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视觉感知训练改善儿童学习障碍的神经机制及干预效果的研究进展

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摘　要

视觉感知训练(Visual Perceptual Training, VPT)是一种通过针对性任务强化特定视觉处理技能的系统性干预方法，旨在优化大脑对视觉信息的接收、组织和理解能力。近年来，VPT在改善儿童学习障碍(Learning Disabilities, LD)方面展现出显著潜力。LD儿童普遍存在视觉感知缺陷，包括眼动控制、视觉空间处理及视觉记忆等核心能力的不足，不仅影响学习信息获取效率，还会引发学业成绩下降、认知资源分配异常和工作记忆超载等问题。VPT的理论基础源于大脑经验依赖性可塑性，可通过调节神经递质平衡、优化白质微结构、重组功能网络、诱导表观遗传代偿以及重塑特定脑区结构与功能等多层面机制，改善LD儿童的视觉信息处理能力。VPT可针对性改善阅读障碍、书写障碍及数学障碍，并在提升学业表现的同时增强学习动机与自信心。本文系统综述了VPT的作用原理与训练方法、改善LD的神经机制及干预效果以及影响干预效果的关键训练参数，旨在为LD的精准康复提供理论与实践依据。

关键词

视觉感知训练，学习障碍，神经可塑性，神经机制，干预效果

Advances in Research on the Neural Mechanisms and Intervention Efficacy of Visual Perceptual Training for Improving Learning Disabilities in Children

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Abstract

Visual Perceptual Training (VPT) is a systematic intervention method that enhances specific visual processing skills through targeted tasks, aimed at optimizing the brain’s ability to receive, organize, and interpret visual information. In recent years, VPT has demonstrated significant potential in ameliorating Learning Disabilities (LD) among children. Children with LD commonly exhibit deficits in visual perception, including core deficiencies in eye movement control, visual-spatial processing, and visual memory. These impairments not only reduce the efficiency of acquiring learning-related information but also contribute to academic underachievement, disrupted allocation of cognitive resources, and working memory overload. The theoretical foundation of VPT stems from the brain’s experience-dependent plasticity. It can improve visual information processing in children with LD through multi-level mechanisms, including: modulating neurotransmitter balance, optimizing white matter microstructure, reorganizing functional brain networks, inducing epigenetic compensation, and reshaping the structure and function of specific brain regions. VPT can effectively target and improve dyslexia, dysgraphia, and dyscalculia. Beyond enhancing academic performance, it concurrently strengthens academic motivation and self-efficacy. This article systematically reviews the principles and methods of VPT, the neural mechanisms and intervention efficacy for LD, as well as the key training parameters that affect intervention outcomes, thereby providing a theoretical and practical framework for the precision rehabilitation of learning disabilities.

Keywords

Visual Perceptual Training, Learning Disabilities, Neuroplasticity, Neural Mechanisms, Intervention Efficacy

1. 引言

视觉感知训练(Visual Perceptual Training, VPT)是一种系统性干预方法，通过针对性练习强化特定的视觉感知加工技能，从而提升个体的视觉认知功能[1]。VPT 包括多种训练类型，如眼动控制、视觉辨别、视觉空间处理、视觉注意及视觉－运动整合等。目前，VPT 主要应用于术后视觉功能重建、弱视和青光眼等视觉障碍的康复、神经康复与脑可塑性研究以及视觉功能评估[2]。近年研究表明，VPT 在改善儿童学习障碍(Learning Disabilities, LD)方面也展现出显著潜力[3]。LD 是一种以特定领域学习能力显著低于预期为特征的神经发育疾病，包括阅读障碍、书写障碍、数学障碍[4]。研究表明，大多数 LD 儿童会伴随视觉感知困难的症状[5]。视觉感知是指大脑接收和处理视觉信息的能力，其包括眼球运动控制、视觉空间处理、视觉辨别及视觉记忆等核心环节[6] [7]。视觉感知困难会直接削弱 LD 儿童的视觉处理能力，降低其学习信息获取效率，进而加剧学业成绩下滑、认知资源分配失衡、工作记忆超载，以及学习动机和自信心的受挫[8]。VPT 的理论基础源于大脑经验依赖性可塑性，可通过多层面机制重塑 LD 儿童的视觉信息处理通路，包括调节神经递质平衡、优化白质微结构、重组功能网络、诱导表观遗传代偿以及重塑特定脑区结构与功能[9]。这些改变可以提升 LD 儿童的视觉信息处理能力，改善基础的阅读技能、书写能力、数学理解以及整体的学习效率和自信心。本文系统综述了 VPT 的作用原理与训练方法以及 VPT

改善 LD 的神经机制及干预效果，为 LD 的精准康复提供理论与实践依据。

2. VPT 的作用原理与训练方法

2.1. 理论基础

VPT 的理论基础源于大脑的经验依赖性神经可塑性，即特定经验可诱导神经系统结构和功能的适应性改变[9]。值得注意的是，婴儿期至 5 岁前是视觉系统神经可塑性的关键窗口期，为早期干预提供了黄金时机[10]。研究表明，6~12 岁儿童视觉系统仍保留显著可塑性，通过高强度 VPT 可有效改善其视觉功能[11]。VPT 的核心机制在于通过设计特定任务，定向刺激受损的视觉处理通路，最大程度诱导大脑跨层级神经重塑[2]。VPT 通过反复训练增强初级视觉皮层的神经元响应及编码效率，促进视觉皮层区域间的连接[12]。同时，动态任务难度调整驱动白质纤维髓鞘化，加速跨脑区信息传递，而功能网络重组进一步优化全局认知资源分配。此外，整合奖励机制可作为关键辅助手段，增强学习动机并间接强化可塑性过程[13]。上述多层级机制协同作用，促进了特定脑区结构和功能的重塑，有效改善了由发育异常或脑损伤引发的多种视觉功能障碍。

