·专家笔谈·

专家介绍



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# 人工智能技术在特定性学习障碍诊疗中的应用

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**摘　要：** 特定性学习障碍（SLD）是学龄儿童中患病率最高的神经发育性障碍之一，其传统诊断方法存在耗时长、成本高、主观性强等局限。人工智能（AI）技术为 SLD 的早期识别、精准诊断与个性化干预提供了新途径。本文概述了 AI 在 SLD 诊疗中的主要应用：在辅助评估方面，结合眼动追踪技术可实现高生态效度的阅读障碍筛查，结合手写分析可量化静态字形特征与动态书写过程，结合语音声学特征分析可评估阅读流利性，结合神经影像学技术可揭示 SLD 的神经生物学特征；在干预方面，构建自适应智能辅导系统可实现个性化干预，利用大语言模型可为社会适应提供辅助支持。但目前仍面临数据集规模偏小、算法可解释性不足、伦理隐私风险及临床验证不充分等挑战。未来需构建大规模多中心中文数据集、发展低成本筛查工具、加强循证评价并完善监管框架，推动 AI 成为 SLD 诊疗体系变革的核心动力。

**关键词：** 特定性学习障碍；人工智能；早期筛查；个性化干预

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# Application of artificial intelligence in the diagnosis and treatment of specific learning disorder

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**Abstract:** Specific learning disorder (SLD) is one of the most prevalent neurodevelopmental disorders in school-aged children. However, conventional diagnostic workflows are frequently constrained by prolonged assessment cycles, high costs, and inherent subjectivity. Artificial intelligence (AI) has provided novel paradigms for the early identification, precision diagnosis, and personalized intervention of SLD. This review outlines the main applications of AI in the diagnosis and treatment of SLD. Regarding assisted assessment, the integration of eye-tracking technology facilitates dyslexia screening with enhanced ecological validity, while computerized handwriting analysis quantifies both static orthographic features and dynamic kinematic processes. Furthermore, acoustic analysis of speech patterns enables the objective evaluation

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of reading fluency, and advanced neuroimaging techniques can elucidate the underlying neurobiological characteristics of SLD. In terms of intervention, adaptive intelligent tutoring systems provide personalized intervention, and large language models offer promising auxiliary tools for social adaptation. Despite these advancements, significant challenges persist, including limited dataset scales, insufficient algorithmic interpretability, ethical concerns regarding data privacy, and inadequate clinical validation. Future efforts should prioritize the construction of large-scale, multi-center Chinese-specific datasets, the development of cost-effective screening tools, and the establishment of robust evidence-based evaluation and regulatory frameworks to promote AI as the core driving force for the transformation of the SLD diagnosis and treatment system.

Keywords: specific learning disorder; artificial intelligence; early screening; personalized intervention

特定性学习障碍(specific learning disorder, SLD)是一类神经发育性障碍,以在阅读、书写、数学运算等特定学业技能的习得和运用方面持续存在实质性困难为核心表现,且这些困难不能归因于智力障碍、感觉障碍、神经系统疾病或不充分的学业教育。依据《精神障碍诊断与统计手册(第 5 版)》的分类框架,SLD 可细分为阅读障碍(dyslexia)、书写表达障碍(dysgraphia)与数学障碍(dyscalculia)三大亚型,上述三类亚型可单独或共病出现[1],且常与注意缺陷多动障碍、语言发育障碍等其他神经发育性疾病高度共患[2]。

流行病学数据显示,SLD 是学龄儿童中患病率最高的神经发育性障碍之一。汉语发展性读写障碍的发病率大约是 5%～10%[3],中国小学生数学困难的总体患病率约为 8.97%[4]。尽管 SLD 在学术界已被广泛研究,但其临床识别与诊断体系在实际运行中仍面临严峻挑战。首先,社会层面普遍存在对 SLD 的认知不足,公众乃至基层教师常将学习困难简单归咎于儿童的学习态度或家庭教育,导致大量患儿错失最佳干预窗口。其次,诊断技术仍高度依赖主观评价量表,耗时长、成本高,且缺乏简便客观的生物学标记物辅助判断[5]。此外,基层儿科与全科医生往往缺乏系统的神经心理学培训,导致 SLD 诊断能力不足,难以惠及广大的基层患儿群体[6]。

人工智能(artificial intelligence, AI)技术,包括机器学习(machine learning, ML)与深度学习(deep learning, DL),在处理高维、非结构化和多模态数据方面具有显著优势,为高效低门槛的 SLD 诊断和干预提供了潜在解决方案[7]。ML 方法,如支持向量机(support vector machine, SVM)、随机森林等,能够从数据中学习复杂的规律并进行预测;DL 方法,如卷积神经网络(convolutional neural networks, CNN)、循环神经网络和 Transformer 架构等,则具备强大的层次化表征学习能力,能自动从眼动轨迹、书写行为时序信号、神经影像学数据及声学-韵律特征等高维非结构化数据中挖掘具有生物学意义的亚临床模式[8]。

