

• 专题研究:神经精神疾病 •

基于多模态神经调控的音乐疗法改善孤独症谱系障碍儿童共同注意功能的眼动机制

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[摘 要] 目的: 探讨音乐治疗对孤独症谱系障碍(autism spectrum disorder, ASD)儿童共同注意眼动特征的改善效果, 为临床干预提供客观依据。方法: 采用随机交叉设计, 纳入26例3~10岁ASD儿童, 随机分为A、B两组, 分别接受音乐治疗干预和静坐对照实验, 间隔7 d洗脱期后交换实验条件。通过眼动追踪技术记录儿童在共同注意范式任务(眼睛注视、眼睛-头部、眼睛-头-手势三种条件)中的首次注视时间(time to first fixation, TFF), 并采用配对样本 t 检验比较音乐干预效果。结果: 音乐治疗后, ASD儿童在所有条件总分的TFF显著短于静坐对照($t=-2.24, P=0.035, \text{Cohen's } d=-0.458$), 眼睛-头-手势条件下的TFF显著短于静坐对照($t=-2.32, P=0.030, \text{Cohen's } d=-0.485$), 仅眼睛注视和眼睛-头部条件下虽差异无统计学意义, 但TFF均值短于对照条件。结论: 音乐治疗可显著缩短ASD儿童对共同注意目标的首次注视时间, 提示其可能通过优化神经信息处理效率改善社交核心缺陷。眼动特征可作为评估音乐治疗疗效的客观指标。

[关键词] 孤独症谱系障碍; 音乐治疗; 共同注意; 眼动追踪; 首次注视时间

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The oculomotor mechanism of joint attention in children with autism spectrum disorder based on multimodal neuromodulation music therapy

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[Abstract] **Objective:** To investigate the effect of music therapy on eye movement characteristics of joint attention (JA) in children with autism spectrum disorder (ASD), providing an objective basis for clinical intervention. **Methods:** A randomized crossover design was employed. Twenty-six ASD children aged 3–10 years were enrolled and randomly assigned to group A or B. They first received either a music therapy intervention or a quiet-sitting control condition, and after a 7-day washout period, crossed over to the alternate condition. Eye-tracking technology was used to record the time to first fixation (TFF) during a joint attention paradigm task (comprising three conditions: Eye Gaze, Eye-Head, and Eye-Head-Gesture). Paired sample t -tests were applied to compare the effects of the music intervention. **Results:** Following music therapy, the TFF for the total score across all conditions was significantly shorter compared to the quiet-sitting control condition ($t=-2.24, P=0.035, \text{Cohen's } d=-0.458$). Specifically, the TFF in the Eye-Head-Gesture condition was significantly shorter than in the control condition ($t=-2.32, P=0.030, \text{Cohen's } d=-0.485$). Although the TFF in the Eye Gaze and

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Eye - Head conditions alone showed no statistically significant difference, the mean TFF was shorter than in the control condition. **Conclusion:** Music therapy can significantly shorten the time to first fixation on joint attention targets in children with ASD, suggesting that it may improve core social deficits by enhancing neural information processing efficiency. Eye movement characteristics may serve as an objective indicator for evaluating the efficacy of music therapy.

[Key words] autism spectrum disorder; music therapy; joint attention; eye tracking; time to first fixation

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孤独症谱系障碍 (autism spectrum disorder, ASD) 是一种起病于儿童早期的神经发育障碍, 以社会交往障碍、语言沟通困难以及重复刻板行为为核心临床表现^[1-3]。该疾病呈终身性, 致残率高且病因未明, 目前尚无特效药物治疗^[4-5], 对患儿的身心发展、家庭生活及社会公共资源均构成严重挑战^[6-8]。近年来, 全球范围内 ASD 的发病率持续攀升^[9]。美国疾病控制与预防中心 2025 年 4 月发布的最新监测数据显示, 每 31 例儿童中即有 1 例被确诊为 ASD^[10]。我国 ASD 患病率也呈急剧增长趋势^[11-12], 世界卫生组织已将其列为危害儿童健康的重大精神疾病^[13]。因此, 深入开展 ASD 相关研究, 不仅对临床诊断、干预与康复具有重要意义, 也是减轻社会负担、响应国家公共卫生重大需求的迫切举措^[14-16]。

