www.nature.com/scientificreports

scientific reports

Check for updates

OPEN

Music intervention for neurodevelopment in the pediatric population: a systematic review and meta-analysis

Daiji Jiang[1,8], Xiaowei Liu[2,8], Qian Lin[3,4], Guyi Wang[5], Gang Wang[6]✉ & Dandan Zhang[3,4,7]✉

This systematic review and meta-analysis aim to summarize and analyze current research on the effects of MI on neurodevelopment in children of all ages and health statuses to provide a reference for music therapy (MT) and its clinical research in pediatrics. We conducted a comprehensive search of PubMed, Embase, Web of Science, and Cochrane Library databases up to December 2023, focusing on randomized controlled trials that evaluated neurodevelopmental outcomes following MI. Our analysis, which included seven studies involving 337 participants, employed standardized mean difference (SMD) calculations to assess outcomes across multiple neurodevelopmental scales. While no significant cognitive improvements were observed on the Bayley-III scale, positive effects were noted in language, motor skills, and IQ scores when assessed via Gesell, CSBQ, and IQ scales. Our research underscores the potential of music intervention in the process of children's neurodevelopment, including cognitive function, language, motor and IQ. Based on the limitations, researchers should carefully design their MI protocols, ensuring standardization and avoiding probable confounding factors such as regional specificity, age ranges and special populations, it will contribute to more robust results and improve the comparability of findings across studies.

Keywords Children, Pediatrics, Music intervention, Neurodevelopment, Meta-Analysis

Abbreviations

CIs	Confidence intervals
CSBQ	Child self-regulation and behavior questionnaire
MI	Music intervention
MT	Music therapy
SMD	Standardized mean differences
TSB	The stanford-binet intelligence scale

Music therapy (MT) is a well-established modality that complements standard treatments for numerous pediatric conditions[1]. Music and music intervention (MI) play a central role in MT, encompassing a spectrum of activities, including active forms such as creating music or playing instruments and receptive forms like listening, often conducted by certified music therapists[2]. MT has been recognized for its neurotherapeutic potential[3], with engagement in music promoting neural plasticity[4] and inducing changes in the grey and white matter[5], predominantly in the frontotemporal regions. Such neurobiological impacts highlight the therapeutic efficacy of music, as evidenced by the accelerated recovery of patients post-major surgeries[6,7].

[1]Heart Center and Shanghai Institute of Pediatric Congenital Heart Disease, Shanghai Children's Medical Center, National Children's Medical Center, School of Medicine, Shanghai Jiao Tong University, Shanghai 200127, China. [2]Department of Traditional Chinese Medicine, Shanxi Provincial People's Hospital, No. 256 Friendship West Road, Xi'an, Shaanxi Province, China. [3]Office of Pediatrics, Pediatric College, Shanghai Jiaotong University School of Medicine, No. 227 South Chongqing Road, Shanghai 200025, China. [4]Shanghai Xinhua Hospital, Shanghai Jiao Tong University School of Medicine, No. 1665 Kongjiang Road, Shanghai 200092, China. [5]Minhang Vocational and Technical College, 4080 Yuanjiang Road, Minhang District, Shanghai 201111, China. [6]National Center for Mental Health, No.7 Yinghuayuan west street, Chaoyang District, Beijing 100029, China. [7]Key laboratory of artificial intelligence music therapy, Shanghai Conservatory of Music, No. 20 Fenyang Road, Shanghai 200031, China. [8]Daiji Jiang and Xiaowei Liu contributed equally to this work. ✉email: StevenWang618@163.com; rainbowdan0513@shsmu.edu.cn

Childhood represents a critical period for neural development, with various scales developed to quantitatively assess children's neurological progress across behavioral, motor, language, and cognitive domains[8]. These developmental metrics emphasize the significance of early neurodevelopmental trajectories and the potential long-term implications of disruptions. Research demonstrated that the functional development of brain cells and signal transmission require stimulation from substantial amounts of appropriate information[9]. Specifically, external sensory stimulation (such as hearing and tactile perception) plays a vital role in neuronal growth, the establishment of synapses, and neural signal conduction within the brain[10,11]. At the same time, Research has consistently demonstrated that interventions during this sensitive period can significantly mitigate the risks of developmental disorders, highlighting the necessity for early and targeted interventions to ensure optimal neurological development in children[12].