## 1 人工智能技术在特定性学习障碍辅助评估中的应用

1.1 基于眼动追踪技术的自然阅读任务筛查 眼动追踪技术是一种能够在高生态效度环境下,以高时间分辨率记录受试者眼动特征的技术。受试者无需佩戴侵入性设备,只需在屏幕前完成日常任务即可完成筛查,适宜于儿童群体和基层的规模化推广[9]。既往研究显示阅读障碍儿童在阅读时表现出特征性眼动异常,包括注视时间延长、注视次数增多、回视频率升高以及眼跳幅度减小等[10-12],可作为可靠的筛查指标。

利用眼动技术结合 AI 分类算法,可实现高精度的阅读障碍早期筛查。大部分研究通过基于任务范式特点提取的特征参数进行 AI 分类,在汉语阅读障碍研究中也证明了其可靠性[13-15]。近年来有研究利用 CNN 将眼动序列作为一个整体进行建模和分类,无需进行显式特征提取[16];另有研究利用 DL 处理直接分析眼动热图[17]或使用 CNN 和 Transformer 架构结合的方法直接处理眼动轨迹[18],均获得了良好的分类效果。

1.2 基于手写分析的自然书写任务筛查 借助 AI 技术,对儿童书写的评价已从“人工主观评价”转向“多维数字化客观评估”,分为静态书写成品的特征提取和书写运动过程的轨迹量化两类。

对于静态书写结果,基于拼音文字的研究报道,可通过计算机视觉技术识别空间布局和形态异常[19],同时融合光学字符识别与自然语言语义分析模块,评价语义组织等高级语言表现[20]。此外,一项基于 CNN 的汉字手写笔迹评分系统研究报告其实现了类似人类的可靠评分能力,整体归一化平均绝对百分比误差(nMAPE)为 9.82%[21]。

数字化压感笔与智能笔迹板的应用为评估动态书写过程提供了量化工具,能以毫秒级精度采集笔尖压力、书写速度波动及空中停顿时间等运动特

征[22]，而联合 AI 能够有效整合运动学与压力等多模态数据，为进一步提升筛查准确性提供了基础[23]。进一步搭建前端架构，可实现交互式的分析结果呈现，如 Al-Strokes 平台可基于 ML 后端通过分析笔画数量、笔画顺序、笔画方向和书写速度实现学生书写错误的自动评分[24]。而近期的一项研究还拓展了硬件开发，该平台整合了具有实时反馈的传感笔 SPRF（sensorised pen with real-time feedback）和腕带，在既往参数的基础上纳入了笔杆倾角、心率和手腕位置等参数，实现对书写过程的握笔和运动特征进行客观评价并利用基于 Keras/TensorFlow 库的 CNN 实现实时反馈和干预指导[25]。

1.3　基于语音声学特征分析的自然阅读流利性评估　口语阅读的声学特征分析是阅读障碍早期筛查的重要技术路径。研究发现多种语音声学特征与阅读流利性和阅读理解能力显著相关，包括停顿、音高和语调轮廓等韵律特征[26-27]，语速/音节率和速率变异等速度特征[28-29]，及强度轮廓和频率动态等[30]。

目前已有多项研究报道利用 AI 自动提取语音材料中流利度特征技术，如 Whisper ASR 系统可用于儿童朗读音频转录、阅读速度和韵律的分析[31]。而 LexiEase AI 则利用 ML 和自然语言处理技术进行发音意识测试、记忆测试和口语阅读流利性测试识别阅读障碍儿童[32]。然而，虽已有研究开发了针对汉语的 AI 语音识别技术，可用于纠正儿童发音错误和提高口语能力[33]，但应用相关技术开展汉语阅读障碍辅助筛查的研究仍非常有限。

1.4　基于神经影像学指标的人工智能辅助评估　脑电图（electroencephalography，EEG）具有非侵入性、高时间分辨率和成本效益等优势，其信号能够反映在学习任务中大脑的认知活动和功能异常，常作为 SLD 的辅助评估依据[34-35]。SVM 因其在处理线性和非线性分类问题上的卓越性能而常被认为是分类 EEG 信号的最佳选择之一[36]。而在 EEG 基础上拓展交互式语言软件工具开展视听觉辨别任务，在随机森林分类器上仍可取得最高超过 95% 的准确率、灵敏度和特异性[37]。在 DL 模型中，一项研究使用 ReliefF 算法选择最相关的特征结合浅层神经网络分类器达到了 95.8% 的平均准确率和 97.5% 的最大准确率[38]。