共同注意 (joint attention, JA) 是指个体通过眼神、手势等方式与他人共同指向某一目标的能力^[17], 是婴幼儿期社交发展和语言习得的关键基础。在正常儿童发育的过程中, JA 的发展与后续认知和社交功能密切相关, 而 ASD 儿童则普遍存在 JA 缺陷, 导致其语言、认知和社会交往受限^[18-19]。已有研究表明, JA 障碍不仅是 ASD 的主要临床表现之一, 也是早期筛查的重要指标^[20]。然而, 目前针对 ASD 儿童 JA 的特异性干预手段仍然有限, 效果差异显著^[21]。

现有 ASD 干预措施包括行为干预、心理干预和药物治疗等, 其中应用行为分析法、丹佛早期干预模型、地板时光和音乐治疗等均已得到实践应用^[22-27]。音乐治疗作为一种非药物干预手段, 因其趣味性、低侵入性和多感官整合特性, 近年来受到广泛关注, 并已经应用到孤独症儿童的干预之中。研究表明, 音乐能激活大脑的奖赏系统, 促进情绪调节和社交互动^[28-30]。然而, 传统音乐疗法多侧重于行为层面的干预, 其背后的神经机制尚未完全阐明。近年来, “基于多模态神经调控的音乐疗法”作为一种新兴的干预范式, 从神经科学视角为 ASD 的康复提供了新思路。该疗法并非单一方法的简单叠加, 其核心在于利用音乐这一天然的多模态 (听觉、节奏、

情感、运动) 刺激, 协同调控 ASD 患儿异常的大脑网络功能与连接。其理论基础建立在神经可塑性原则上, 旨在通过系统性的音乐活动, 对与 ASD 核心症状相关的大脑区域和环路进行“再校准”。

眼动追踪技术作为一种客观、精确的研究手段, 为探索 ASD 患儿的视觉注意模式与社会认知机制提供了重要支持^[31-35]。该技术通过红外眼动仪记录个体在观看视觉刺激时的眼球运动轨迹, 获取包括首次注视时间 (time to first fixation, TFF)、总注视时间 (total fixation duration, TFD) 等多个量化指标, 从而实现对注视行为的精细化分析。在 JA 研究中, 眼动技术常结合兴趣区设定, 用于揭示 ASD 群体对社会性线索 (如眼睛、头部朝向、手势等) 的注意分配特征。现有眼动研究表明, ASD 个体在早期发展阶段就表现出共同注意缺陷, 例如对社交场景中关键区域的注视时间较短、注视次数较少, 反映出其社交信息整合能力的异常^[36-37]。这些注视模式不仅与非社会性刺激偏好、行为线索处理异常及视觉追随障碍等相关, 还可能涉及更深层次的心理机制变化。因此, 眼动追踪不仅作为评估 ASD 社交障碍的客观工具, 也被逐步应用于干预效果评估, 为揭示 ASD 社交障碍成因及康复机制提供了可靠的技术路径^[38]。

综上, JA 对于早期孤独症儿童至关重要, 音乐治疗作为 ASD 儿童 JA 干预的重要手段, 虽已有研究证实其干预效果, 但其在改善 ASD 儿童 JA 方面的作用及其眼动机制尚未得到系统阐明。现有研究主要存在两方面不足: 其一, 音乐治疗对 ASD 儿童 JA 的干预疗效缺乏充分实证支持; 其二, 音乐治疗是否能够通过改变眼动特征来促进 JA 尚未明晰。基于此, 本研究结合心理测量与眼动追踪技术, 系统考察音乐治疗对 ASD 儿童 JA 的影响机制, 旨在为临床干预提供客观证据和科学依据。