Currently, research on the application of MI in pediatric neurodevelopment is limited and uncertain. Existing studies mainly focus on specific subsets, such as preterm infants[13], rather than overall covering the full range of ages across childhood, including children and adolescents. Therefore, our study aims to extend these insights to the entire pediatric population to obtain continuous, extensive and scientific research results. Meanwhile, evaluating the effectiveness of neurodevelopmental scales in related research was also a key objective. Expanding research subjects and results could provide a more thorough understanding of the potential neurological benefits of MI across the entire stage of childhood and serve as a significant reference for future research on MT in pediatric neurodevelopment, including patients diagnosed with neurological diseases.

Methods

Search strategy and selection criteria

Four databases, PubMed, Embase, Web of Science, and Cochrane Library, were used for studies on the effectiveness of MI in pediatric neurodevelopment, and all retrieval results from the database were completed on December 13, 2023. Using the PICOS framework according to the Cochrane Handbook for Systematic Reviews of Interventions[14], we set "music intervention" as "Intervention" and "neurodevelopment" as "Outcome." As to the "Outcome," neurodevelopmental scales, such as Bayley-III, Gesell, and Wechsler, were included. "Participants" were set as pediatrics, including infant, toddler, and premature. Search strategies varied slightly across databases (Stable 1). Two authors (Jiang and Zhang) independently searched and screened the relevant literature. EndNote 20 software was utilized to delete duplicates and non-pediatric literature. After that, Full texts of eligible articles were independently assessed for meta-analysis by Jiang, Liu and Wang, with disagreement resolved through discussions with Lin, Wang, and Zhang.

Data extraction

A data extraction form was developed to extract the suitable data including (1) study characteristics (authors, publication year, and country); (2) participant characteristics (sample size, mean age, sex ratio, and types of neurodevelopmental assessments); (3) study design and methodological quality (random allocation, blinding, selection process of participants, loss to follow-up); (4) details of the music interventions (method, music style, and use of equipment); (5) outcome measures and statistical data (types of neurodevelopmental scales and results of neurodevelopmental assessments). Data extraction was independently conducted by two authors (Jiang, Liu and Wang), with disagreements resolved through discussions with another pair of authors (Lin, Wang, and Zhang).

Assessment of risk of bias

Three authors (Jiang, Liu and Wang) independently assessed the risk of bias in the included studies using the Cochrane Collaboration tool[15]. They evaluated 7 specific items for quality and bias: (1) Random sequence generation, (2) Allocation concealment, (3) Blinding of participants and personnel, (4) Blinding of outcome assessment, (5) Incomplete outcome data, (6) Selective reporting, and (7) Other bias. Each item was classified as "low risk," "unclear risk," or "high risk" based on the study details. Discrepancies were resolved through discussions with Lin, Wang, and Zhang.

Statistical analysis

Continuous outcome data were analyzed using standardized mean differences (SMD) with 95% confidence intervals (CIs), focusing on neurodevelopment scores post-intervention for both music intervention and control groups. The longest follow-up time point was selected for time-varied outcomes, with professional reports prioritized for multiple assessments. Missing SD or 95% CIs were estimated from available statistical measures. Statistical heterogeneity was assessed using I^2 statistics. A fixed-effect model was applied for low heterogeneity ($I2 < 50\%$), whereas a random-effects model was employed when substantial heterogeneity was present ($I2 \geq 50\%$), interpreted as "small" (0.2), "medium" (0.5), or "large" (0.8). P-values were two-sided, with 0.05 marking significance. Publication bias was explored using funnel plots and Egger's regression[16].

Results

Identification of eligible studies

Figure 1 illustrates the result of our screening process. The titles and abstracts of all identified articles were assessed for eligibility based on the following inclusion criteria: (1) randomized controlled trials; (2) intervention group receiving music intervention with rhythm, melody, and harmony; (3) outcomes including neurodevelopmental measures; (4) participants aged under 18 years. Exclusion criteria were as follows: (1) reviews, protocols, conference papers, case reports, letters, and editorials; (2) control group received music components; (3) studies lacking sufficient meta-analysis data. We identified 8719 articles using our search strategy. Duplicate articles

