivotal Response Training (PRT), The Early Start Denver Mode (ESDM), Joint Attention, Symbolic Play, Engagement and Regulation (JASPER), Learning Experiences and Alternative Program (LEAP), and so on (Tiede & Walton, 2019). ESDM is an evidence-based intervention primarily focused on enhancing socio-emotional, cognitive and language development in children with ASD (Rogers & Dawson, 2020). This approach emphasizes individualized intervention and active parental involvement. PRT places greater emphasis on critical developmental domains of children with ASD, such as motivation, self-management, response to equivocal cues, etc. (Song et al., 2024). In PRT sessions, typically engages with the child individually and focuses on the use of natural reinforcers to encourage participation. JASPER represents a targeted NDBI approach that addresses core social communication deficits in children with ASD by integrating a range of natural developmental behavioral strategies into play activities(Alzrayer et al., 2021). In contrast, LEAP's primary objective is to mitigate the impact of ASD characteristics on learning opportunities emphasizes integrated learning environments where peers serve as social instructors and interveners (Boyd et al., 2014).

However, previous meta-analyses have solely synthesized intervention effects between measures of NDBIs and non-NDBI approaches, thereby creating a dearth of evidence comparing multiple NDBIs and limited knowledge regarding the most appropriate interventions for children with ASD. Furthermore, there exists a wide variety of NDBIs, each possessing its own merits; however, it remains uncertain which intervention yields the optimal effect on different aspects of ASD in the actual intervention process. Utilizing an inappropriate NDBI may inevitably impact the final outcome of the intervention. Therefore, apart from confirming the effectiveness of various NDBIs across different aspects of intervention, it is imperative to evaluate and compare specific interventions that are more developmentally suitable for children with ASD.

Network meta-analysis (NMA) allows for the integration of multiple interventions and the joint ranking of their effectiveness based on uniform outcome metrics, overcoming the shortcomings of traditional meta-analysis that requires multiple two-by-two analyses and does not allow for the direct integration of all outcomes. NMA can effectively synthesize all available information by integrating evidence from many routes, reducing the uncertainty of a single pathway, and improving estimation accuracy as compared to standard meta-analysis, even in cases when direct evidence is limited or insufficient(Chaimani et al., 2013; Zhang et al., 2025). Ultimately, this methodology facilitates the identification of effective NDBIs to improve a wide range of abilities for children with ASD through a more comprehensive mapping of network evidence.

In this study, we conducted a comprehensive network meta-analysis and systematic review of relevant literature to address the following research objectives.

Research objective 1: To compare the efficacy of various NDBIs on receptive language, expressive language, cognitive development, social skills and reduction of ASD symptoms.

Research objective 2: To rank the effectiveness of different interventions in order to identify the most efficacious ones.

2. Methods

2.1. Registration

This review is registered in the International Prospective Register of Systematic Reviews (PROSPERO) (CRD42024518553). According to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA-NMA)

statement (Hutton et al., 2015), this review conducted a comprehensive search of the relevant literature.

2.2. Search strategy

We conducted an electronic database search of Academic Search Ultimate, APA PsycArticles, Education Resources Information Center (ERIC), MEDLINE, Psychology and Behavioral Sciences Collection, Library, Information Science & Technology Abstracts, Teacher Reference Center databases in EBSCO, and SSCI and CSCD databases in CNKI from their inception to 31 January 2024. The search strategy was based on previously published meta-analyses to develop and refine it (Jenna E Crank et al., 2021; Tiede & Walton, 2019).

The following search terms were used to search the literature: (autis* OR Asperger) AND (intervention OR treatment OR therapy) AND (development* OR behav* OR naturalistic) AND (social OR communication OR language OR joint attention). In addition to searching the databases, previously published systematic reviews and corresponding references were manually searched to fully include studies that met the inclusion criteria.

2.3. Study selection

Endnote 21 literature management software was used to manage the records of the literature searches. All search results were screened by a researcher to exclude duplicates. Any study that potentially met our inclusion criteria or had conflicting studies were subjected to full-text assessment. Afterwards, two researchers independently assessed the included literature based on the identified inclusion and exclusion criteria. Any inconsistencies were adjudicated by a third reviewer.

2.4. Inclusion and exclusion criteria

The literature screening criteria for this review were based on the PICOS principle, as detailed in Table 1. In this review, the control group was permitted to utilise non-NDBIs, to treat as usual or to wait-list, and we excluded the use of NDBIs that were identical to the experimental group but did not have the same frequency of interventions.

2.5. Data extraction

Study characteristics and outcome statistics were independently extracted by two researchers using an Excel data extraction form, including the publication information (first author, year and country), study design (RCT or CT), participant characteristics (sample size, gender, age), diagnostic criteria for ASD, severity, intervention content (study design, sample size, frequency, duration) and outcome measures (measurement objectives, measurement tools). In addition, the mean, standard deviation and sample size of the intervention and control groups pre- and post-intervention for each study will be extracted to calculate the effect size. The classification of intervention techniques for NDBIs in this review is primarily derived from the framework established by Schreibman et al. (2015), with further reference to the categorization employed in previous reviews(Jenna E Crank et al., 2021; D'Agostino et al., 2019; Duncan et al., 2024; Song et al., 2024; Tiede & Walton, 2019).

2.6. Risk of bias assessment

Two researchers independently assessed each study using The Risk of Bias 2 (RoB 2.0) tool (Sterne et al., 2019), and non-randomized studies– of interventions (ROBINS-I). RoB 2.0, largely developed by Cochrane, assessed the included studies in five main areas: randomization process, deviation from intended intervention, missing outcome data, outcome measurement, and selection of the reported result. The assessment results were categorized into three categories: low risk, some concerns and high risk. The

Table 1
Selection criteria.

Variable	Inclusion Criteria	Exclusion Criteria
Publication source	Peer-reviewed journal articles	Conference abstracts and registered trials
Participants	Participants who are autistic or show red flags for ASD and be under the age of 8 years	Children with other diseases or typically developing children
Study design	Randomized controlled trials or controlled trials	Single-subject experimental design or studies without control groups
Intervention	Using NDBIs	Other interventions
Comparison	Treat as usual, wait-list or non-NBDIs	Using the same NDBIs
Outcome	Language abilities (receptive language and expressive language), cognitive development, the symptom of ASD, and social skills.	What did not report the four major competencies of ASD above pre- and post-intervention

ROBINS-I tool consists of seven major domains. The non-randomized controlled trial (CT) and the randomized controlled trial (RCT) quality assessment items differed significantly in the first three domains (bias due to confounding, bias in selection of participants into the study, and bias in classification of interventions), because of variations in randomization. Nonetheless, there was a significant overlap in the risk of bias assessment in the last four areas (bias due to deviations from intended interventions, bias due to missing data, bias in measurement of outcomes, and bias in selection of the reported result)(Sterne et al., 2016). Therefore, we finally decided to evaluate all included studies using ROB 2.0, while using ROBINS-I to supplement the evaluation of non-randomized controlled trials. Any disagreements in the assessment results were judged by a third researcher.