1 对象和方法

1.1 对象

选取 2024 年 6 月—2025 年 6 月在南京市儿童医

院康复医学科治疗的ASD儿童,根据表1所呈现的纳入与排除标准,共计筛选出30例3~10岁ASD儿童,在实验过程中,共有4例被试流失(脱落率为13.33%),具体流失情况如下:①被试父母因时间冲突退出音乐治疗3例;②被试未能完成基线或后测1例。最终,符合实验整体评价标准的被试为26例,其中男19例,女7例。通过Gpower软件进行事后分析,将效应量(effect size, ES)设为0.5, α 值设为0.05, 样本量设为26, 计算出统计功效1- β 值为0.798。本实验获得南京医科大学附属儿童医院医学伦理委员会审批(批号:202303054-1),并在中国临

床试验登记处注册(注册号:ChiCTR2500111218)。该实验得到所有参与者的家长或法定监护人的书面同意。

1.2 方法

1.2.1 研究设计

本研究采用随机交叉实验设计,其中干预实验条件为组内因素。招募被试采用随机表分组方法分为A、B两组,分别进行先音乐治疗,后静坐对照;和先静坐对照,后音乐治疗的实验流程,并在每次干预条件后进行共同注意范式的眼动追踪评估。实验流程如图1。

表1 研究对象的纳入标准和排除标准

Table 1 Inclusion and exclusion criteria for study participants

Inclusion criteria	Exclusion criteria
① Han Chinese ethnicity	①Children with a history of definite head trauma
② Children diagnosed with ASD according to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) criteria	② Children with neurological or psychiatric disorders, such as epilepsy or tic disorders
③ All participants must provide consent from their legal guardians to participate in this study	③ Use of medications affecting the central nervous system within the past six months
④ Ability to meet the conditions for music therapy intervention, such as no hearing impairment or visual impairment.	④ Participation in music therapy intervention programs within the past six months
	⑤ Visual impairment, including red-green color blindness in children

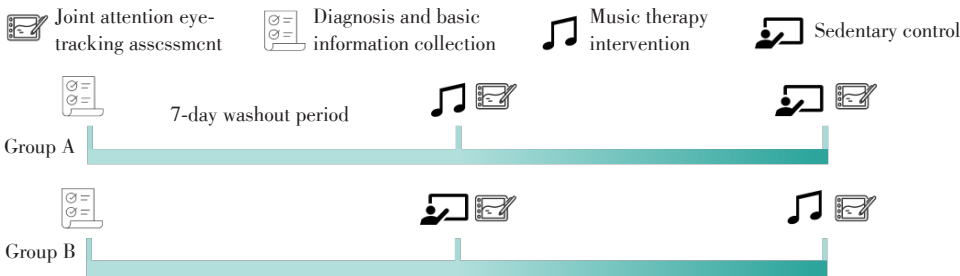


图1 音乐治疗实施流程图

Figure 1 Music therapy implementation flowchart

1.2.2 音乐治疗方案

本干预研究采用由2名注册音乐治疗师执行的个体化音乐治疗方案^[39-40]。治疗师均毕业于南京特殊教育师范学院音乐治疗专业,具备扎实的特殊儿童音乐治疗理论基础与丰富的临床实践经验。为控制环境干扰,所有干预均在受试者所在医院的标准音乐治疗室中进行。该治疗室环境安静、安全,经专业设计并配备多种奥尔夫打击乐器及其他音乐治疗设备。

干预采用“一对一”个体治疗模式,每次时长60 min,以“即兴演奏式音乐治疗”为主要方法。整

个干预过程遵循“个体化与动态化”原则,治疗师根据儿童的发展水平、兴趣动机及实时反应动态调整音乐互动的方式、复杂度和支持强度,以确保干预始终处于儿童的“最近发展区”,最大化其参与度与治疗效果。