2.2. 主要训练方法

VPT 包含视觉辨别、眼动控制、视觉－运动整合、视觉空间、视觉注意及多模态训练等方法。视觉辨别训练通过训练个体识别相似图形、字母、汉字的细节差异、分离图形背景及完成视觉闭合任务，提升视觉特征觉察敏感度与加工速度[14]。其中方向辨别任务采用连贯运动方向辨别范式，在黑色背景上呈现白色运动光点，要求儿童通过按键区分光点的向上或向下运动方向；词汇、假词辨别任务使用 Microsoft Sans Serif 字体、白底黑字的保加利亚语多音节词与假词，儿童需按键区分词与假词[15]。图形背景辨别任务要求个体从视觉噪声背景中识别出目标刺激，任务材料包含静态点阵分组、动态点阵分组以及生物运动光点刺激，均以随机运动噪点作为干扰背景，实验过程中通过逐步增加噪声点数量来提升背景复杂度与任务难度[16]。完形填空练习采用 Bender Gestalt Closure 任务，呈现部分缺失的图形并要求儿童补全缺失部分或识别完整图形，训练内容从简单图形逐步过渡到复杂图形[17]。

眼球运动控制训练通过扫视定位、平稳追随及注视稳定性训练，优化运动精度和视觉注意稳定性[18]。扫视定位训练是让受试者头部保持静止不动，眼睛按照固定节奏在前后排列的两个目标点之间快速来回跳转，每次跳转在 150~200 毫秒内完成，连续执行 10~20 次[19]。平稳追随训练是受试者头部固定不动，眼睛持续平滑地跟随前方水平或垂直缓慢移动的目标物，保持视线始终锁定目标轨迹[20]。注视稳定性训练是受试者面向前方固定目标，头部进行左右或上下旋转运动，眼睛通过反向补偿运动维持对目标的清晰注视，连续训练 5~10 分钟[21]。

视觉－运动整合训练通过描摹、连线、在限定空间内书写或绘画及基于视觉反馈的动作调整，强化手眼协调能力[22]。受试者使用惯用手握笔在 iPad 屏幕上描摹圆形、三角形及兔子图形，触控笔触碰屏幕启动计时后，系统实时监测描摹路径，一旦偏差超过 3.5 毫米即触发警告声，要求受试者立即从断点处重新描摹直至完成，该范式通过数字化设备量化记录完成时间、错误次数及总位移量等指标，实现了毫米级路径监测与即时声音反馈，为视觉－运动整合训练提供了标准化评估与干预方案[23]。

视觉空间训练通过心理旋转、空间关系判断、视觉记忆及模式识别与复制任务，提升空间信息处理能力，强化非符号数量处理及符号－数量表征联系[24]。心理旋转任务要求儿童观察一张示例图片，并从三个经过旋转的选项图片中识别出与示例完全匹配的那一张[25]。空间关系判断任务包括表达性和接受性两部分，前者让儿童对展示的几何形状和空间关系图片进行口头命名，后者则由研究者提供标签，儿童需从编号选项中指出对应的图片[26]。视觉记忆及模式识别与复制任务则涵盖了更具体的操作，在 Rey

复杂图形测试中先临摹图形，随后进行延时回忆，在 Corsi 积木敲击测试中按顺序敲击积木块以测试视觉空间记忆广度，以及在模式延伸任务中通过拖拽操作将图形序列补全到指定的方框中[27]。

视觉注意训练通过视觉搜索、选择性注意、分配性注意及持续性注意，优化注意力资源分配效率[28]。视觉搜索采用颜色、符号目标搜索范式，要求儿童在 CIELab 色轮梯度干扰项中定位目标色，或在形似字母、符号干扰阵列中快速定位目标字母，如从 b/d/p/q、f/k/t 等易混淆符号中找到指定目标，任务难度随目标－干扰项相似性梯度递增[29]。选择性注意使用 Sky Search 视觉筛选任务与视觉注意广度训练，让儿童在干扰背景中完成字母序列报告、全局或局部特征切换判断，抑制无关视觉信息并精准提取目标特征[30]。分配性注意依托多任务并行训练，要求儿童同步完成视觉搜索与听觉判断、字母归类与空间定位等双任务加工，提升注意力并行分配与切换灵活性[31]。持续性注意采用长时程视觉特征监测范式，让儿童在随机呈现的彩色动点序列中持续追踪目标颜色亮度变化，维持长时间稳定的特征定向与目标监测状态[32]。

多模态视觉刺激训练通过整合视觉与其他感官输入，重塑脑区白质网络微结构与功能连接，提升信息整合能力[33]。视觉－触觉训练采用纯触觉盲文阅读练习，仅通过单指触摸辨识盲文字符并隔绝视觉线索，内容从字母逐级进阶至词句阅读，提升触觉分辨与符号认知能力[34]。视觉时序知觉训练开展即时反馈式视觉时序辨别练习，以不同时延的视觉光点序列为刺激，训练前后采用视听同步判断任务评估，可缩窄多感官时间绑定窗口，提升跨模态时序精准加工能力[35]。跨模态言语知觉训练以配对联想形式进行视觉唇读训练，分别同步搭配噪声编码语音或前臂振动触觉刺激，可增强视听、视触信息整合效率，提升视觉言语识别与学习泛化能力[36]。