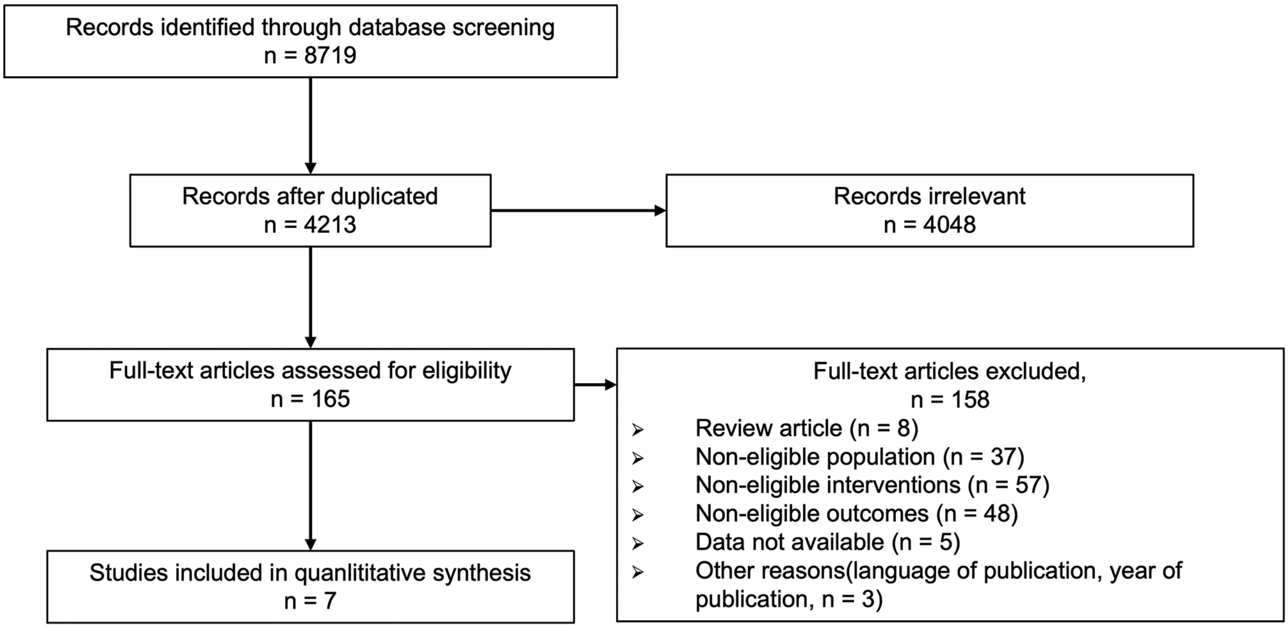

Fig. 1. Study flow diagram.

Study	Country	Population	Pediatric category	Intervention	Duration	Control condition	Measurement
Lejeune 2019	Switzerland	17	Infant/toddler	Recorded music	5 times per week * 5 weeks (mean)	Standard care	[1]Bayley – III
Kaviani 2014	UK	60	Preschool	Music lesson	2 times per week * 13 weeks	No music class	[2]TSB
Slevin 2020	Ireland	18	Preschool	Recorded music	5 times per week * 6 months	Standard care	Bayley – III
Haslbeck 2021	Switzerland	56	Infant	Creative music therapy	2-3 times per week	Standard care	Bayley – III
Haslbeck 2023	Switzerland	31	Infant	Creative music therapy	2-3 times per week	Standard care	Bayley – III
Gao 2023	China	76	Infant	Recorded music	During hospitalization	Standard care	[4]Gesell
Bentley 2023	Australia	79	preschool	Recorded rhythmic form	30 min per week * 8 weeks	Standard care	[5]CSBQ
Total		337					

Table 1. Summary characteristics of included studies.

($n = 4506$) and irrelevant abstracts ($n = 4048$) were excluded. Finally, 7 articles out of 165 available full-text articles were included in this meta-analysis.

Patient populations and study characteristics

The analysis included seven studies published between 2014 and 2023, encompassing 337 participants were included (Table 1). The sample sizes of each study ranged from 17 to 79. 4 studies included infants[17–20], while 3 studies[21–23] included preschool participants in the analysis. The studies were conducted by researchers from around the world, including Europe ($n = 5$), Asia ($n = 1$)[20], and Australia ($n = 1$)[23]. We identified 6 parallel-group RCTs and 1 cross-over RCT[23]. All trials were single-center studies except for one multi-center trial[23]. Based on the particularity of MI, we identified different MI types, frequencies, and durations, including recorded music[17,20,21], rhythmic form[23], creative music therapy[18,19], and music lessons[22]. Standardized care referred to the control group received routine care without any music education/training during interventions.

As to the neurodevelopment measurements, quantitative scales were used in all 7 studies. Bayley Scales of Infant and Toddler Development, Third Edition (Bayley-III) were primarily used in 4 studies[17–19,21]. The Stanford-Binet Intelligence Scale, Fourth Edition (TSB)[22], the Gesell Development Scale[20], and the Child Self-Regulation and Behavior Questionnaire (CSBQ)[23] were used in different 3 studies. As to the aspects of the neurodevelopmental measurement, the 4 scales covered different aspects of neurodevelopment from cognitive scores, language scores, and motor scores to behavioral scores and general intelligence scores. As to the attrition bias, 3 studies exhibited a high risk of bias for their incomplete cohort assessment[17,20,23].