在乐器与音乐形式方面,治疗师使用吉他作为和声支持乐器以建立稳定的音乐框架,通过即兴歌唱实现模仿、回应与情感连接,并借助鼓、沙锤、木琴、铃圈等节奏与互动乐器供儿童操作和回应。治疗方法以“接受性/再创造式”音乐治疗中的即兴演奏技术为核心,并根据儿童的沟通能力水平采用差

异化策略,具体方案如表2所示。

1.2.3 行为学测量

本研究的ASD患者根据《精神障碍临床诊断和统计手册》(The Diagnostic and Statistical Manual of Mental Disorders, DSM-V)进行入组,使用儿童孤独症评定量表(Childhood Autism Rating Scale, CARS)^[41],对孤独症、阿斯伯格症或未分类广泛发育障碍进行诊断^[42]。

1.2.4 眼动数据的采集与分析

1.2.4.1 实验仪器及操作

在被试所在机构的评估室,采用Tobii Pro Fusion高性能便携式眼动仪(记录近红外光在角膜和瞳孔

上反射的双眼注视)和一台装有Tobii Pro Lab软件的笔记本电脑(呈现刺激材料、采集被试眼动特征)进行,显示屏幕的分辨率设为1 920×1 080像素;眼动仪被安置于笔记本电脑的屏幕下方;被试眼睛距离显示屏的距离为50~60 cm;允许头动的自由度为45 cm(左右)×25 cm(上下);研究采用Tobii Studio软件自带的卡通发声玩具吸引被试目光进行5点校准。采样精确度为0.5°,眼动仪采样频率为120 Hz(图2)。

1.2.4.2 实验刺激材料

采用先前研究中使用的JA眼动追踪范式^[43-45]。图3~5为任务范式的具体图片,内容涉及一个中国

表2 基于儿童沟通能力的差异化音乐治疗方案
Table 2 Differentiated music therapy protocol based on children's communication abilities

Dimension	Basic interaction model	Intermediate interaction model	Advanced symbolic interaction model
Target participants	Non-verbal children	Children with partial non-verbal communication abilities	Children with basic verbal communication abilities
Core therapeutic goals	To establish preliminary communicative intent and joint attention	To expand the diversity and initiative of communicative behaviors	To promote social cognition, abstract thinking, and understanding of rules
Therapist's role & musical framework	To construct clear, predictable "start-stop" musical structures; to create communication opportunities through waiting and prompting	To design interactive, task-oriented musical activities; to serve as a "trigger" for responses and a "reinforcer" for behaviors	To embed musical interactions within a pretend-play framework; to serve as a play partner and a guide to rules
Key techniques & activity examples	①Synchronization & imitation: mimicking the child's breathing, vocalizations, or movement rhythms using guitar or voice ② Musical contingency: music begins when the child makes eye contact; using anticipatory pauses to guide the child to "request" music continuation via gaze, gestures, etc	① Turn-taking in play: engaging in rhythmic dialogues with the child(e.g., "your turn, my turn") ②Controlling musical elements: guiding the child to control the volume (loud/soft) or tempo (fast/slow) of the music through their playing ③ Action-music association: requiring the child to perform a specified action (e.g., clapping) to initiate or change the music	① Musical role-play: co-creating stories where different instruments/timbres represent different characters, with the child performing ②Rule-based musical games: playing games like "musical chairs" or "freeze/move" to understand and follow rules ③ Collaborative creation: co-improvising a simple song or rhythmic pattern
Child's response & participation forms	Non-verbal behaviors: • Eye contact • Body orientation • Gestures/actions • Vocalizations	Proactive communicative behaviors: • Actively playing instruments • Executing specified actions • Intentional vocalizations • Using picture exchange communication system(PECS)	Verbal and complex behaviors: • Using language to express and respond • Engaging in role-play • Understanding and adhering to rules • Collaborating with the therapist to complete tasks