2.7. Statistical analysis

In this study, network meta-analyses based on the frequentist statistical approach were conducted mainly using STATA Software (Version 16.0, College Station, Texas, USA) with the Stata package (Shim et al., 2017), in compliance with the PRISMA-NMA guidelines; heterogeneity tests of the studies were conducted through Review Manager 5.3. Due to the differences between study designs and outcome measures, we chose to use random effects models rather than fixed effects models. The I^2 statistic will be used to assess heterogeneity, with 25 %, 50 %, and 75 % respectively corresponding to low, medium, and high heterogeneity (Huedo-Medina et al., 2006). To mitigate these discrepancies stemming from differences in measurement tools and units between studies (Higgins & Green, 2008), we utilized SMD as an effect size indicator which partially mitigates their influence on results. Effect sizes of 0.2, 0.5, and 0.8, respectively, correspond to thresholds for small, medium, and large effect sizes(Cohen, 2016). Independent intervention programs that fall into the NDBI category and at least one study are all study nodes in the network meta-analysis graphs. Sensitivity analysis was used to assess the stability of the meta-analysis results on the P value of the forest plot and the ranking of the SUCRA plot. Studies in

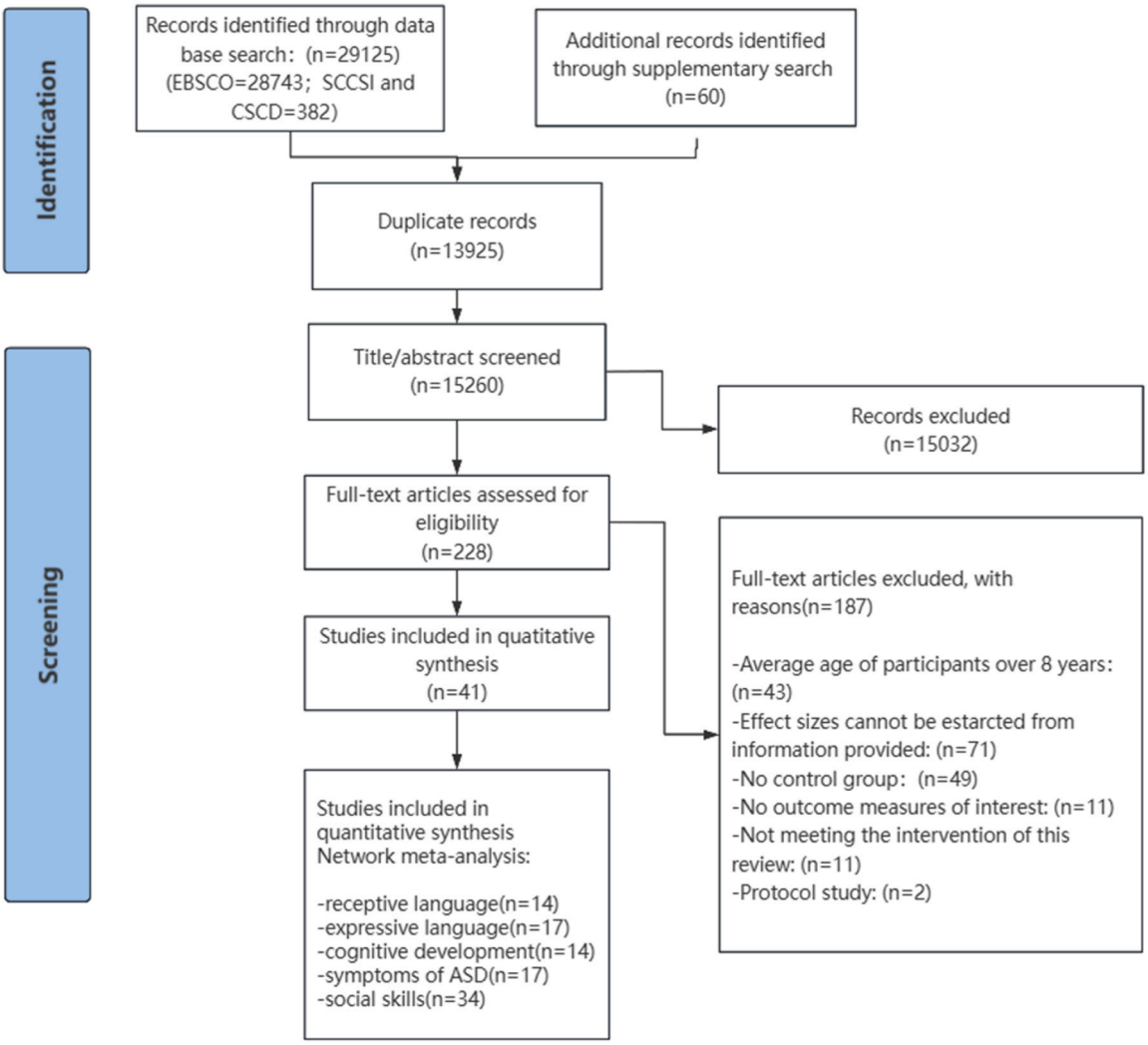

Fig. 1. Flow chart of literature screening.

which the sample size was less than 20 participants or the number of subgroup studies was less than 2 were excluded from the sensitivity analysis. Finally, comparison-adjusted funnel plots were generated and visually inspected using the symmetry criterion for the presence of publication bias.

Transitivity is an important prerequisite assumption for conducting NMA. In order to assess transitivity (i.e., similarity in clinical characteristics and methodology) relative to treatment effect, we conducted a series of sensitivity analyses of potential effect modifiers that could have an impact on the different intervention groups. Combined with the characteristics of the present study, we finalized the analysis of the following potential moderators in four domains: location of intervention (North America, Europe, Oceania, and Asia), intervention implementer (clinician, caregiver, peers, and educator) and intervention duration (12 weeks and less or more than 12 weeks). In case any covariates could be considered a potential effect modifier, the NMAs were repeated including the specific variable that could violate the assumption on transitivity.

