

执行功能成分及其评估方式研究综述

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摘要

执行功能(executive function, EF)是个体实现目标导向行为的核心认知控制系统, 对其成分与评估方式进行梳理对科研与临床实践至关重要。本文聚焦于抑制控制、工作记忆和认知灵活性三大被普遍认同的核心成分, 系统阐述了其认知与神经机制。进而, 综述了当前主要的评估方法, 包括神经生理与心理学实验范式, 以及行为评定量表, 并分析了各类方法的适用性与局限性。针对该领域现状, 本文指出其存在评估工具标准化不足、生态效度有限、国内软件化与成套化工具缺失等问题。最后展望提出, 未来应通过多中心合作建立本土常模、促进与信息技术的跨学科融合, 以推动执行功能评估向标准化、生态化与智能化方向发展, 为执行功能的深入研究与临床应用提供清晰的理论框架与方法学参考。

关键词

执行功能, 成分, 评估方式, 综述

A Review of Research on Executive Function Components and Their Assessment Methods

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Abstract

Executive function (EF) serves as the core cognitive control system for individuals' goal-directed behaviors, making the systematization of its components and assessment methods crucial for both scientific research and clinical practice. This review focuses on the three widely recognized core components—inhibitory control, working memory, and cognitive flexibility—and elaborates on their cognitive and neural mechanisms. Furthermore, it summarizes the primary assessment approaches, including neurophysiological and psychological experimental paradigms, as well as behavioral rating

scales, while analyzing the applicability and limitations of each method. In light of current challenges in the field, this paper highlights issues such as the lack of standardization in assessment tools, limited ecological validity, and the scarcity of software-based and integrated test batteries in the domestic context. Finally, it proposes future directions, emphasizing the need for multi-center collaborations to establish local norms and promoting interdisciplinary integration with information technology. These efforts are expected to advance the field toward standardized, ecologically valid, and intelligent assessment frameworks, thereby providing a clear theoretical and methodological reference for further research and clinical application of executive function.

Keywords

Executive Function, Components, Assessment Methods, Review

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1. 引言

执行功能(executive function, EF)是当前心理学研究的一个重要概念,也是一个定义混乱的概念。这一概念最早出自神经心理学对前额叶损伤病人的研究。研究发现,前额叶皮层的损伤会引起一系列神经心理的缺陷,如计划、抽象思维、概念形成、决策、认知灵活性、动作监控等诸多方面的困难,这些能力是“执行功能”这一术语最初的定义来源。随着正电子断层扫描和磁共振成像等神经成像技术在执行功能领域中的应用,研究发现执行功能并不仅仅依赖于前额叶皮层,它还依赖于前额叶皮层与边缘系统等其它皮层及皮层下区域之间动态的交互作用(Alvarez & Emory, 2006; Friedman & Robbins, 2022; Zhang et al., 2020)。一般来说,执行功能是指个体在完成复杂认知活动时,为了达成特定目的,对认知、情感和行为进行有意识控制的能力(Bridgett et al., 2013; Doebel, 2020; Perone et al., 2021; Zelazo, 2020)。

2. 执行功能的成分

受认知心理学影响,研究者认为执行功能由很多不同的认知加工成分组成。当前普遍认同的一个观点认为,执行控制由抑制控制(inhibitory control),工作记忆(working memory)和认知灵活性(cognitive flexibility)三个核心成分组成,在此基础上衍生出更高级的执行功能成分如推理,问题解决和计划(Diamond, 2013; Ferguson et al., 2021; Spaniol & Danielsson, 2022)。

2.1. 抑制控制

抑制控制指的是个体控制自己的心理与行为,克服内部冲动,抵抗外部刺激吸引的能力(Dhir et al., 2021; Wegmann et al., 2020)。抑制控制让人们可以完成更适合当下任务。失去抑制控制人们不能专注于更有意义的事物,并被冲动和环境中的刺激所影响(Mirabella, 2021)。抑制控制是一种有意地运用心理资源的能力,使人们抑制与当前任务不匹配的优势反应,控制自发反应(Hofmann et al., 2012; Kräplin et al., 2021; Miyake et al., 2000)。抑制控制包括自我控制和干扰控制两个部分。自我控制,也叫行为抑制,指控制个体行为,或通过控制情绪来控制个体行为,让人们抵制诱惑,不冲动行事的能力。自我控制使人们抵制过度放纵,抵制不符合社会规范的行为,或者抑制冲动反应。自我控制的另一个方面是自律,这使个体能够完成延迟满足(Mischel et al., 1989)。干扰控制,也叫选择性抑制、认知抑制、注意控制等,是指个体在知觉层面上能够控制干扰,并将注意有选择地集中在需要注意的事物上,并抑制对其他刺激的关注。