这些训练方法通过靶向受损视觉通路，利用神经可塑性机制实现功能重塑，最终改善视觉处理缺陷。

3. VPT 改善 LD 的神经机制及干预效果

3.1. 调节神经递质平衡

LD 儿童常因多巴胺系统异常导致学习过程中的奖赏动机削弱，并损害工作记忆功能及运动决策功能，表现为学习兴趣低下、决策犹豫和动作执行效率低下[37]。VPT 采用视觉－运动整合训练结合奖励机制可能动态调节多巴胺系统活性，优化神经网络同步性与信息整合效率，增强学习动机。动物实验表明，小鼠在进行视觉－运动训练时，其伏隔核、背侧纹状体的多巴胺会随奖励传递升高、随奖励遗漏降低，训练后选择正确率提升，未出现明显犹豫或错误重复的行为[38]。需要注意的是，小鼠模型的发现直接外推至人类 LD 儿童时存在局限性。Sporn 等[39]发现受试者在视觉引导的运动序列训练中，奖励通过运动激活与认知调控双路径提升训练效果，多巴胺仅参与奖励－运动活力通路，是奖励驱动提升动作速度的关键调节因子。

谷氨酸(Glutamic acid, Glu)与 γ-氨基丁酸(GABA)系统平衡失调会导致局部抑制过度，破坏前额叶－纹状体环路同步性，进而影响感知决策能力[40]。VPT 中的视觉辨别训练可能通过调节 GABA 能抑制平衡，优化神经信息处理功能。Jia 等[41]的临床研究发现，视觉定向辨别训练可通过提升早期视觉皮层 GABA 浓度及 GABA/Glu 比率，降低方向辨别阈值，从而优化抑制平衡，增强定向辨别能力。Kam 等[42]发现受试者在接受视觉辨别训练中的双眼分视训练后，早期视觉皮层的 GABA 能抑制平衡发生改变，表现为优势眼抑制升高、非优势眼抑制降低，从而优化了双眼协同的神经信息处理功能。上述结果在阅读障碍儿童中的适用性尚需进一步实证研究验证。

3.2. 白质微结构优化

LD 儿童的胼胝体、钩束等白质通路结构完整性受损，导致脑区间信息传递效率低下，表现为执行功

能低下、认知动机不足及运动协调障碍[43] [44]。VPT 包括视觉－运动整合训练及视觉辨别训练可能通过重塑白质微结构，提高关键通路的各向异性分数(Fractional Anisotropy, FA)，优化脑区间信息传输效率。Piervincenzi 等[45]发现通过视觉－运动训练干预，弥散张量成像技术显示皮质脊髓束、丘脑前辐射、钩束、胼胝体等与感觉运动和认知功能相关通路 FA 值显著增加，而 FA 值升高与创造力和自我效能感的提升存在相关性。Willis 等[46]发现视觉辨别训练后，背外侧膝状体与人类额外视觉运动处理区连接通路的远端部分 FA 值显著增加，患者在运动辨别任务中的正确率也显著提高。现有证据表明 VPT 与白质微结构及行为表现的改善存在关联，但其因果作用及长期效果仍需进一步因果推断研究验证。

3.3. 功能网络重组

默认模式网络(Default Mode Network, DMN)是静息状态下持续活跃的脑区网络，正常情况下任务态需被抑制，其任务态下的抑制功能异常，导致 LD 儿童难以抑制任务无关的内部思维，表现为注意力分散、执行功能低下和学习效率下降[47]。VPT 中的视觉注意训练可能通过抑制 DMN 过度活动，强化任务相关网络，优化大脑注意力资源分配效率。Gao 等[48]对受试者进行视觉分类任务干预后，发现训练可引发 DMN 内部去同步化以减少无关内省消耗，同时整合外部认知控制网络，使其适应任务需求，最终提升反应速度、准确率及注意分配质量。Zhou 等[49]研究发现，选择性注意训练可通过任务准备阶段调整枕叶和顶叶神经状态，并在任务执行中定向调控目标特征与非目标特征的表征起始时间，实现神经资源向任务相关特征的优先分配。Zhang 等[50]发现视觉搜索训练通过优化注意网络功能，显著提升辨别力、缩短反应时间，表现为扫视次数减少、扫描时间缩短；在低拥挤条件下，无需眼动即可识别的目标比例增加且搜索启动阶段的注意定向效率提升。

3.4. 表观遗传功能代偿

人类遗传学关联研究表明，LD 与 DYX1C1、KIAA0319、ROBO1 等基因变异相关，可能通过干扰神经元迁移、轴突生长和突触连接，导致左侧颞顶枕叶区域的神经发育异常，表现为特定学习能力低下[51]。尽管 VPT 无法直接修正 DNA 变异，但基于动物实验的发现，多模态视觉刺激训练可能通过上调神经营养因子(Brain-Derived Neurotrophic Factor, BDNF)的表达水平，补偿遗传缺陷，重塑视觉神经环路，提高信息处理效率。在动物模型中，环境丰富化(Environmental Enrichment, EE)是 VPT 的关键策略。de Sousa Fernandes 等[52]通过动物研究发现，EE 动态调节组蛋白乙酰化重塑表观遗传图谱，增强神经可塑性，缓解脑功能异常。Cooper 等[53]研究发现，EE 组小鼠海马及视觉皮层的 BDNF 蛋白表达水平上调，驱动突触结构与功能重塑，改善认知行为与神经环路协同性。动物实验提示 VPT 通过表观遗传上调 BDNF 改善神经可塑性与信息处理效率，但其对 LD 儿童核心学习能力的改善需进一步验证。

3.5. 重塑特定脑区结构与功能

VPT 可能通过协同调节神经递质的平衡、优化白质微结构、重组网络功能及诱导表观遗传代偿，重塑特定脑区结构和功能，改善 LD 儿童阅读流畅性、书写准确性与数学运算能力等核心学习能力。