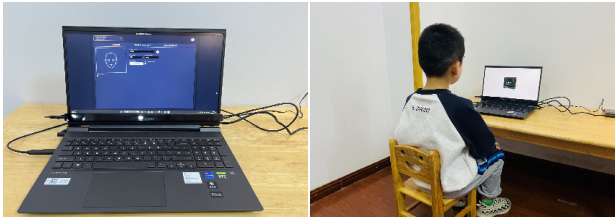


图 2 高性能便携式眼动仪与测试患儿

Figure 2 High - performance portable eye tracker and a Child undergoing testing

女性模特穿着西装,在白色背景前,在模特头部的左边和右边分别有一个红色和绿色的苹果。在共

同注意任务中使用了3种情况:①只用眼睛注视,②眼睛-头部,③眼睛-头-手势。在只用眼睛的情况下,模特将她的视觉目光指向目标“苹果”,而不转头或做手势。在“眼睛-头部”条件下,模特通过转动头部将目光指向目标苹果,在“眼睛-头部-手势”条件下,模特转动头部并目光和手指向目标苹果。

1.2.4.3 眼动数据采集流程

本研究眼动实验的全过程在 ASD 儿童所在医院的评估室内进行并完成。每次实验由1名测试人员和被试构成,两次眼动的测试人员保持一致。实验开始前,被试到达评估室后,先由测试人员与被

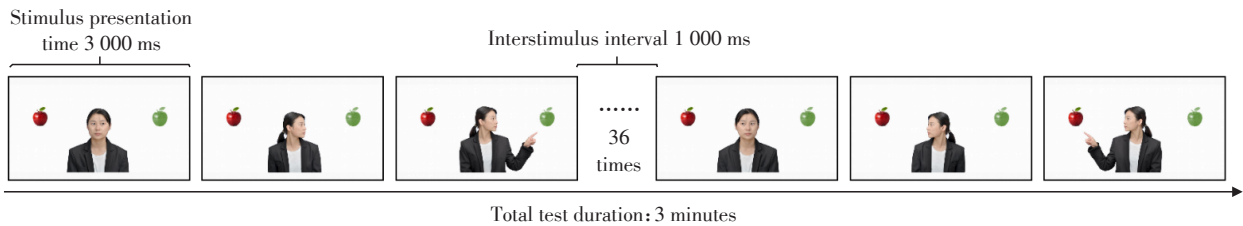


图 3 共同注意眼动追踪范式

Figure 3 Eye-tracking paradigm for joint attention

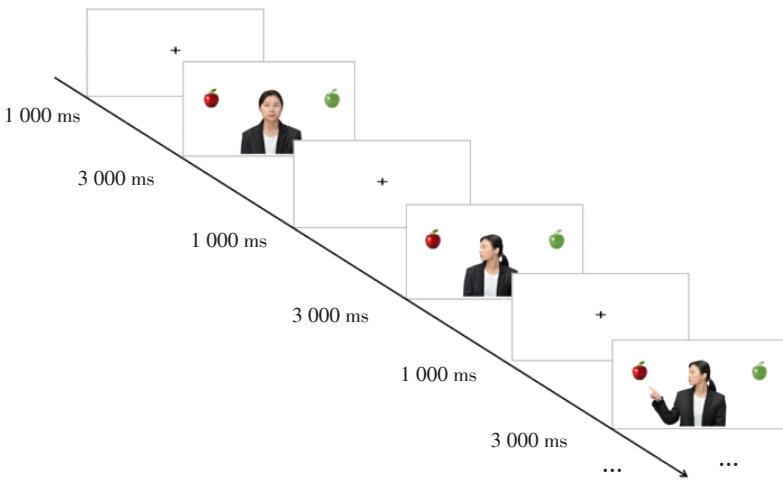


图 4 眼动实验程序图

Figure 4 Eye-tracking experimental procedure

试互动并建立良好的关系,以达到测试的最好效果;实验开始后,被试需要坐到笔记本电脑的对面,距离显示屏幕的距离 50~60 cm,其次,在启动眼动软件后,显示屏呈现软件自带的发声玩具对其进行五点校准(采样精确度需在 0.5°以下),校准通过则开始进行正式眼动实验。指导语:“请您观看以下图片,认真看电脑屏幕哦”,在被试观看实验刺激材料期间,测试人员不得要求其做任何反应,只有看到被试动作幅度过大或者注意力不集中时,可稍作提醒认真观看,直到所有的实验刺激材料播