3. Results

3.1. Study selection

The systematic review process is illustrated in Fig. 1. In this study, 29125 records were retrieved from the electronic databases, and 60 records were included by supplementary search. Among them, 28803 records were in English and 382 were in Chinese. After removing 13925 duplicate records, a total of 15,260 records were included in the review. After cascade screening, 228 were included in the full text review, of which 187 did not meet the literature inclusion criteria, and 41 studies were finally included in the NMA.

3.2. Characteristics of the studies

A detailed coding for this review is shown in Supplementary Table 1. Of the 41 studies ultimately included, these studies were conducted in the United States (n = 25), Norway (n = 2), Canada (n = 2), Belgium (n = 1), Australia (n = 2), Israel (n = 1), United Kingdom (n = 1), Spain (n = 1), Netherlands (n = 2), and China (n = 4). 41 studies published between 1998 and 2024, of which 35 were RCTs and 6 were CTs. Of the 2781 children with ASD involved in the 41 studies (1447 in the intervention group and 1334 in the control group), 1913 (68.81 %) of them were males, and gender was not reported exactly in five studies (Chiang et al., 2016; Goods et al., 2013; Lawton & Kasari, 2012; Roberts et al., 2011; Strain & Bovey, 2011).

The age of the intervention group ranged from 21.02 months (SD=3.51) to 5.9 years (SD=1.5), and the age of the control group ranged from 20.94 months (SD=3.42) to 5.74 years (SD=0.72). 20 studies used the Statistical Manual of Mental Disorders (DSM) as a diagnostic criterion for ASD, and 16 studies reported the Autism Diagnostic Observation Scale (ADOS) total score, 3 studies (Gengoux et al., 2019; Gengoux et al., 2021; Hardan et al., 2015) reported the Social Responsiveness Scale (SRS) total score, 4 studies (Jocelyn et al., 1998; Song et al., 2024; Strain & Bovey, 2011; Xu et al., 2018) used the Childhood Autism Rating Scale (CARS) to assess the severity of ASD, and 18 studies did not use the above scales to assess the symptom of ASD or did not report scale total scores.

In terms of intervention duration, studies ranged from 5 to 192 weeks. Of the 41 studies, 30 (73.17 %) studies had interventions of 5 to 24 weeks. 11 (26.83 %) studies lasted more than 24 weeks, of these, 8 studies lasted more than one year. In terms of frequency of interventions, the average number of interventions was 5 per week (SD = 6.34) and the mean duration of interventions was 7.72 h per week (SD = 8.69), except for unreported studies.

In terms of interventions, 41 studies involved 6 interventions: PRT (studies: $n = 8$, participants: $n = 305$), ImPACT (studies: $n = 3$, participants: $n = 254$), JASPER (studies: $n = 15$, participants: $n = 1124$), ESI (studies: $n = 5$, participants: $n = 268$), ESDM (studies:

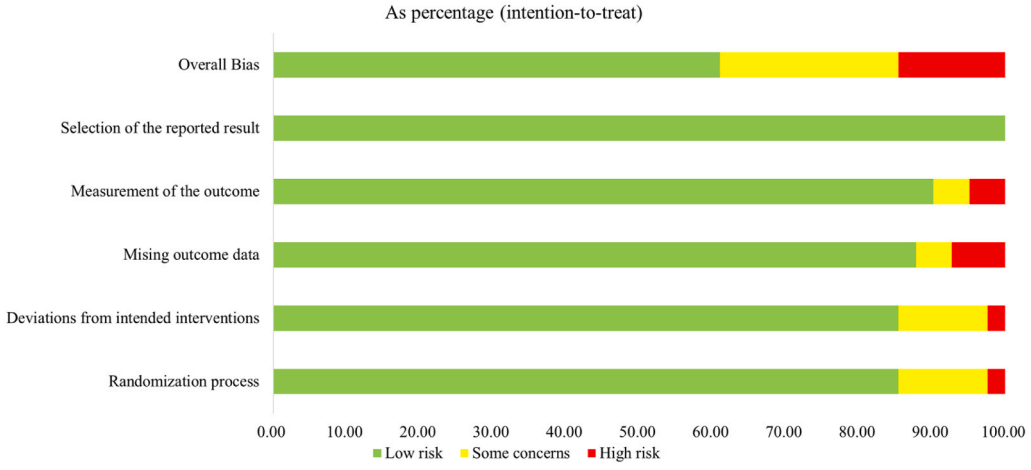

Fig. 2. Risk of bias for included studies. Risk of bias was categorized as low, some concerns and high risk, as assessed by the Cochrane risk-of-bias tool (RoB 2.0). The randomization process was only for randomized controlled trials.

$n = 8$, participants: $n = 423$), LEAP (studies: $n = 2$, participants: $n = 407$).

3.3. Risk of bias assessment

The result of the risk of bias assessment is shown in Fig. 2. According to the overall assessment of risk of bias, the quality of the included studies was moderate to high, of which 61.0 % were low risk, 24.4 % were some concerns, and 14.6 % had a high risk. In the randomization process, excluding controlled trial studies, 85.4 % of randomized controlled trials were low risk. On deviation from the intended intervention, only 12.2 % of studies had some risk. Most studies (90.2 %) had a low risk of bias in measurement of the outcome. When it comes to missing outcome data, more than half of the studies (87.8 %) were low risk, and some (7.3 %) were high risk. The reason for this may be that most of the studies had a long intervention period of more than six months and would also have a follow-up after the intervention to capture the maintenance effect. During this process, some participants may be lost or excluded from the data due to factors such as family reasons, failure to faithfully pursue treatment and so on (Chiang et al., 2023; Gengoux et al., 2019; s. s Wang et al., 2021; Z. Wang et al., 2021). The three domains of the randomization process were further assessed in six non-randomized controlled trials (Table 2). The results showed that among the 18 outcomes, only two were of moderate risk, while the remaining outcomes were of low risk.

4. Results of the network meta analysis

4.1. Receptive language

Fourteen studies (Brian et al., 2017; Chiang et al., 2023; Dawson et al., 2010; Hampton et al., 2020; Hardan et al., 2015; Kaale et al., 2014; Kasari et al., 2015; Kasari et al., 2008; Roberts et al., 2011; Roberts et al., 2023; Sinai-Gavrilov et al., 2020; Strain & Bovey, 2011; Vernon et al., 2019; Vivanti et al., 2014) assessed receptive language, involving five interventions. In the absence of direct comparative studies, network meta-analyses offer evidence of indirect comparisons.