功能性磁共振成像（functional magnetic resonance imagina，fMRI）能够监测大脑活动时的血氧水平依赖信号，从而揭示大脑在执行认知任务时的功能激活模式[39]。多项研究应用 AI 技术提升分类预测效果。例如，一项研究利用 3D CNN 对 3 种不同阅读任务中的激活 3D 体积进行分类，总体平均分类准确率达到 72.73%[40]。在计算障碍方面，研究利用静息态功能连接调查了发展性计算障碍儿童与正常发育同龄人之间的神经差异。通过基于种子的功能连接分析和基于全脑连接组的预测建模方法，全脑分类 AUC 值达到了 0.816[41]。随着 AI 模型在 SLD 诊断中准确性的提高，可解释性成为重要研究方向。一项研究通过 GRAD-CAM 技术进行视觉解释识别对分类贡献最大的大脑区域，并印证了模型的可靠性[42]。多模态数据融合是提高 SLD 检测准确性和泛化能力的关键趋势。研究报道整合 MRI、fMRI 和 EEG 数据的混合模型在各数据集上可达超过 98% 的准确率[43]。

## 2　人工智能技术在特定性学习障碍干预和改善中的应用

2.1　自适应智能辅导系统　自适应智能辅导系统（intelligent tutoring system，ITS）区别于固定化的教学内容，能够基于贝叶斯知识追踪、深度强化学习等算法，实时评估学习者的知识掌握状态与认知负荷，动态调整练习内容的难度、形式与呈现顺序，实现个性化精准干预。基于 ITS 的数学技能平台（The Number Race）的干预研究显示，多维自适应算法使儿童正确率维持在 75% 左右，并在数字知识的掌握和错误纠正能力方面显著提升[44]。Character Alive 是一项针对中文阅读障碍的干预平台，其利用动画和颜色阐明部首和语素概念，结合实体部首卡片和人工智能模块，显著提高了儿童在汉字阅读和构成方面的准确性表现[45]。CNReader 阅读辅助器则通过中文辅助阅读和阅读训练，显著降低了受试者的阅读错误率、改善了阅读流畅性和阅读理解能力，并在 1 个月的训练期后仍可保持中长期效果[46]。部分研究还结合增强现实与人机交互，提升被试的干预体验[47]。然而，一项系统综述指出，虽然 AI 干预具有一致性的阳性效果，但研究者还需关注出版偏倚的影响[48]。

2.2　大语言模型与对话式人工智能辅助工具　大语言模型（large language model，LLM）和对话式 AI 辅助工具可支持用户进行快速写作并降低语言表述错误，为 SLD 的社会适应提供支持。LaMPost 系统以 LaMDA 大语言模型为核心，为成人阅读障碍用户提供实时拼写纠错、语法建议与文本结构重组，显著降低了书写表达障碍者在职场写作中的功能性障碍[49]。但对于学习阶段的 SLD 患者，LLM 的应用仍需权衡利弊。CHATTING 是基于 ChatGPT 的

阅读障碍中英文辅助写作系统，虽然其能够积极提升阅读障碍学生在行为和情感上的参与度与内在学习动机，但对认知参与度的提升较小，且并未显著提高学生的写作表现，甚至存在无意抄袭的风险[50]。

## 3 人工智能技术在特定性学习障碍诊疗中面临的挑战与未来发展方向

虽然 AI 对 SLD 的诊疗技术具有长足的推动作用，但其落地应用和推广仍面临多重挑战。

首先，现有公开的 SLD 相关数据集规模普遍偏小，且多以英语或其他表音文字群体为主。这种数据局限性不仅容易导致 DL 模型在小样本训练中出现过拟合，更难以支撑模型跨语言、跨文化背景的泛化应用。特别是中文独特的形-音-义映射机制，使得直接迁移基于英文语境训练的 AI 模型面临巨大困难，亟需构建本土化的大规模规范数据库[43]。其次，DL 模型固有的“黑箱”特性阻碍了其在临床上的广泛接受度。临床医生在做出诊断与干预决策时，必须明确算法得出结论的具体行为学或神经生物学依据。因此，未来需深化可解释 AI 方法的研究，通过特征可视化、注意力机制等技术手段提升模型的透明度，使其决策逻辑契合真实临床路径[19,51]。

此外，现有研究大多仍停留在回顾性数据的技术验证与初步模型建立阶段，当前领域内缺乏多中心、大样本的高质量随机对照试验，直接限制了 AI 技术向标准化临床指南和诊疗常规的整合与推广。其中，儿童神经发育数据涉及敏感隐私，模型训练中也应遵循数据最小化与算法公平性原则[52]。

因此，为利用 AI 技术支持中文背景下的 SLD 诊疗，未来需构建大规模多中心中文数据集，发展低成本端侧筛查工具，加强 AI 干预的循证评价，完善儿童神经发育 AI 产品的监管框架，推动 AI 真正成为 SLD 诊疗体系变革的核心动力。

**利益冲突声明** 本文不存在利益冲突

**数据可用性声明** 本研究未生成新的数据，对于纳入的每项研究均已在参考文献列表中列出。

AIGC **工具使用声明** 在本研究的准备过程中，作者使用了玻尔来辅助文献检索和整理。作者已对生成内容进行了审查和编辑，并对出版物内容承担全部责任。

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