放完毕后实验才能结束,整个数据采集的流程时间约为5 min。

1.2.4.4 眼动数据分析

应用测试电脑自带的Tobii Pro Lab软件包对眼动数据进行分析。根据之前实验刺激图片绘制好感兴趣区(area of interest, AOI):在Tobii Pro Lab软件中采用四边形工具,以1 cm为边界,在实验刺激材料上面手动绘制AOI:分别为:①线索区(A1),当线索出现时,模特以及模特所活动的区域;②目标区(T1),当线索出现后,线索所示意的区域;③非目

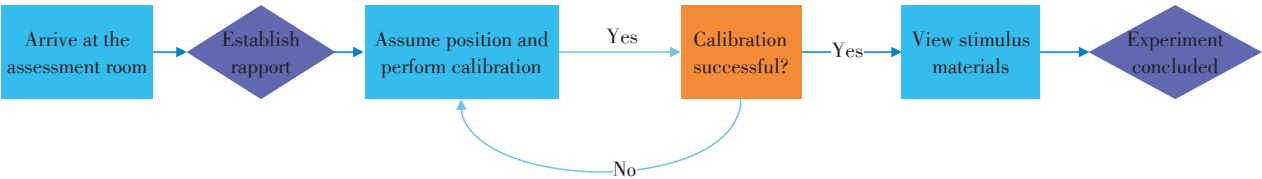


图5 眼动数据采集流程
Figure 5 Eye-tracking data acquisition pipeline

标区(R1),当线索出现后,线索未示意的区域。选定该眼动任务所研究的指标、选定数据预处理的格式、浏览预处理数据的指标。

眼动任务指标的选取为注视类指标,注视指被试者眼睛中央对准某一感兴趣物体或者区域,视线聚焦保持不动。该指标是眼动仪内置软件+采样率+采样点距离+时间等综合计算出来的,首次注视时间越短说明该感兴趣区越能引起被试注意。在刺激条件下未进行目标区域注视的样本将被剔除。本研究眼动选取指标:TFF:从开始呈现刺激图片线索后到受试首次进入目标区(T1)的时间。利用该软件的自动化处理数据,提取有效共同注意眼动任务的数据结果(图6)。

1.3 统计学方法

利用 Jamovi 2.3.18 软件(<https://www.jamovi.org/>)进行数据处理与分析。所有结果均采用均值±标准



图6 显示屏幕绘制感兴趣区示例图
Figure 6 Example of delineating areas of interest on the stimulus screen

差($\bar{x} \pm s$)表示,通过配对样本 t 检验分析单次音乐治疗与静坐对照条件对 ASD 儿童共同注意眼动特征的影响差异。效应量采用 partial η^2 表示, $P < 0.05$ 为差异有统计学意义。

2 结果

2.1 人口统计学信息结果

招募被试的人口统计学结果见表。参与实验的 ASD 儿童平均年龄为(5.36±1.44)岁,CARS 评分平均值为(34.08±3.65)分,其中男 19 例,女 7 例。

2.2 眼动特征分析结果

基于正态分布检验方法,发现研究的结局指标符合正态分布,随后采用配对样本 t 检验分析发现,与静坐对照的干预条件相比,在所有条件总分($t=-2.24, P=0.035, \text{Cohen's } d=-0.458$)下,ASD 儿童音乐治疗后的 TFF 显著变短,这种显著性主要发生在“眼睛-头-手势”条件下($t=-2.32, P=0.030, \text{Cohen's } d=-0.485$)。在仅“眼睛”和“眼睛-头”条件下,尽管两种干预条件差异无统计学意义,但从均值可以发现音乐治疗后更短的 TFF(表3)。