Comparisons between interventions yielded different relative effect sizes, for which we will use league tables to present the results of all possible pairs of interventions. In this study, the five interventions for receptive language produced 15 relative effect values, as shown in Table 3 and Supplementary Figure 2. Among them, compared with controls, LEAP produced the best intervention effect (SMD: 1.40, 95 % CI: 0.74 to 2.06) on receptive language. ESDM intervention effect second (SMD: 0.59, 95 % CI: 0.24 to 0.95). JASPER had the worst intervention effect (SMD: −0.03, 95 % CI: −0.25 to 0.18), which was lower than the controls. Comparison of adjusted funnel plots are shown in Supplementary Figure 3, no significant bias was found in the included studies using the symmetry criterion visual inspection method.

4.2. Expressive language

Seventeen studies (Brian et al., 2017; Chiang et al., 2023; Dawson et al., 2010; Gengoux et al., 2019; Goods et al., 2013; Hampton et al., 2020; Hardan et al., 2015; Kaale et al., 2014; Kasari et al., 2015; Roberts et al., 2011; Roberts et al., 2023; Schreibman & Stahmer, 2014; Sinai-Gavrilov et al., 2020; Strain & Bovey, 2011; Vernon et al., 2019; Vivanti et al., 2014; s Wang et al., 2021) assessed expressive language, including four interventions. The League table was showed in Table 3. We found that ESDM (SMD: 0.46, 95 % CI: 0.20 to 0.71) and PRT (SMD:0.21, 95 % CI: −0.11 to 0.53) yielded better outcomes for improving expressive language compared to the control group, and JASPER (SMD: 0.12, 95 % CI: −0.10 to 0.33) resulted in the worst intervention effect. Comparison of the adjusted funnel plot is shown in Supplementary Figure 6, and no significant asymmetry was found in the included studies.

In order to confirm the plausibility of transitivity, an analysis was conducted to identify potential moderators (location of intervention, implementer, and intervention duration) affecting the domain of language development. As evidenced by the results of the sensitivity analysis (see Supplement 17), the majority of studies were conducted in North America, and the intervention duration exceeded 12 weeks. With the exception of the JASPER intervention, the majority of the studies involved clinicians delivering the intervention. Overall, the distribution of effect sizes was more concentrated across groups, with the largest difference being for LEAP in only one study. However, it is unlikely that this difference was due to moderators and did not lead to significant changes in NMA results. Thus, the intervention studies were comparable.

Table 2
Bias judgement of non-randomized comparison studies (ROBINS-I).

Signalling questions	Risk of bias judgement					
	Wetherby,2006	Duifhuis,2016	Vivanti,2014	Sinai-Gavrilov,2020	Carruthers,2024	Chiang,2016
bias due to confounding	Moderator	Low	Low	Low	Low	Low
bias in selection of participants into the study	Low	Moderator	Low	Low	Low	Low
bias in classification of interventions	Low	Low	Low	Low	Low	Low

Table 3
League table representing summary estimates from network meta-analysis. Comparisons of the effects (SMD (95 % CI)) of different interventions on receptive language, expressive language, cognitive development, reduction in symptoms of ASD, and social skills using network meta-analysis.

LEAP		Receptive language			
0.81 (0.12,1.49)	ESDM				
1.06 (0.28,1.84)	0.26 (−0.29,0.81)	PRT			
1.16 (0.44,1.88)	0.35 (−0.11,0.81)	0.09 (−0.50,0.69)	ESI		
1.37 (0.74,1.99)	0.56 (0.28,0.85)	0.30 (−0.17,0.78)	0.21 (−0.15,0.57)	JASPER	
1.40 (0.74,2.06)	**0.59 (0.24,0.95)**	0.34 (−0.18,0.86)	0.24 (−0.18,0.67)	−0.03 (−0.25,0.18)	CON

ESDM	Expressive language			
0.25 (−0.16,0.66)	PRT			
0.32 (−0.12,0.76)	0.08 (−0.41,0.56)	ESI		
0.34 (0.01,0.67)	0.09 (−0.30,0.48)	0.02 (−0.40,0.44)	JASPER	
0.46 (0.20,0.71)	0.21 (−0.11,0.53)	0.13 (−0.23,0.50)	0.12 (−0.10,0.33)	CON

LEAP		Cognitive development			
1.07 (0.28,1.86)	ESI				
1.10 (0.41,1.79)	0.03 (−0.49,0.55)	ESDM			
1.09 (0.09,2.10)	0.02 (−0.87,0.92)	−0.01 (−0.81,0.80)	JASPER		
1.36 (0.36,2.35)	0.28 (−0.60,1.17)	0.26 (−0.54,1.05)	0.26 (−0.82,1.34)	ImPACT	
1.37 (0.52,2.23)	0.30 (−0.42,1.02)	0.27 (−0.33,0.88)	0.28 (−0.67,1.23)	0.02 (−0.92,0.96)	PRT
1.38 (0.74,2.03)	0.31 (−0.14,0.77)	**0.29 (0.04,0.53)**	0.29 (−0.48,1.06)	0.03 (−0.73,0.79)	0.01 (−0.55,0.57)	CON

		Reduction in Symptoms of ASD				
LEAP						
−0.24 (−1.07,0.60)	PRT					
−0.50 (−1.44,0.44)	−0.26 (−1.08,0.56)	ImPACT				
−0.58 (−1.37,0.21)	−0.35 (−0.98,0.29)	−0.09 (−0.86,0.69)	ESDM			
−0.78 (−1.94,0.38)	−0.54 (−1.60,0.52)	−0.28 (−1.43,0.86)	−0.20 (−1.22,0.83)	JASPER		
−0.81 (−1.98,0.37)	−0.57 (−1.65,0.51)	−0.31 (−1.47,0.85)	−0.23 (−1.27,0.82)	−0.03 (−1.37,1.32)	ESI	
−0.80 (−1.47,−0.12)	**−0.56 (−1.05,−0.07)**	−0.30 (−0.95,0.36)	−0.21 (−0.62,0.20)	−0.02 (−0.96,0.92)	−0.01 (−0.97,0.95)	CON