3.5.1. 阅读障碍

阅读障碍核心表现为左侧颞顶区激活水平降低、神经表征特异性不足及眼球控制能力差，导致语音－字形整合困难，表现为视觉相似字母识别困难、注视时间延长、眼跳幅度异常[54]。VPT 中的视觉辨别训练与眼球运动控制训练可能通过强化左侧颞顶区功能，提升阅读流畅性与准确性。Werth 等[55]发现，针对 LD 儿童进行易混淆字母的视觉辨别训练，增强视觉词形区(Visual Word Form Area, VWFA)对字母特征的编码能力，加强 VWFA 与左侧颞顶区的神经连接，促进颞顶区高效完成语音转换，减少解码错误。

Lawton 等[56]发现，在计算机引导的阅读策略干预后，可优化 LD 儿童的眼球运动，使字母序列高效纳入中央视觉区，减少视觉信息碎片化，确保左侧颞顶区接收连贯的字形输入，从而提升字形–语音转换的准确性。

3.5.2. 书写障碍

书写障碍与背侧前运动皮层(Premotor cortex, PMd)异常相关，导致运动序列编码和空间规划障碍，表现为书写流畅性差和空间布局混乱[57]。VPT 中的视觉–运动整合训练，可能通过优化 PMd 对运动序列与空间规划的功能，改善手眼协调能力。研究发现，基于 VPT 的分段书写练习可重构 PMd 的运动序列的分级激活模式，提升书写流畅度和准确性[58]。Bartov 等[59]的随机对照实验发现，视觉反馈下的书写训练，通过实时校准运动输出，优化 PMd 功能，提升书写效率，具体表现为异常运动轨迹减少，字母高度变异度降低，书写时间与笔尖离纸时间缩短。Vinci-Booher 等[60]通过研究发现，“有墨水书写”组较其他三组反应更快、准确率更高，且一周后仍保持优势，表明视觉–运动实时关联可强化运动记忆。

3.5.3. 数学障碍

数学障碍的核心神经机制是顶内沟(Intraparietal Sulcus, IPS)激活不足，导致数量表征和空间映射能力低下，表现为基础数感薄弱和运算困难[61]。VPT 中的视觉空间训练可能通过促进 IPS 的功能重塑，改善非符号化数量处理、运算流畅性及空间数学表征能力。Tablante 等[62]通过元分析汇总发现，符号–数量匹配与数字识别训练相关的研究显示 IPS 激活模式改变，数量判断错误减少、算术任务准确性与效率提高，数量表征清晰度增强。Matejko 等[63]通过脑成像探究发现，儿童视觉空间工作记忆(Visual-Spatial Working Memory, VSWM)与算术能力共同依赖右侧 IPS 神经回路，且此回路的激活随年龄向左侧额顶叶转移。这一发现表明，数学障碍儿童可能也存在 IPS 功能方面的基础性缺陷，同时也提示通过视觉空间训练可能促进其数学神经回路的发展，从而改善其核心缺陷。然而，上述推论仍有待针对该人群的干预研究加以验证。

4. 影响 VPT 效果的关键训练参数

干预参数的精确设定是实现神经重塑的核心因素。训练频率、时长、强度以及个体化适应性策略，直接影响神经突触连接的稳定性及学习效果的泛化能力。

训练频率是指单位时间内的干预次数。研究表明，高频率刺激对建立新的神经通路至关重要。Lawton 等[56]的研究指出，每周 2 次、每次 30 分钟的运动辨别训练在 12 周内显著改善了 LD 儿童的阅读流畅度。而在 Caldani 等[18]的研究中，虽然单次干预时间极短，但通过连续多日强化，同样观察到眼动稳定性的即时提升。高频率的训练不仅有助于运动技能的自动化过程，还能利用睡眠周期促进记忆巩固。研究表明，快速眼动睡眠在处理纹理辨别等视觉任务的学习中发挥不可替代的作用[64]。因此，将训练任务分布在多个连续日而非集中在单日，能够获得更为持久的长时程学习收益。

训练时长涉及单次干预的持续时间及总干预周期。常规的 VPT 建议每名儿童至少累积 30 小时的训练量，通常分布在为期六周的周期内，每日练习 30 至 60 分钟。对于存在注意力缺陷的 LD 儿童，单次时长需根据其注意广度动态调整，以防过度疲劳导致认知资源耗竭[65]。元分析证据表明，针对手眼协调与精细运动的干预，当总时长超过 720 分钟时，其效应量会显著增大，提示神经重塑过程中存在总剂量阈值。然而，短时程训练，如 10 分钟的视觉注意练习，同样被证明具有显著的短期启动效应，能够迅速激活负责扫视触发的皮层结构[18]。

训练强度主要与任务的复杂程度和认知要求相关。Silva 等[66]采用阈值设置法，设定 55%正确率的初始阈值，将任务难度控制在既具挑战性又不诱发挫败感的水平。这种强度控制通过逐步缩小刺激的对

比度或增加背景噪声来实现。研究发现，中等至高强度条件下的练习，对 LD 儿童抑制控制能力的提升最为显著，呈现出倒 U 型曲线关系，即过低或过高的强度均不利于神经可塑性的优化[67]。

LD 患儿的异质性要求干预方案具备高度的个体化适应性，不仅体现在初始水平的基准测试上，更体现在训练过程中的动态调整。在 LD 干预中，个体化适应性常通过计算机辅助系统实现，如 iVision 程序利用人工智能和强化学习算法，根据患儿的实时表现自动调节任务难度[68]。如果儿童进步迅速，系统会缩短刺激呈现时间或增加视觉拥挤度；反之，若错误率上升，系统则提供更多视觉辅助线索或降低空间频率[69]。此外，针对不同年龄段的 LD 儿童，参数设定也存在差异。6 岁左右的学龄初期儿童对空间频率变化的敏感度更高，而年龄较大的青少年则可能从更复杂的视觉记忆任务中获益[70]。