Quality of the included articles

The general risk of bias in the included studies varied from "Low" to "High" risk of bias, with many areas described as "Unclear" due to missing detailed descriptions. The risk of bias is described in the overview in Fig. 2 and detailed in Fig. 3. MI was administered by professional music therapists in only two studies with a low risk of performance bias[17,21], while others had a high risk of performance bias. Notably, two studies lacked standard deviation data[19,21]. To facilitate data analysis, we extracted the maximum and minimum values of the standard deviation in another entirely data-driven study that matched a similar population[17], and in those two studies, random values of this interval were used as the standard deviation for subsequent analyses.

Cognitive outcomes for Bayley-III and CSBQ

No significant effect of MI on cognitive scores was observed compared to standard care by Bayley-III and CSBQ (Fig. 4, $n = 122$, 4 studies; MD 0.47; 95% CI −3.29 to 4.23; $P = 0.81$). With the scale of Bayley-III, 4 studies showed a minor change in cognitive neurodevelopment, and no significant difference was found in cognitive development either of CSBQ (Intervention 3.34 V.S. Control 3.3, $n = 79$). Due to differences in CSBQ[23] methodology compared to Bayley-III, Fig. 4 restricted the inclusion of CSBQ results.

Language outcomes for Bayley-III and Gesell

Figure 5 shows that although the MD for language scores was the lowest among comparisons, no significant decrease was observed in the language score following intervention ($n = 122$, 4 studies; MD -4.14; 95% CI -11.85 to 3.56; $P = 0.29$). One study reported a significant decrease in the language score through Bayley-III[21], but the children participating in the trial were all preterm infants, and the number was less than 10. In contrast, the Gesell Development Scale[20] showed a significant increase in language development (Intervention 92.29 V.S. Control 87.05, $n = 21$ V.S. 19, $P = 0.023$).

Motor outcomes for Bayley-III, Gesell and CSBQ

No significant difference was found in motor scores of Bayley-III (Fig. 6, $n = 122$, 4 studies; MD -0.73; 95% CI -4.77 to 3.31; $P = 0.72$). However, significant improvements were observed in motor scores of Gesell[20], including the gross motor (Intervention 95.43 V.S. Control 91.05, $n = 21$ V.S. 19, $P < 0.001$) and the fine motor (Intervention 93.24 V.S. Control 90.32, $n = 21$ V.S. 19, $P = 0.016$). Similarly, CSBQ[23] scores showed significant improvements (After intervention 3.76 V.S. Before intervention 3.29, $n = 79$, $P = 0.003$).

General IQ outcomes for TSB

It was quite a pity that only one study measured the IQ in the MI groups[22]. The music lessons were treated to 30 preschool children as the MI. After the music lessons, an average increase of 5 was observed in the general IQ in the MI group. Compared to the control group, there was a significant main effect for assessment ($P < 0.001$).

Discussion

This meta-analysis represents the first comprehensive and overall review of the impact of MI on the neurodevelopment of children across all age groups. The study, involving 337 participants, revealed significant effects on some neurodevelopmental scales such as Gesell, CSBQ and TSB, with implications for the potential and positive effects on cognitive, language, motor skills, and IQ. Our findings indicate that MI led to significant