LEAP		Social skills				
0.35 (−0.51,1.21)	ESI					
0.60 (−0.26,1.45)	0.25 (−0.24,0.73)	PRT				
0.70 (−0.19,1.59)	0.35 (−0.19,0.89)	0.11 (−0.43,0.65)	ImPACT			
0.74 (−0.08,1.55)	0.39 (−0.02,0.79)	0.14 (−0.27,0.55)	0.03 (−0.44,0.50)	JASPER		
0.78 (−0.06,1.61)	0.43 (−0.02,0.87)	0.18 (−0.27,0.63)	0.07 (−0.43,0.58)	0.04 (−0.32,0.40)	ESDM	
0.90 (0.11,1.68)	**0.55 (0.20,0.89)**	0.30 (−0.04,0.65)	0.19 (−0.22,0.61)	0.16 (−0.06,0.38)	0.12 (−0.17,0.41)	CON

4.3. Cognitive development

Fourteen studies (Brian et al., 2017; Chiang et al., 2023; Dawson et al., 2010; Estes et al., 2015; Gengoux et al., 2019; Jocelyn et al., 1998; Kasari et al., 2008; Landa et al., 2011; Rogers et al., 2012; Sinai-Gavrilov et al., 2020; Strain & Bovey, 2011; Vernon et al., 2019; Vivanti et al., 2014; s Wang et al., 2021) assessed cognitive development, including six interventions. The network plot of specific comparisons of different interventions is shown in Fig. 3. From the league table (Table 3), we found that LEAP(SMD: 1.38, 95 % CI: 0.74 to 2.03) was the most effective intervention and most able to enhance the cognitive development compared to the control group. Comparison of adjusted funnel plots are shown in Supplementary Figure 9, no significant bias was found in the included studies. As shown by the sensitivity analysis (see Supplement 17), most of the studies were conducted in North America, with clinician-implemented interventions and intervention durations longer than 12 weeks. The intervention effects of the different interventions were not affected by location of intervention, implementer or intervention duration, and were comparable across

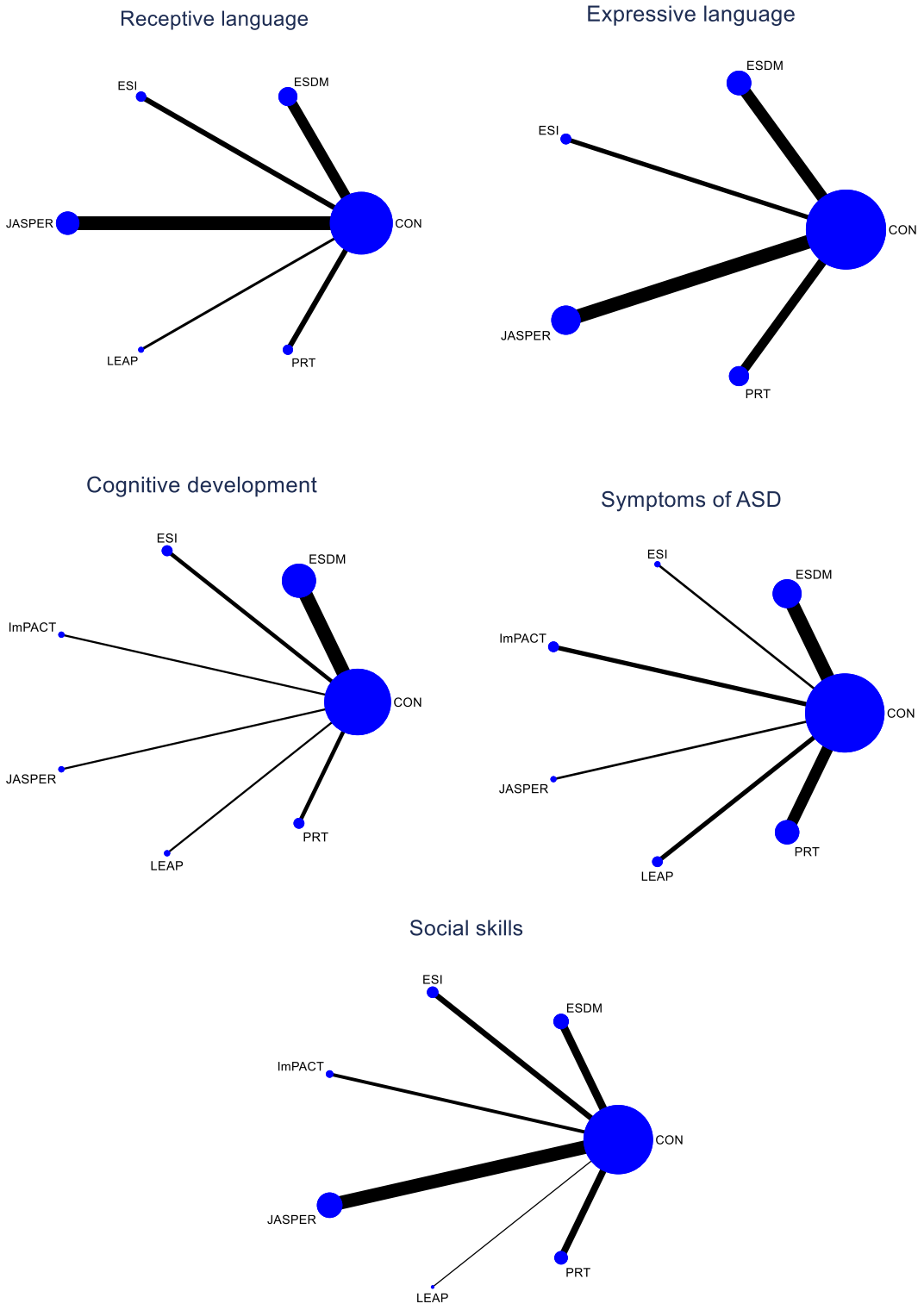

Fig. 3. Network meta-analysis graphs for comparison of different interventions on receptive language, expressive language, cognitive development, reduction in symptoms of ASD, and social skills. The size of the nodes relates to the number of participants in that intervention type, and the thickness of lines between the interventions relates to the number of studies for that comparison. (PRT=Pivotal Response Treatment; JASPER=Joint Attention, Symbolic Play, Engagement, and Regulation; ESI=Early Social Interaction Project; ESDM=Early Start Denver Model; LEAP=Learning Experiences Alternative Program; ImPACT= Improving Parents as Communication Teachers) .