5. 结论

本文系统综述了 VPT 的作用原理、训练方法及其改善 LD 的神经机制与干预效果，为 LD 的精准康复提供理论与实践依据。VPT 通过设计特定任务定向刺激受损视觉通路，最大程度诱导大脑跨层级神经重塑，具体表现为调节神经递质平衡、优化白质微结构、重组功能网络、诱导表观遗传代偿及重塑特定脑区结构与功能。这些机制协同促进视觉通路神经可塑性，有效改善 LD 儿童的阅读流畅性、书写准确性和数学运算能力，同时增强其学习动机与自信心。此外，VPT 的干预效果显著依赖于训练频率、训练时长、训练强度及个体化适应性等关键参数，合理设定这些参数是实现神经重塑和提升干预效果的核心环节。尽管 VPT 在 LD 的干预中展现出巨大潜力，当前研究仍存在局限性。VPT 的神经可塑性机制在动物模型中得到支持，但在 LD 儿童中的直接证据仍显不足。针对 LD 亚型的 VPT 方案相对有限，未来需通过大量的随机对照试验验证其干预效果。此外，现有研究多聚焦短期干预效果，缺乏对 VPT 干预后儿童在成年期学习能力的长期追踪。

参考文献

[1] Pulay, M.Á. and Feketéné Szabó, É. (2024) Developing Visual Perceptual Skills with Assistive Technology Supported Application for Children with Cerebral Palsy. *Acta Polytechnica Hungarica*, **21**, 25-38. https://doi.org/10.12700/aph.21.3.2024.3.3

[2] Yu, D. (2022) Training Peripheral Vision to Read: Using Stimulus Exposure and Identity Priming. *Frontiers in Neuroscience*, **16**, Article 916447. https://doi.org/10.3389/fnins.2022.916447

[3] Leung, K.Y., Chan, H.H.L. and Leung, M.P. (2018) Subjective and Objective Evaluation of Visual Functions in Dyslexic Children with Visual Perceptual Deficiency—Before and after Ten-Weeks of Perceptual Training. *Research in Developmental Disabilities*, **80**, 112-130. https://doi.org/10.1016/j.ridd.2018.06.008

[4] Muktamath, V.U., Hegde, P.R. and Chand, S. (2022) Types of Specific Learning Disability. In: *Learning Disabilities—Neurobiology*, *Assessment*, *Clinical Features and Treatments*, IntechOpen, 10.

[5] Diplock, K. and Mehta, J. (2021) Utilising the Orthoptic Skill Set to Improve Access to Eye Care for Adults with Severe/Profound Learning Disabilities—A Service Evaluation. *British and Irish Orthoptic Journal*, **17**, 41-50. https://doi.org/10.22599/bioj.162

[6] Ovalle-Cijanes, I.S. (2020) Habilidades Visoperceptivas y Perfil Psicomotor: Análisis de una Muestra de Estudiantes en Etapa Preescolar. *Búsqueda*, **7**, e531. https://doi.org/10.21892/01239813.531

[7] Spencer, J.P., Ross-Sheehy, S. and Eschman, B. (2022) Testing Predictions of a Neural Process Model of Visual Attention in Infancy across Competitive and Non-Competitive Contexts. *Infancy*, **27**, 389-411. https://doi.org/10.1111/infa.12457

[8] Alrasheed, S.H. and Elmadina, A.E.M. (2020) Effect of Binocular Vision Problems on Childhood Academic Performance and Teachers' Perspective. *Pakistan Journal of Ophthalmology*, **36**, 162-167. https://doi.org/10.36351/pjo.v36i2.896

[9] Jaffe-Dax, S., Potter, C.E., Leung, T.S., Emberson, L.L. and Lew-Williams, C. (2023) The Influence of Memory on Visual Perception in Infants, Children, and Adults. *Cognitive Science*, **47**, e13381. https://doi.org/10.1111/cogs.13381

[10] Ellis, B.J., Sheridan, M.A., Belsky, J. and McLaughlin, K.A. (2022) Why and How Does Early Adversity Influence Development? Toward an Integrated Model of Dimensions of Environmental Experience. *Development and Psychopathology*, **34**, 447-471. https://doi.org/10.1017/s0954579421001838

[11] Alrasheed, S.H. and Aldakhil, S. (2024) Childhood Amblyopia: A Systematic Review of Recent Management Options. *Saudi Journal of Ophthalmology*, **38**, 201-213. https://doi.org/10.4103/sjopt.sjopt_212_23

[12] He, Q., Yang, X., Zhao, D. and Fang, F. (2022) Enhancement of Visual Perception by Combining Transcranial Electrical Stimulation and Visual Perceptual Training. *Medical Review*, **2**, 271-284. https://doi.org/10.1515/mr-2022-0010

[13] Richter, A., Barman, A., Wüstenberg, T., Soch, J., Schanze, D., Deibele, A., *et al*. (2017) Behavioral and Neural Manifestations of Reward Memory in Carriers of Low-Expressing versus High-Expressing Genetic Variants of the Dopamine D2 Receptor. *Frontiers in Psychology*, **8**, Article 654. https://doi.org/10.3389/fpsyg.2017.00654

[14] Pleisch, G., Karipidis, I.I., Brauchli, C., Röthlisberger, M., Hofstetter, C., Stämpfli, P., *et al*. (2019) Emerging Neural Specialization of the Ventral Occipitotemporal Cortex to Characters through Phonological Association Learning in Preschool Children. *NeuroImage*, **189**, 813-831. https://doi.org/10.1016/j.neuroimage.2019.01.046

[15] Dushanova, J.A. and Tsokov, S.A. (2020) Small-World EEG Network Analysis of Functional Connectivity in Developmental Dyslexia after Visual Training Intervention. *Journal of Integrative Neuroscience*, **19**, 601-618. https://doi.org/10.31083/j.jin.2020.04.193