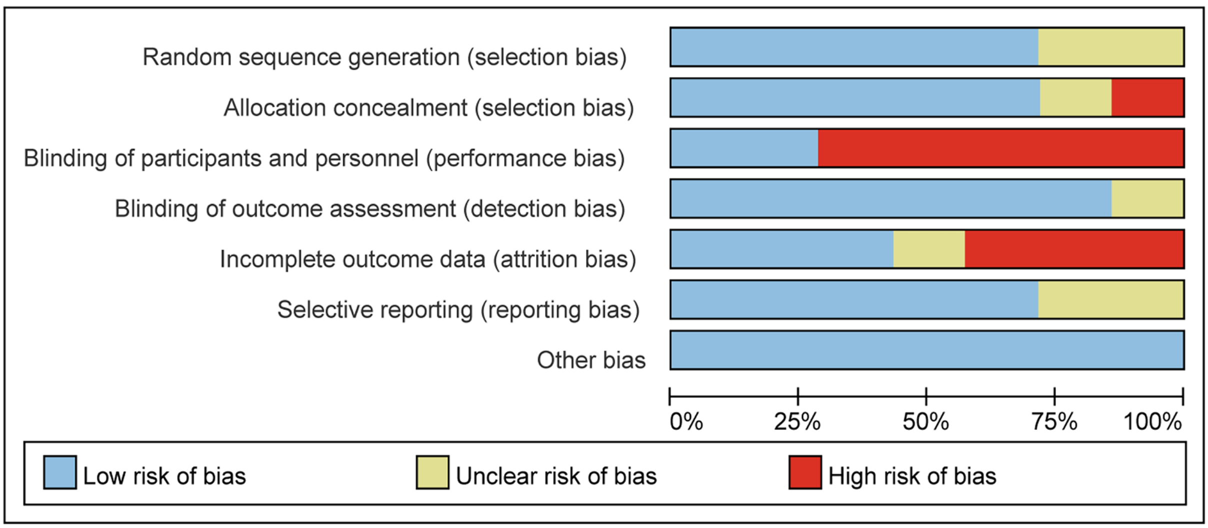

Fig. 2. Risk of bias graph.

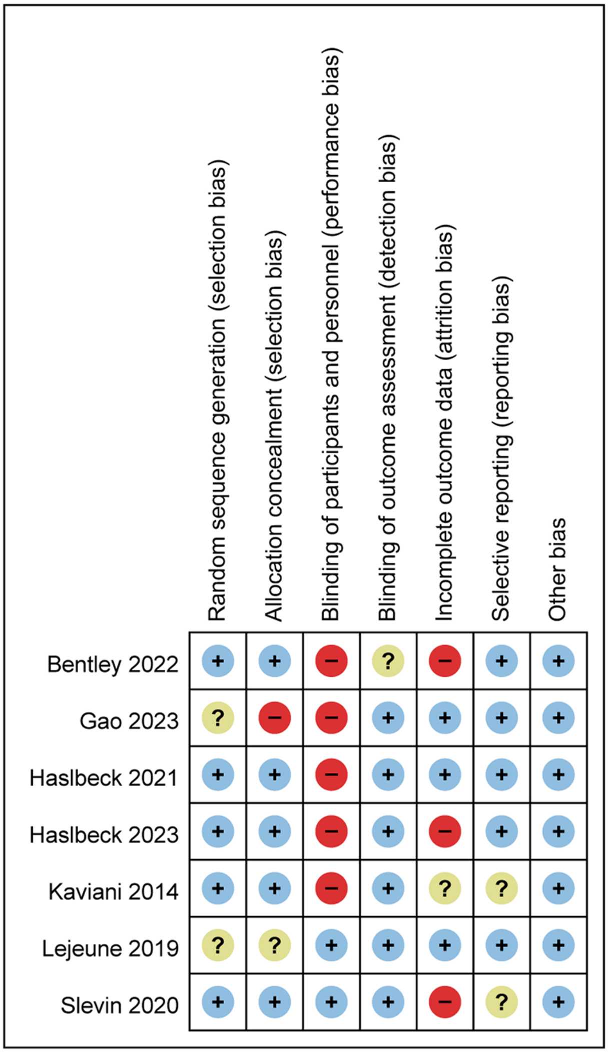

Fig. 3. Risk of bias summary.

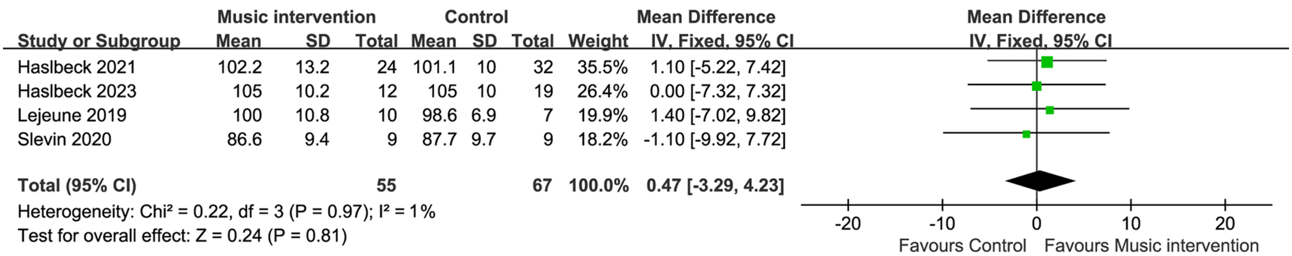

Fig. 4. Comparison: music intervention versus control, outcome 1: cognitive score.

improvements on the Gesell, CSBQ, and TSB scales in several parameters, while no significant differences were observed in Bayley-III scales.