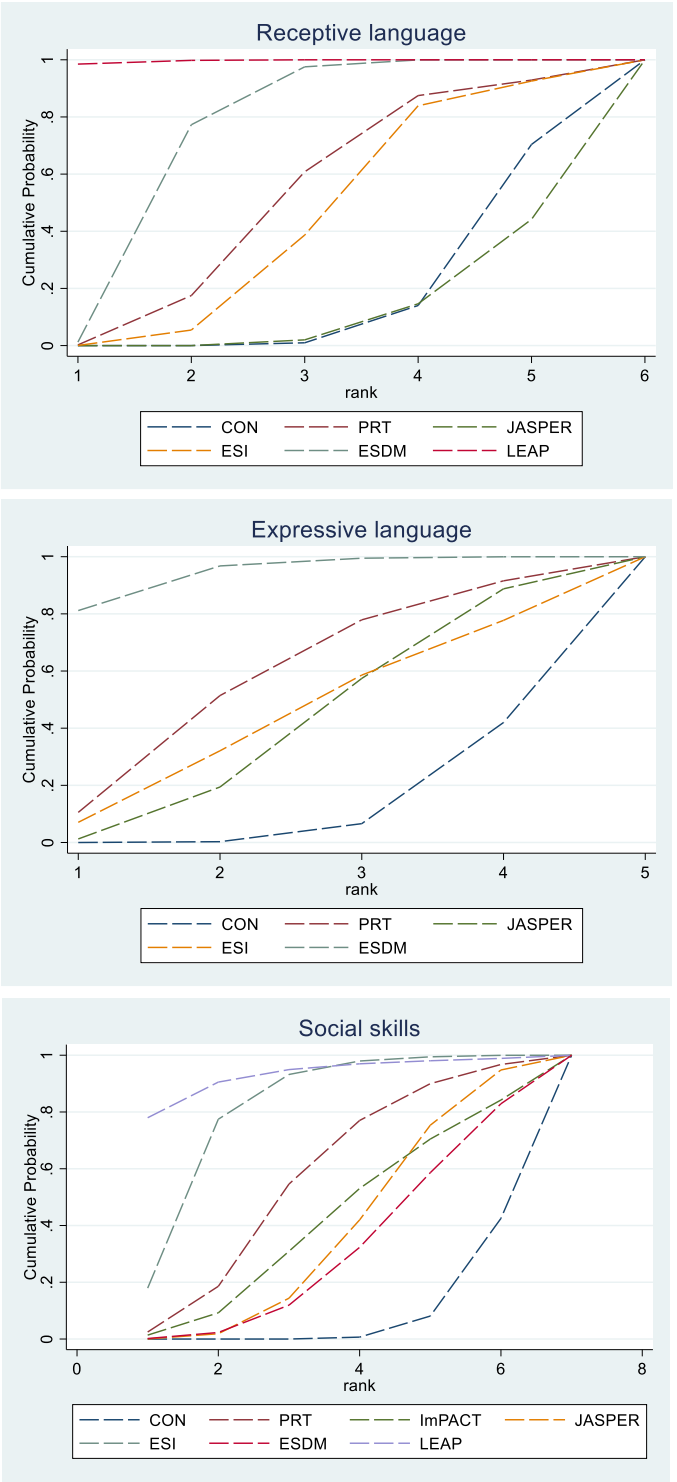

Fig. 4. The surface under cumulative ranking curves (SUCRAs) for the assessment of different interventions on receptive language, expressive language, cognitive development, reduction in the symptoms of ASD and social skills.

intervention groups.

4.4. Reduction in symptoms of ASD

Seventeen studies (Boyd et al., 2014; Brian et al., 2017; Sophie Carruthers et al., 2024; Chiang et al., 2023; Dawson et al., 2010; Duifhuis et al., 2016; Estes et al., 2015; Gengoux et al., 2019; Hardan et al., 2015; Kasari et al., 2015; Oosterling et al., 2010; Rogers et al., 2012; Song et al., 2021; Strain & Bovey, 2011; Vernon et al., 2019; Vivanti et al., 2014; Xu et al., 2018) assessed the degree of reduction in symptoms of ASD, including six interventions. The network plots are shown in Fig. 3. We found (Table 3) that LEAP (SMD: −0.80, 95 % CI: −1.47 to −0.12) and ESDM (SMD: −0.56, 95 % CI: −1.05 to −0.07) had relatively better intervention effects, effectively reducing autism symptoms in children with ASD. ESI (SMD: −0.01, 95 % CI: −0.97 to 0.95) had the worst intervention effect, and all six interventions were more effective than the controls. Comparison of adjusted funnel plots are shown in Supplementary Figure 12, there was no significant publication bias. As demonstrated by the sensitivity analyses (see Supplement 17), the majority of the studies were conducted in North America, the intervention was delivered by clinicians, and the duration of the intervention exceeded 12 weeks. Consequently, the intervention effects of different interventions were less likely to be moderated by location of intervention, implementer, and intervention duration, thereby enhancing comparability across intervention groups..

4.5. Social skills

Thirty-four studies (Brian et al., 2017; Sophie Carruthers et al., 2024; Chang et al., 2016; Estes et al., 2015; Gengoux et al., 2019; Gengoux et al., 2021; Goods et al., 2013; Hampton et al., 2020; Hardan et al., 2015; Kaale et al., 2011; Kasari et al., 2015; Kasari et al., 2010; Kasari et al., 2014; Kasari et al., 2008; Landa et al., 2011; Lawton & Kasari, 2012; Rogers et al., 2012; Schreibman & Stahmer, 2014; Shire et al., 2017; Sinai-Gavrilov et al., 2020; Vernon et al., 2019; Vivanti et al., 2014; Warreyn & Roeyers, 2014; Wetherby & Woods, 2006) studied social skills, including six interventions. The results of the comparison of the different interventions are shown in Fig. 3. According to the results of network meta-analyses (Table 3), LEAP (SMD: 0.90, 95 %CI: 0.11 to 1.68) and ESI (SMD: 0.55, 95 %CI: 0.20 to 0.89) had a significantly greater effect on enhancing social skills. Comparison of adjusted funnel plots are shown in Supplementary Figure 15, we did not find significant bias in the included studies. The results of the sensitivity analyses demonstrate that the intervention groups are not significantly influenced by location of intervention, implementer, or length of intervention (see Supplement 17). Therefore, the transitivity hypothesis is fulfilled, and the indirect evidence can be considered comparable.Ranking the NDBIs in different developmental domains.