[16] Ceple, I., Skilters, J., Lyakhovetskii, V., Jurcinska, I. and Krumina, G. (2023) Figure-Ground Segmentation and Biological Motion Perception in Peripheral Visual Field. *Brain Sciences*, **13**, Article No. 380. https://doi.org/10.3390/brainsci13030380

[17] Fonteyn-Vinke, A., Huurneman, B. and Boonstra, F.N. (2022) Viewing Strategies in Children with Visual Impairment and Children with Normal Vision: A Systematic Scoping Review. *Frontiers in Psychology*, **13**, Article 898719. https://doi.org/10.3389/fpsyg.2022.898719

[18] Caldani, S., Gerard, C., Peyre, H. and Bucci, M.P. (2020) Visual Attentional Training Improves Reading Capabilities in Children with Dyslexia: An Eye Tracker Study during a Reading Task. *Brain Sciences*, **10**, Article No. 558. https://doi.org/10.3390/brainsci10080558

[19] Thiagarajan, P., Ciuffreda, K.J., Capo-Aponte, J.E., Ludlam, D.P. and Kapoor, N. (2014) Oculomotor Neurorehabilitation for Reading in Mild Traumatic Brain Injury (mTBI): An Integrative Approach. *NeuroRehabilitation*, **34**, 129-146. https://doi.org/10.3233/nre-131025

[20] Park, S.E. (2016) Effects of Eye Movement with Functional Electrical Stimulation on Balance in Stroke Patients with Neglect Syndrome. *Journal of Physical Therapy Science*, **28**, 1577-1581. https://doi.org/10.1589/jpts.28.1577

[21] Roh, M. and Lee, E. (2019) Effects of Gaze Stability Exercises on Cognitive Function, Dynamic Postural Ability, Balance Confidence, and Subjective Health Status in Old People with Mild Cognitive Impairment. *Journal of Exercise Rehabilitation*, **15**, 270-274. https://doi.org/10.12965/jer.1938026.013

[22] Bleau, M., Paré, S., Chebat, D., Kupers, R., Nemargut, J.P. and Ptito, M. (2022) Neural Substrates of Spatial Processing and Navigation in Blindness: An Activation Likelihood Estimation Meta-Analysis. *Frontiers in Neuroscience*, **16**, Article 1010354. https://doi.org/10.3389/fnins.2022.1010354

[23] Wijesundera, C., Crewther, S.G., Wijeratne, T. and Vingrys, A.J. (2022) Vision and Visuomotor Performance Following Acute Ischemic Stroke. *Frontiers in Neurology*, **13**, Article 757431. https://doi.org/10.3389/fneur.2022.757431

[24] Schaefer, S.Y., Hooyman, A., Haikalis, N.K., Essikpe, R., Lohse, K.R., Duff, K., *et al*. (2022) Efficacy of Corsi Block Tapping Task Training for Improving Visuospatial Skills: A Non-Randomized Two-Group Study. *Experimental Brain Research*, **240**, 3023-3032. https://doi.org/10.1007/s00221-022-06478-5

[25] Soylu, F. and Newman, S.D. (2020) Editorial: Towards an Understanding of the Relationship between Spatial Processing Ability and Numerical and Mathematical Cognition. *Frontiers in Psychology*, **11**, Article 14. https://doi.org/10.3389/fpsyg.2020.00014

[26] Castelhano, J., Duarte, I., Bernardino, I., Pelle, F., Francione, S., Sales, F., *et al*. (2022) Intracranial Recordings in Humans Reveal Specific Hippocampal Spectral and Dorsal vs. Ventral Connectivity Signatures during Visual, Attention and Memory Tasks. *Scientific Reports*, **12**, Article No. 3488. https://doi.org/10.1038/s41598-022-07225-0

[27] Bambha, V.P. and Casasola, M. (2021) From Lab to Zoom: Adapting Training Study Methodologies to Remote Conditions. *Frontiers in Psychology*, **12**, Article 694728. https://doi.org/10.3389/fpsyg.2021.694728

[28] Wolfe, J.M. (2021) Guided Search 6.0: An Updated Model of Visual Search. *Psychonomic Bulletin & Review*, **28**, 1060-1092. https://doi.org/10.3758/s13423-020-01859-9

[29] Vialatte, A., Aguera, P., Bedoin, N., Witko, A., Chabanat, E. and Pisella, L. (2023) Enhancing Reading Accuracy through Visual Search Training Using Symbols. *Scientific Reports*, **13**, Article No. 4291. https://doi.org/10.1038/s41598-023-31037-5

[30] Lancaster, H.S., Li, J. and Gray, S. (2021) Selective Visual Attention Skills Differentially Predict Decoding and Reading Comprehension Performance across Reading Ability Profiles. *Journal of Research in Reading*, **44**, 715-734. https://doi.org/10.1111/1467-9817.12368

[31] Harrar-Eskinazi, K.L., De Cara, B., Leloup, G., Nothelier, J., Caci, H., Ziegler, J.C., *et al.* (2022) Multimodal Intervention in 8- to 13-Year-Old French Dyslexic Readers: Study Protocol for a Randomized Multicenter Controlled Crossover Trial. *BMC Pediatrics*, **22**, Article No. 741. https://doi.org/10.1186/s12887-022-03701-8

[32] Chapman, A.F. and Störmer, V.S. (2022) Feature Similarity Is Non-Linearly Related to Attentional Selection: Evidence from Visual Search and Sustained Attention Tasks. *Journal of Vision*, **22**, Article No. 4. https://doi.org/10.1167/jov.22.8.4

[33] Dakos, A.S., Jiang, H., Stein, B.E. and Rowland, B.A. (2020) Using the Principles of Multisensory Integration to Reverse Hemianopia. *Cerebral Cortex*, **30**, 2030-2041. https://doi.org/10.1093/cercor/bhz220