Music therapy may play a crucial role in enhancing cognitive functions in children. Evidence suggests that MI promotes neurobiological processes by facilitating the differentiation, activation, readjustment, and growth of neurons[24,25]. Studies have shown that engagement with music can improve various cognitive abilities, including attention, memory, and executive functions[26]. This is particularly evident in tasks that require the manipulation of information in the brain, where trained musicians exhibit superior memory and organizational skills.

Our research identified cognitive function as a key index for evaluating neurodevelopment, as over half of the research studied focused on cognitive improvement. Both the Bayley-III and CSBQ scales, which assess cognitive function, revealed no significant effects of MI on the development of cognitive scores compared to

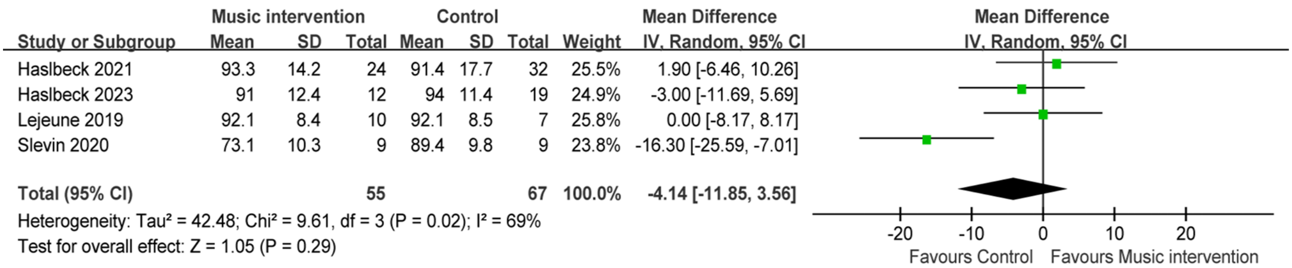

Fig. 5. Comparison: music intervention versus control, outcome 2: language score.

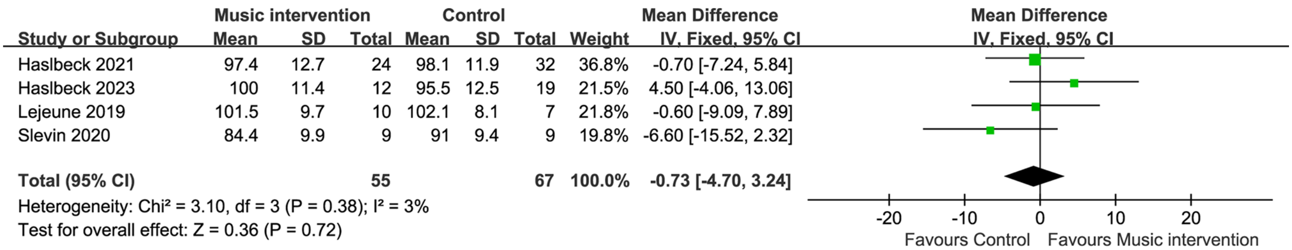

Fig. 6. Comparison: music intervention versus control, outcome 3: motor score.

standard care[23]. The study utilizing the CSBQ established a metered model that differs from other research, potentially obscuring the findings[23], implying that consistencies in participant demographics might serve as a key factor that may influence the results and should be paid more attention during the future research design process. Future research could explore the effectiveness of MT on cognitive function.

Music therapy has a significant impact on language development. Structured musical activities enhance linguistic abilities by engaging critical areas of the brain, such as Broca's and Wernicke's areas, which are essential for language processing. Research has demonstrated that children participating in musical training displayed improved reading skills and phonemic awareness[18], suggesting that the rhythmic and melodic aspects of music support the acquisition and development of language skills. Our study found a significant improvement in language development on the Gesell scale ($n = 43$, $P = 0.023$)[20], while no difference was found in the studies with the Bayley-III scale. We considered the high heterogeneity in the language score was due to the low sample size in one study ($n = 18$)[21], which also indicated us a larger sample size was needed and important in the future study design.

Additionally, music therapy contributes to motor skill development. Activities, such as playing an instrument, involve fine motor control, coordination, and timing, all of which are transferable to other areas of motor development. One research indicates that children engaged in regular musical training show enhanced motor abilities and structural brain changes in regions associated with movement coordination[26]. Our findings on the Gesell scale revealed significant improvements in both the gross motor and fine motor skills after the MI ($n = 40$, $P < 0.001$ in gross motor, $P = 0.016$ in fine motor), indicating the potential benefits of MI on the motor skill, the related application needs more exploration in the future.

Enhancing IQ is one of the most significant outcomes of music therapy in children. Studies have found that music lessons can lead to measurable improvements in IQ scores. However, our review revealed mixed results, which may stem from variations in study designs and the intensity of musical training. This underscores the need for more controlled studies to better understand the relationship between music therapy and IQ development.