3 讨论

ASD 是一种在儿童早期发病的终身性严重神经发育障碍,其核心症状为社会交往障碍和重复刻

表3 眼动指标描述性统计
Table 3 Descriptive statistics of eye movement indicators

Variable	Music therapy($s, \bar{x} \pm s$)	Control intervention($s, \bar{x} \pm s$)	t	P	Power
Eye Gaze	3.91 ± 0.81	4.54 ± 0.91	-0.532	0.601	-0.116
Eye-Head	3.42 ± 0.63	4.36 ± 0.70	-1.090	0.289	-0.222
Eyes-Head-Gesture	2.76 ± 0.43	5.52 ± 0.99	-2.320	0.030	-0.485
Total	9.86 ± 1.09	14.38 ± 1.70	-2.240	0.035	-0.458

板行为。近年来,全球ASD患病率显著上升,已成为影响儿童健康发展的重要公共卫生问题^[46-51]。JA作为社交沟通的基础能力,其缺陷被认为是ASD儿童社交障碍的核心表现之一,主要表现为主动性注意(initiating joint attention, IJA)和回应性注意(responding to joint attention, RJA)的受损^[52-54]。眼动追踪技术为客观量化ASD儿童在JA任务中的视觉注意特征提供了有效手段。

眼动指标是神经功能的外在行为表现,本研究聚焦音乐治疗对ASD儿童JA的影响,并首次结合眼动追踪进行量化评估。结果显示,接受单次音乐治疗的儿童在“头-眼睛-手势”条件下的TFF显著缩短,且JA总分提高,提示音乐治疗能够增强ASD儿童对多模态社交线索的加工效率。这一发现不仅支持音乐治疗在改善ASD核心社交功能方面的价值,也为其潜在的神经加工机制提供了新的实证依据。

3.1 基于多模态神经调控的音乐疗法改善JA功能的潜在机制

已有研究进展初步揭示了该疗法可能涉及的神经调控机制。首先,在神经振荡层面,具有稳定、可预测节拍的音乐能够通过“神经夹带”机制,调节ASD个体常存在异常的伽马波(Gamma波)和 θ 波(Theta波)等活动,从而改善大脑皮层的信息同步处理能力,这为提升对快速变化社交线索的注意与整合提供了神经基础。其次,在情绪调节层面,音乐能直接作用于杏仁核、伏隔核及前额叶等脑区,有效缓解ASD儿童的焦虑与紧张情绪,降低其对社会性刺激的回避倾向,从而为发起和响应共同注意创造积极的情绪状态^[55-56]。第三,在社会认知层面,节奏同步、动作模仿等音乐互动显著激活镜像神经元系统,该系统的功能增强与动作意图理解、共情及社会学习密切相关,是JA发展的关键神经基础。最后,在多感觉整合层面,音乐活动天然要求个体整合听觉(旋律、节奏)、视觉(治疗师表情、动作)及动觉(自身律动)信息,这对ASD儿童普遍存在的多感觉整合功能障碍具有直接训练作用,而该功能的改善是准确解读复杂社交线索(如眼神与手势的联合指向)的前提。

基于上述“多模态神经调控”框架,本研究假设,音乐疗法并非仅通过行为强化起效,而是通过上述多层次的神经协同作用,优化ASD大脑对社会性信息的处理效率。这种内部神经效率的提升,可在外显行为上表现为更敏锐、更快速的视觉注意模式。本研究结果支持这一假设:在提供最丰富社交

线索的“眼睛-头-手势”条件下,音乐干预后TFF显著缩短,这可能得益于音乐治疗对多感官整合能力的促进,使儿童更能应对复杂社交场景。相比之下,在社交信息单一的“仅眼睛”条件下未观察到显著改善,提示ASD儿童对于直接眼神注视的回避或处理困难可能更为核心,改变这一模式需更长期、更具针对性的干预。