[34] Stevenson, R.A., Wilson, M.M., Powers, A.R. and Wallace, M.T. (2013) The Effects of Visual Training on Multisensory Temporal Processing. *Experimental Brain Research*, **225**, 479-489. https://doi.org/10.1007/s00221-012-3387-y

[35] Eberhardt, S.P., Auer Jr., E.T. and Bernstein, L.E. (2014) Multisensory Training Can Promote or Impede Visual Perceptual Learning of Speech Stimuli: Visual-Tactile vs. Visual-Auditory Training. *Frontiers in Human Neuroscience*, **8**, Article 829. https://doi.org/10.3389/fnhum.2014.00829

[36] Stein, B.E., Stanford, T.R. and Rowland, B.A. (2019) Multisensory Integration and the Society for Neuroscience: Then and Now. *The Journal of Neuroscience*, **40**, 3-11. https://doi.org/10.1523/jneurosci.0737-19.2019

[37] Boyle, N., Betts, S. and Lu, H. (2024) Monoaminergic Modulation of Learning and Cognitive Function in the Prefrontal Cortex. *Brain Sciences*, **14**, Article No. 902. https://doi.org/10.3390/brainsci14090902

[38] Princz-Lebel, O., Skirzewski, M., Rai, H., *et al.* (2024) Dissociable Patterns of Dopamine Dynamics and Causal Contributions to Stimulus-Response Behaviors across Striatal Subregions. *bioRxiv*.

[39] Sporn, S. and Galea, J.M. (2023) Reward-Based Improvements in Motor Sequence Learning Are Differentially Affected by Dopamine. *bioRxiv*.

[40] Gonçalves, J., Violante, I.R., Sereno, J., Leitão, R.A., Cai, Y., Abrunhosa, A., *et al.* (2017) Testing the Excitation/Inhibition Imbalance Hypothesis in a Mouse Model of the Autism Spectrum Disorder: *In Vivo* Neurospectroscopy and Molecular Evidence for Regional Phenotypes. *Molecular Autism*, **8**, Article No. 47. https://doi.org/10.1186/s13229-017-0166-4

[41] Jia, K., Wang, M., Steinwurzel, C., Ziminski, J.J., Xi, Y., Emir, U., *et al.* (2024) Recurrent Inhibition Refines Mental Templates to Optimize Perceptual Decisions. *Science Advances*, **10**, eado7378. https://doi.org/10.1126/sciadv.ado7378

[42] Kam, K.Y. and Chang, D.H.F. (2024) The Neurochemistry of Learning-Driven Sensory Eye Dominance Plasticity. *Imaging Neuroscience*, **2**, 1-18. https://doi.org/10.1162/imag_a_00237

[43] Shao, Z.D., Gong, Y.J., Ren, J. and Wang, J. (2023) Exploring the Arcuate Fasciculus from a Clinical Perspective. *Frontiers in Neuroscience*, **17**, Article 1307834. https://doi.org/10.3389/fnins.2023.1307834

[44] Wang, N.Y., Wang, H.S., Liu, Y., Chang, Y.E. and Weng, J. (2021) Investigating the White Matter Correlates of Reading Performance: Evidence from Chinese Children with Reading Difficulties. *PLOS ONE*, **16**, e0248434. https://doi.org/10.1371/journal.pone.0248434

[45] Piervincenzi, C., Ben-Soussan, T.D., Mauro, F., Mallio, C.A., Errante, Y., Quattrocchi, C.C., *et al.* (2017) White Matter Microstructural Changes Following Quadrato Motor Training: A Longitudinal Study. *Frontiers in Human Neuroscience*, **11**, Article 590. https://doi.org/10.3389/fnhum.2017.00590

[46] Willis, H.E., Caron, B., Cavanaugh, M.R., Starling, L., Ajina, S., Pestilli, F., *et al.* (2024) Rehabilitating Homonymous Visual Field Deficits: White Matter Markers of Recovery—Stage 2 Registered Report. *Brain Communications*, **6**, fcae323. https://doi.org/10.1093/braincomms/fcae323

[47] Schimmelpfennig, J., Topczewski, J., Zajkowski, W. and Jankowiak-Siuda, K. (2023) The Role of the Salience Network in Cognitive and Affective Deficits. *Frontiers in Human Neuroscience*, **17**, Article 1133367. https://doi.org/10.3389/fnhum.2023.1133367

[48] Gao, W., Gilmore, J.H., Alcauter, S. and Lin, W. (2013) The Dynamic Reorganization of the Default-Mode Network during a Visual Classification Task. *Frontiers in Systems Neuroscience*, **7**, Article 34. https://doi.org/10.3389/fnsys.2013.00034

[49] Zhou, Y., Zhang, L., Dai, Y., *et al.* (2024) Selective Attention Modulates Feature Accumulation Speed during Perception and Memory Retrieval. *bioRxiv*.

[50] Zhang, Q., Huang, Z., Li, L. and Li, S. (2022) Visual Search Training Benefits from the Integrative Effect of Enhanced Covert Attention and Optimized Overt Eye Movements. *Journal of Vision*, **22**, Article No. 7. https://doi.org/10.1167/jov.22.8.7

[51] Zaki, Z.M.M., Ali, S.A., Ghazali, M.M. and Jam, F.A. (2024) Genetic Modifications of Developmental Dyslexia and Its Representation Using *in Vivo*, *in Vitro* Model. *Global Medical Genetics*, **11**, 76-85. https://doi.org/10.1055/s-0044-1781456

[52] de Sousa Fernandes, M.S., Costa, M.R., Badicu, G., Yagin, F.H., Santos, G.C.J., da Costa, J.M., *et al.* (2024) Can

Environmental Enrichment Modulate Epigenetic Processes in the Central Nervous System under Adverse Environmental Conditions? A Systematic Review. *Cellular and Molecular Neurobiology*, **44**, Article No. 69. https://doi.org/10.1007/s10571-024-01506-0