In our research, regarding the evaluation tools that were most widely used in pediatrics with higher evaluation validity,, we further analyzed the Bayley-III and the Gesell Scale that had similar modules. The Bayley-III scale[27], typically designed for infants, is an ability test of global development[28]. It contains 5 domains in the assessment: cognitive, language (receptive and expressive) and motor (fine and gross). The Gesell scale is a screening test for demonstrating developmental quotients in the 5 fields: gross motor, fine motor, adaptive behavior, language and personal-social behavior[29]. The Bayley-III, which was measured on the participants ($n = 122$) in our study, did not capture significant results, while the Gesell Scale demonstrated more significant results. However, as noted in related pediatric research, the Gesell Scale was mostly used on moderate or late preterm infants in hospitalization, a relatively specific pediatric group. This specialization may limit the generalizability of the findings. At the same time, in the studies with Bayley-III, it was mostly used to evaluate the growth and development of normal children. Therefore, the selection of these two scales should fully consider the applicable population and their background to improve the credibility of the results in future applied research, and the potential confounding factors such as individual status (and age differences (including factors related to growth and development) should also be identified and excluded to eliminate the effect on results in related meta-analysis researches. Meanwhile, the variability in outcomes across studies highlights the need for more standardized population and assessment scales in research methodologies to clarify music's role in the function of cognitive, language, motor, and IQ.

Furthermore, the stimulated effect of music on the brain system may vary between temporary and sustainable outcomes, with duration and frequency potentially influencing research consequences in the neurodevelopment of different subjects. Current intervention programs often focus on hospitalized or preterm infants with different durations and frequencies. To understand its function and mechanism, future research should consider standardizing the duration, frequency, music methods, and environment from MI or MT to verify different research. Despite ongoing progress in neuroscience regarding the interaction between music and brain electrical signals[25], positive clinical outcomes will continue to support research advancement in this field.

Limitation

Our study has several important limitations that warrant emphasis. First, the included MI protocols exhibited substantial regional and cultural variability—unlike standardized tools or methods, which limited cross-study comparability. It underscored the urgent need for standardized MI protocols in future research. Additionally, while we systematically included all eligible RCTs in children, the current sample size remains small and is not enough. Although we tried to broaden the scope of research, targeting the 0–18 age range, confirmed the consistency of the subjects on age in each article. Nevertheless, there is no existing study that spanned the entired developmental period (0–18 years old), factors related to growth and development across different research may influence the results of review or meta-analysis research, and may be a breakthrough point that warrants our future exploration. Furthermore, the studies involved participants from diverse geographic regions, inherent cultural or sociocultural context across different research in our meta-analysis, it might be a probable confounding factor that had an influence on the results. By delineating these limitations, we aim to catalyze efforts toward standardized MI protocols and larger-scale, lifespan-focused RCTs, ultimately enhancing the validity and cross-study comparability of research in the future. We hope our systematic synthesis could make a reference for future research with a overall insight and basic understanding on children aged from 0 to 18 years old and encourage more robust RCTs research in this area.

Conclusion

In summary, our research underscores the potential of music intervention in the process of children's neurodevelopment, including cognitive function, language, motor skills and IQ. Based on the limitations, future research should carefully design its MI protocols, ensuring standardization and avoiding probable confounding factors such as regional specificity, age ranges, special populations, etc.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Received: 25 September 2024; Accepted: 10 March 2025
Published online: 26 March 2025