此外,音乐本身所具有的明确时间结构与重复性,有助于ASD儿童建立对事件序列的预测,从而减少认知负荷,增强对即将出现的社交线索的准备性注意,这可能是其在JA任务中能更快定位目标的原因之一。在动机与奖赏层面,音乐可激活中脑边缘多巴胺系统(包括伏隔核和前额叶皮层),提升愉悦感与社交动机,使儿童更主动地关注并响应JA任务中的社交提示^[57]。同时,治疗中的节奏同步活动(如共同击打乐器)通过促进感觉运动同步和模仿行为,增强了儿童与他人的动作协调性及意图理解能力,为JA的发展提供了重要支持。

尽管如此,本研究仍存在若干局限性。首先,因本研究关注的重点为音乐治疗在ASD儿童群体中的急性效益,因此采用的单次干预进行验证,干预周期相对较短,未来研究可能考虑进行队列研究或长期干预,进一步验证音乐治疗的干预疗效;其次,受限于孤独症群体的特殊性以及招募的标准,本研究纳入的样本量有限,尤其是未对不同严重程度的ASD儿童进行亚组分析,结论的普适性尚待进一步验证。最后,本研究使用了眼动追踪技术来探索ASD群体的眼动特征,并未深入探索其神经机制,在未来的研究中应进一步考虑结合多模态脑成像技术等,深入探索其干预的神经机制。

3.2 眼动特征的指标意义

本研究首次将眼动追踪技术应用于音乐治疗对ASD儿童JA功能影响的评估中。结果显示,音乐治疗不仅提高了所有条件总分,还加快了视觉注意捕获和转移,提示其在潜意识水平优化了注意资源分配和信息前处理。尽管在“仅眼睛”和“眼睛-头部”条件下未达到统计显著性,但TFF均值的下降趋势仍暗示音乐治疗对不同类型的JA可能存在广泛效应,未来需扩大样本量或延长干预周期以进一步验证^[58]。

3.3 研究意义与未来方向

本研究从眼动机制角度为音乐治疗改善ASD儿童JA功能提供了初步的实证依据,强调其作为一种无创、易实施且接受度高的干预手段的潜力。本

研究为音乐治疗作为一种神经调控手段提供了行为层面的证据,未来研究可结合多模态神经影像技术(如功能性近红外光谱脑功能成像、功能性磁共振成像等),深入探讨音乐治疗过程中大脑网络动态变化与眼动行为之间的关联,尤其关注默认模式网络、背侧注意网络和社交脑网络的功能连接变化。此外,建议进一步区分不同类型的音乐干预(如接受式*vs.*主动式音乐治疗)、不同音乐元素(节奏、和声、旋律)对JA功能影响的差异,推动个体化和精准化音乐治疗方案的制定。

综上所述,音乐治疗可能通过增强多感官整合、优化预测加工、调节情绪及促进运动同步等多重机制,改善ASD儿童的共同注意功能。眼动追踪为评估干预效果和揭示机制提供了客观工具,对ASD的临床康复与科学研究均具有重要价值。本研究未来可进一步加大样本量,并进行长期随访,以评估单次干预的长期效果和疗效的持久性,同时可进一步结合脑成像技术直接验证其潜在的神经机制,以推动该领域向神经机制驱动的精准确干预迈进。

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Author's Contributions:

ZHANG Ling was responsible for drafting and revising the manuscript. YANG Chang contributed to the design and implementation of the music therapy protocol. SHI Yifan was responsible for literature screening and manuscript revision. LIU Zhimei was responsible for eye-tracking data acquisition and analysis. ZHANG Hongmei was responsible for participant recruitment and assessment. SUN Yaojin was responsible for data collation and statistical analysis. DI Siyu was responsible for reference management and formatting proofreading. CHEN Aiguo supervised the framework design of the manuscript and reviewed its content. GAO Funing was responsible for the overall research design, project coordination, and final approval of the manuscript.

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