A sensitivity analysis of the forest map and SUCRA values for different domains was conducted (see Supplementary 16). The overall forest map was found to remain relatively stable, with some changes in the SUCRA rankings of other domains. This may be due to the fact that some studies covered only individual areas of them and the small number of studies analysed in some subgroups. Therefore, in subsequent analyses, NDBIs with fewer than two subgroup studies were excluded to minimise possible errors in the NMA.

In the development of language, the SUCRA results indicated that ESDM (SUCRA: 93.9 %, 94.5 %, 75.3 %) was the most effective intervention for enhancing receptive language skills, expressive language skills and cognitive development. In terms of reducing the symptoms of ASD, LEAP (SUCRA: 87.0 %) was identified as the most effective intervention, followed by PRT (SUCRA: 71.3 %). With regard to social skills, the SUCRA results indicated that ESI (SUCRA: 93.4 %) was the most effective intervention for improving social skills, followed by PRT (SUCRA: 66.6 %). Furthermore, PRT was the second most efficacious intervention for enhancing receptive language, expressive language, social skills, and mitigating the symptoms of autism.

5. Discussion

5.1. Summary of evidence

This first network meta-analysis of NDBIs for ASD sought to evaluate the impact of diverse interventions on various outcomes, including receptive and expressive language skills, cognitive development, the symptoms of ASD, and social skills in children with autism. The findings of the study indicated that ESDM was the intervention with the greatest potential for enhancing receptive language, expressive language, and cognitive development. LEAP was the intervention most likely to result in reducing in the symptoms of ASD. Furthermore, ESI was identified as the intervention with the greatest potential for enhancing social skills.

5.2. Comparisons with previous studies and theoretical implications of results

Consistent with the findings of this study, previous systematic reviews and meta-analyses have also demonstrated significant effects of NDBIs on language, cognitive and social skills, however, there is some ambiguity regarding reductions in ASD symptoms and improvements in joint attention skills (Jenna E Crank et al., 2021; Song et al., 2024; Tiede & Walton, 2019). This inconsistency may be attributed to variations in outcome measures across different studies and the quantity as well as quality of studies included in the reviews.

Despite numerous studies demonstrating the positive impact of early intervention on children with ASD, there remains a need to further investigate the most effective NBDIs that can enhance their abilities. In recent years, researchers have utilized meta-analysis to summarize the intervention effects of NBDIs and identify potential moderating variables. The promising outcomes observed in these interventions can be attributed to their ability to integrate behavioral and developmental learning strategies, incorporate natural

developmental environments and conditions, as well as target cognitive, language, and social skills as key developmental goals.

According to the results of the NMA, ESDM (SUCRA: 93.9 %, 94.5 %, 75.3 %) was the most effective intervention for enhancing receptive language skills, expressive language skills and cognitive development. Previous studies have reported mixed outcomes in language development and cognitive development. Some scholars have argued that ESDM significantly promotes social communication, enhance linguistic capabilities (Rogers et al., 2019; Rogers et al., 2012), and foster cognitive development in young children diagnosed with autism (Eapen et al., 2013). Nevertheless, other researchers have reached markedly divergent conclusions (Colombi et al., 2017; Li et al., 2018; Rogers et al., 2012; Xu et al., 2018). A comprehensive meta-analysis conducted by Fuller et al. (2020) revealed that ESDM significantly enhanced cognitive abilities (g=0.41) and language skills (g=0.41) in young children with ASD, a finding that aligns with the results of the present study. Therefore, this review argues, firstly, ESDM is grounded in children's intrinsic motivation and effectively fosters their interest in learning interest in learning (s. s Wang et al., 2021; Z. Wang et al., 2021). Secondly, the intervention incorporates behavioral teaching techniques within shared activities, emphasizing adult communication cues and sensitive responses towards children (Sinai-Gavrilov et al., 2020). Warlaumont et al. (2014) demonstrated that immediate adult responses to children's vocalizations significantly increased subsequent language-related vocalizations, highlighting the crucial role of prompt adult feedback. Lastly, ESDM emphasizes progressively detailed teaching paradigms embedded within everyday natural life situations (Vivanti et al., 2014). The utilization of verbal symbols serves to enhance language comprehension, thereby facilitating the maximization of opportunities for verbal expression and communicative motivation. Moreover, ESDM emphasizes the significance of imitation, non-verbal communication (including joint attention), verbal communication, social development (including emotional sharing), and play; all of which are pivotal aspects in children's development. Cognitive development is facilitated through integrated training in these domains. Prior research has demonstrated that ESDM intervention significantly enhances children's cognitive, linguistic, and adaptive abilities, while simultaneously reducing the prevalence of autistic symptoms. Furthermore, the observed improvements in children's social behavior following intervention have been associated with the restoration of typical patterns of brain activity (Dawson et al., 2012).

LEAP adopts a distinctive approach to ameliorating autism symptoms by integrating the fundamental principles of applied behaviour analysis and early childhood education (Hoyson et al., 1984; Strain & Cordisco, 1994; Strain & Hoyson, 2000). This integration is designed to effectively reduce the barriers hindering autistic traits learning in children. Consequently, LEAP demonstrates enhanced targeting and intervention efficacy, which has been substantiated by empirical research (Boyd et al., 2014; Strain & Bovey, 2011; Tsang et al., 2007), further corroborating its effectiveness in alleviating ASD symptoms. The core strengths of the LEAP model extend beyond its immediate therapeutic impact to encompass its innovative teaching model. The incidental teaching model employed in LEAP significantly enhances positive interactions between children with ASD and their typically developing peers, providing a more enriching social environment and opportunities for practicing more complex developmental skills than would be possible with one-to-one traditional tutorial instruction (Raulston et al., 2019). Such interactions have been demonstrated to enrich the learning experience and promote overall social, emotional, and cognitive development in children. Furthermore, the parental skills training component of the LEAP model has a profound and enduring impact. This training enables parents to effectively apply learned skills in natural settings, thereby improving interaction dynamics within families and significantly reducing challenging behaviors. Moreover, it promotes positive changes in children's behaviors that contribute to reducing autism symptoms among young children with ASD.