References

1. Zhang, D. et al. Music therapy in pediatric asthma: A short review. *J. Asthma Allergy* **16**, 1077–1086 (2023).
2. Bhandarkar S, Salvi B V, Shende P. Current scenario and potential of music therapy in the management of diseases. *Behav. Brain. Res.* **458**, 114750 (2024).
3. Stegemann T. et al. Music therapy and other music-based interventions in pediatric health care: an overview. *Medicines (Basel)* **6**(1). (2019).
4. Chatterjee D, Hegde S, Thaut M. Neural plasticity: the substratum of music-based interventions in neurorehabilitation. *NeuroRehabilitation* **48** (2), 155–166 (2021).
5. Zuk, J. et al. Neurobiological predispositions for musicality: white matter in infancy predicts school-age music aptitude. *Dev. Sci.* **26** (5), e13365 (2023).
6. Karpati F J, Giacosa C, Foster N E V, et al. Dance and music share gray matter structural correlates. *Brain Res.* **1657**, 62–73 (2017).
7. Sihvonen A J, Särkämö T, Leo V, et al. Music-based interventions in neurological rehabilitation. *Lancet Neurol.* **16** (8), 648–660 (2017).
8. Wang, S. The neuroscience of music; a review and summary. *Psychiatr. Danub.* **30** (Suppl 7), 588–594 (2018).
9. Blankenship A G, Feller M B. Mechanisms underlying spontaneous patterned activity in developing neural circuits. *Nat. Rev. Neurosci.* **11** (1), 18–29 (2010).
10. Sur, M. & Rubenstein, J. L. Patterning and plasticity of the cerebral cortex. *Science* **310** (5749), 805–810 (2005).
11. Katz L C, Shatz C, J. Synaptic activity and the construction of cortical circuits. *Science* **274** (5290), 1133–1138 (1996).
12. Pascal, A. & Govaert, P. Neurodevelopmental outcome in very preterm and very-low-birthweight infants born over the past decade: a meta-analytic review. *Dev. Med. Child. Neurol.* **60** (4), 342–355 (2018).
13. Allen, K. A. Music therapy in the NICU: is there evidence to support integration for procedural support? *Adv. Neonatal Care* **13** (5), 349–352 (2013).
14. Chandler, J. et al. *Cochrane Handbook for Systematic Reviews of Interventions* (Wiley, 2019).
15. Higgins, J. P. et al. The Cochrane collaboration's tool for assessing risk of bias in randomised trials. *Bmj* **343**, d5928 (2011).
16. Egger M. et al. Bias in meta-analysis detected by a simple, graphical test. *Bmj* **315** (7109), 629–634 (1997).
17. Lejeune F. et al. Effects of an early postnatal music intervention on cognitive and emotional development in preterm children at 12 and 24 months: preliminary findings. *Front. Psychol.* **10**, 494 (2019).
18. Haslbeck F B, Bucher H U, Bassler D, et al. Creative music therapy and neurodevelopmental outcomes in pre-term infants at 2 years: A randomized controlled pilot trial. *Front. Pead.*, 9. (2021).
19. Haslbeck F B, Adams M, Schmidli L, et al. Creative music therapy for long-term neurodevelopment in extremely preterm infants: results of a feasibility trial. *Acta Paediatr.* **112** (12), 2524–2531 (2023).
20. Gao, H. et al. Effect of combined procedural pain interventions during neonatal intensive care on sleep, cognitive development, and internalizing behavior: a follow-up analysis of a randomized controlled trial. *Pain* **164** (8), 1793–1800 (2023).

21. Slevin, M. et al. Therapeutic listening for preterm children with sensory dysregulation, attention and cognitive problems. *Ir. Med. J.* **113** (1), 4 (2020).
22. Kaviani H. et al. Can music lessons increase the performance of preschool children in IQ tests?. *Cogn. Process.* **15** (1), 77–84 (2014).
23. Bentley L A, Eager R, Savage S, et al. A translational application of music for preschool cognitive development: RCT evidence for improved executive function, self-regulation, and school readiness. *Dev. Sci.* **26** (5), e13358 (2023).
24. Rickard N S, Toukhsati S R, Field S E. The effect of music on cognitive performance: insight from Neurobiological and animal studies. *Behav. Cogn. Neurosci. Rev.* **4** (4), 235–261 (2005).
25. Vuust, P. et al. Music in the brain. *Nat. Rev. Neurosci.* **23** (5), 287–305 (2022).
26. Forgeard M. et al. Practicing a musical instrument in childhood is associated with enhanced verbal ability and nonverbal reasoning. *PLoS ONE* **3** (10), e3566 (2008).
27. Haslbeck F B, Mueller K, Karen T, et al. Musical and vocal interventions to improve neurodevelopmental outcomes for preterm infants. *Cochrane Database Syst. Rev.* **9** (9), Cd013472. (2023).
28. Bayley N. Bayley scales of infant and toddler development. *Psychol. Co* (2006).
29. Dukes L, Buttery T J. Comparison of two screening tests: Gesell developmental test and meeting street school screening test. *Percept. Mot. Skills* **54** (3 Pt 2), 1177–1178 (1982).

Author contributions

J.D.J and Z.D.D: Writing-original draft, review and editing; J.D.J, L.X.W, L.Q and W.G.Y: visualization, data curation, formal analysis and methodology; W.G and Z.D.D: project administration and supervision. All authors contributed to and approved the final version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

This study was approved by Medical Ethics Committee of Xinhua Hospital Affiliated to Shanghai Jiao Tong University School of Medicine (No. XHEC-D-2024-133).

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-93795-8.

Correspondence and requests for materials should be addressed to G.W. or D.Z.