[53] Cooper, D.D. and Frenguelli, B.G. (2021) The Influence of Sensory Experience on the Glutamatergic Synapse. *Neuropharmacology*, **193**, Article ID: 108620. https://doi.org/10.1016/j.neuropharm.2021.108620

[54] Yan, X., Jiang, K., Li, H., Wang, Z., Perkins, K. and Cao, F. (2021) Convergent and Divergent Brain Structural and Functional Abnormalities Associated with Developmental Dyslexia. *eLife*, **10**, e69523. https://doi.org/10.7554/elife.69523

[55] Werth, R. (2021) Is Developmental Dyslexia Due to a Visual and Not a Phonological Impairment? *Brain Sciences*, **11**, Article No. 1313. https://doi.org/10.3390/brainsci11101313

[56] Lawton, T. and Shelley-Tremblay, J. (2017) Training on Movement Figure-Ground Discrimination Remediates Low-Level Visual Timing Deficits in the Dorsal Stream, Improving High-Level Cognitive Functioning, Including Attention, Reading Fluency, and Working Memory. *Frontiers in Human Neuroscience*, **11**, Article 236. https://doi.org/10.3389/fnhum.2017.00236

[57] Pilacinski, A. and Lindner, A. (2019) Distinct Contributions of Human Posterior Parietal and Dorsal Premotor Cortex to Reach Trajectory Planning. *Scientific Reports*, **9**, Article No. 1962. https://doi.org/10.1038/s41598-019-39188-0

[58] Costa, L.C., Spencer, S.V. and Hooper, S.R. (2022) Emergent Neuroimaging Findings for Written Expression in Children: A Scoping Review. *Brain Sciences*, **12**, Article No. 406. https://doi.org/10.3390/brainsci12030406

[59] Bartov, R., Wagner, M., Shvalb, N. and Hochhauser, M. (2023) Enhancing Handwriting Performance of Children with Developmental Coordination Disorder (DCD) Using Computerized Visual Feedback. *Children*, **10**, Article No. 1534. https://doi.org/10.3390/children10091534

[60] Vinci-Booher, S., James, T.W. and James, K.H. (2021) Visual-Motor Contingency during Symbol Production Contributes to Short-Term Changes in the Functional Connectivity during Symbol Perception and Long-Term Gains in Symbol Recognition. *NeuroImage*, **227**, Article ID: 117554. https://doi.org/10.1016/j.neuroimage.2020.117554

[61] Soltanlou, M., Dresler, T., Artemenko, C., Rosenbaum, D., Ehlis, A. and Nuerk, H. (2022) Training Causes Activation Increase in Temporo-Parietal and Parietal Regions in Children with Mathematical Disabilities. *Brain Structure and Function*, **227**, 1757-1771. https://doi.org/10.1007/s00429-022-02470-5

[62] Tablante, J., Krossa, L., Azimi, T. and Chen, L. (2023) Dysfunctions Associated with the intraparietal Sulcus and a Distributed Network in Individuals with Math Learning Difficulties: An ALE Meta-Analysis. *Human Brain Mapping*, **44**, 2726-2740. https://doi.org/10.1002/hbm.26240

[63] Matejko, A.A. and Ansari, D. (2021) Shared Neural Circuits for Visuospatial Working Memory and Arithmetic in Children and Adults. *Journal of Cognitive Neuroscience*, **33**, 1003-1019. https://doi.org/10.1162/jocn_a_01695

[64] Dosher, B. and Lu, Z.L. (2017) Visual Perceptual Learning and Models. *Annual Review of Vision Science*, **3**, 343-363. https://doi.org/10.1146/annurev-vision-102016-061249

[65] Shi, W.Y., *et al*. (2025) Effects of Exercise Interventions on Hand-Eye Coordination and Fine Motor Skills in Children with Developmental Coordination Disorder: A Meta-Analysis. *Frontiers in Physiology*, **16**, Article 1689256. https://doi.org/10.3389/fphys.2025.1689256

[66] Silva, A.E., Mungalsingh, M.A., Raudzus, L. and Thompson, B. (2025) Improving Peripheral Reading with Noninvasive Transcranial Electrical Stimulation of Early Visual Areas. *Translational Vision Science & Technology*, **14**, Article No. 33. https://doi.org/10.1167/tvst.14.9.33

[67] Gkintoni, E., Sortwell, A., Vassilopoulos, S.P. and Nikolaou, G. (2026) Neuroplasticity-Informed Learning under Cognitive Load: A Systematic Review of Functional Imaging, Brain Stimulation, and Educational Technology Applications. *Multimodal Technologies and Interaction*, **10**, Article No. 5. https://doi.org/10.3390/mti10010005

[68] Kostkova, K., Ben Itzhak, N., Stijnen, L., Ortibus, E. and Jansen, B. (2023) Dynamic Difficulty Adjustment in Serious Games for Cerebral Visual Impairment. 2023 *IEEE* 11*th International Conference on Serious Games and Applications for Health* (*SeGAH*), Athens, 28-30 August 2023, 1-8. https://doi.org/10.1109/segah57547.2023.10253769

[69] Ibrahimi, D., Aviles, M. and Rodríguez-Reséndiz, J. (2024) Perceptual-Motor Abilities and Reversal Frequency of Letters and Numbers in Children Diagnosed with Poor Reading Skills. *Bioengineering*, **11**, Article No. 1197. https://doi.org/10.3390/bioengineering11121197

[70] Wu, D., Zhang, P., Li, C., Liu, N., Jia, W., Chen, G., *et al*. (2020) Perceptual Learning at Higher Trained Cutoff Spatial Frequencies Induces Larger Visual Improvements. *Frontiers in Psychology*, **11**, Article 265. https://doi.org/10.3389/fpsyg.2020.00265