In terms of social competence, ESI has demonstrated significant intervention effects that are consistent with the findings of previous studies. Two potential explanations for this phenomenon can be proposed. Firstly, ESI is an evidence-based approach that integrates behavioral and developmental techniques to enhance young children's competence through interventions for parents of children with ASD. This contributes to the development of young children's competence (Wetherby et al., 2014). The intervention is based on adult learning principles, where parents are taught to implement relevant evidence-based strategies in their natural environment (Wetherby & Woods, 2006). Practically speaking, parents are equipped with the ability to identify issues related to their children's social and linguistic communication, enabling them to provide timely interventions when necessary. Moreover, implementing the intervention in everyday life resulted in more pronounced generalization and maintenance effects. Secondly, early implementation distinguishes ESI from other NDBIs. Starting interventions before 24 months old when symptoms are typically less severe may reduce the need for more intensive interventions delivered by clinicians later on (Guthrie et al., 2023). This period is particularly crucial for a child's brain and social development (Wetherby et al., 2014), making earlier intervention essential support at a critical stage.

Not all of the studies included in this systematic review met high quality standards, as 34.1 % of the literature exhibited some risk to validity. Moreover, limitations in the research methodology may introduce bias into the meta-analysis results, thereby reducing the reliability. Additionally, similar to previous meta-analyses, the current NMA was constrained by outcome measurement instruments and a limited number of studies (Jenna E Crank et al., 2021; Tiede & Walton, 2019). The transitivity of a study may also be affected by the lack of literature on interventions such as LEAP, ImPACT and others. This may, in turn, impact the reliability of the results assessed. Furthermore, as there are no established statistical tests for the transitivity hypothesis, this NMA could only assess its plausibility through a clinical and methodological review of previous studies. The final results corroborated the findings of several previous meta-analyses(Tiede & Walton, 2019; s Wang et al., 2021; Z. Wang et al., 2021). However, they also yielded results that were inconsistent with the conclusions of other studies(Jenna E. Crank et al., 2021; s Wang et al., 2021; Z. Wang et al., 2021). Nevertheless, these findings contribute to our understanding and provide valuable insights into the intervention effects of NBDIs for children with ASD.

This study represents the comprehensive synthesis of NMA examining the effect of NBDIs in interventions for children with ASD, surpassing previous research studies. In addition to delineating the specific types of NBDIs employed for receptive language, expressive language, cognitive development, social skills, and symptom reduction in children with ASD, this paper further elucidates the most

suitable interventions for ASD by providing additional information and synthesizing existing research.

5.3. Strengths and limitations

Based on the outcomes of our investigation, this study represents a pioneering effort in utilizing the NMA approach to comprehensively summarize the intervention effects of various NBDIs for children with ASD. By integrating evidence from prior empirical studies, and employing league tables and surface under cumulative ranking curves derived from data analysis, we have evaluated the potential optimal interventions in terms of effectiveness across different developmental aspects for children with ASD. These findings aim to offer valuable guidance for future selection of early interventions targeting children with ASD. Furthermore, this NMA offers an insightful examination of the transitivity of direct comparisons between disparate indirect evidence, a methodological advancement over many review articles(Wang et al., 2023), and a means of enhancing the reliability of the results.

However, there are several notable limitations of this NMA. Firstly, the included studies varied significantly in terms of their number across interventions. Despite the implementation of sensitivity tests to control for the number of studies in the subgroup analyses, the results of this study must be interpreted with caution. Secondly, variations existed among the studies regarding outcome measures, intervention duration and other characteristics. Intervention effects could be influenced not only by the specific intervention but also by study and participant characteristics, and these differences likely contributed to a high degree of heterogeneity between studies. In order to minimize discrepancies across measurements tools and units used in different studies' findings biasing our results interpretation, this review predominantly utilized SMD as an effect size indicator. Lastly, yet importantly for comprehensive reporting purposes within this field of research scope inclusion criteria allowed for some literature with a higher risk of bias; nevertheless, we also presented results excluding these high-risk studies separately in the appendix.

5.4. Implications and future research

Although numerous research findings exist, future research should address several considerations. Firstly, despite the fact that this study took into account as many potential moderators as possible when assessing the reasonableness of transitivity, it was not possible to achieve a definitive conclusion due to the limitations of the assessment methodology, the lack of relevant studies, and the limitations of the number of included studies. Therefore, we conducted sensitivity analyses to provide as much explanation as possible and to prove the comparability between different studies. It would be beneficial for future studies to place a greater emphasis on the comparability of indirect evidence in NMA. Additionally, it would be advantageous for studies examining the effects of different NDBIs to consider a wider range of factors influencing the outcomes. Secondly, although the findings from this review suggest that ESDM may be the most effective intervention for improving receptive language, expressive language, and cognitive development; however, more empirical evidence can be expected in forthcoming studies. Thirdly, due to a lack of direct comparison studies, this NMA was limited to examining indirect comparisons. It would be advantageous for future studies to directly compare different NDBIs in order to provide more empirical research evidence on optimal interventions. Finally, the outcomes of the present study must be regarded with caution due to the absence of direct evidence and the reliance upon indirect comparative evidence. It is hoped that more studies will provide evidence of direct comparison of NDBIs in the future to validate the findings.

6. Conclusions

The present systematic review employed NMA to evaluate the efficacy of various NBDIs and identify the most suitable interventions for children diagnosed with ASD. Our findings indicate that ESDM may yield superior outcomes in terms of enhancing receptive language, expressive language and cognitive development among children with ASD. Additionally, LEAP appears to be a promising intervention in reduction the symptoms of ASD and ESI probably the most effective intervention to enhance social skills.

Table 4
SUCRA values of NDBIs in main domains.

Domains	NDBIs	SUCRA	Domains	NDBIs	SUCRA
Receptive language	ESDM	93.9 %	Reduction in symptoms of ASD	LEAP	87.0 %
	PRT	64.7 %		PRT	71.3 %
	ESI	54.8 %		ImPACT	45.8 %
	JASPER	15.3 %		ESDM	36.8 %
Expressive language	ESDM	94.5 %	Social skills	ESI	93.4 %
	PRT	58.3 %		PRT	66.6 %
	ESI	44.5 %		ImPACT	48.8 %
	JASPER	40.7 %		JASPER	43.3 %
Cognitive development	ESDM	75.3 %		ESDM	37.3 %
	ESI	74.5 %			
	PRT	29.9 %			

CRediT authorship contribution statement

LI Dan: Writing – review & editing, Supervision. **Huang Yaping:** Writing – original draft. **Cui Xiaobing:** Methodology. **Bing Jiaojiao:** Validation. **Yin Huazhan:** Conceptualization.

Declaration of Competing Interest

All authors disclosed no relevant relationships.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.reia.2025.202656.

Data availability

No data was used for the research described in the article.

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