这是一种内源性的,自上而下的,主动的,由目标驱动的,自愿的,需要付出意志的活动(Theeuwes, 2010),与由外部刺激本身属性所驱动,自下而上的注意相区分。抑制优势反应心理表征也是干扰控制的能力之一,能够主动地对记忆和想法进行筛选和采择,去除不需要的(Anderson & Levy, 2009),抵抗前摄干扰和后摄干扰(Postle et al., 2004)。

抑制控制过程需要抑制无关反应并对过程中的错误进行监控。成功地抑制控制与右侧额下回(inferior frontal gyrus, IFG)的激活密切相关(Aron et al., 2004; Chuah et al., 2006; Aron et al., 2014),反应误报与前扣带(anterior cingulate cortex, ACC)和内侧额回(medial frontal gyrus)的激活密切相关(Garavan et al., 2003; Hester & Fassbender, 2004; Rubia et al., 2003)。其中,前扣带回对于冲突监测非常重要(Braver et al., 2001; Carter et al., 1998; Salehinejad et al., 2021),而额下回可能负责持续性的注意控制(Egner & Hirsch, 2005)以及抑制无关反应(Aron et al., 2004; Aron et al., 2014)。

2.2. 工作记忆

工作记忆指将信息保存在大脑中,并在心理上对其进行处理(Baddeley & Hitch, 1994),包括内容-言语工作记忆和非语言(视觉-空间)工作记忆。工作记忆对于理解任何随着时间推移而展开的事物,发现事物之间的联系,以及将元素从整体中分离等活动都是至关重要的,是推理能力的基础,因此,工作记忆对于创造力也至关重要(van Ede & Nobre, 2023)。工作记忆与抑制控制通常同时发生,相互支持。

工作记忆包括空间存贮,空间复述,客体保持,词语存贮,词语复述和执行加工等成分。研究指出,右侧顶叶后部主要与空间存贮相关,其复述加工通过包括前运动区在内的右侧额顶回路实现(Anderson & Hulbert, 2021; Ishihara et al., 2020; Li et al., 2022)。客体信息通过左侧颞叶下部和顶叶后部实现,尚无明确证据表明客体信息存贮与复述的分离。词语信息的缓冲存贮激活左顶叶后部区域,其复述加工受 Broca 区、左侧前运动区和补充运动区组成的额叶皮层回路调节(Caciagli et al., 2023; Deldar et al., 2021)。客体信息保持激活左腹侧前额叶(prefrontal cortex, PFC)的 BA47 区,空间信息保持激活右腹侧 PFC 的 BA47 区。空间信息复述激活右侧顶叶上部皮层区域,其存贮激活枕叶皮层和颞叶下部皮层,可能与视觉缓冲存贮区对应(Zhou et al., 2021; Otstavnov et al., 2024)。执行加工负责操作工作记忆中保持的信息,对信息进行编码、刷新、转换与监控等高级控制,这些功能主要依赖背外侧前额叶皮层的激活(Menon & D'Esposito, 2022)。研究者认为,相比特征和刺激特异性表征多与后部皮层相关,前额叶更多地参与高级信息的组织,例如任务规则,目标,或种类的抽象表征(Yang et al., 2020; Pupíková et al., 2021)。前额叶自上而下的控制主要体现在两方面:其一,增强任务相关信息并抑制任务无关信息的信号;其二,对后侧皮层的信息表征进行选择(D'Esposito & Postle, 2015)。

2.3. 认知灵活性

认知灵活性也是执行功能的一个重要成分,主要指当两项任务竞争同一认知资源时,对这两项任务相互转换的控制过程(Malambo et al., 2022; Hauser et al., 2015)。认知灵活性的一个方面是能够在空间上改变视角(如从物体的另一个角度看过去是什么样子),或在人际关系上能够改变角度(如从他人角度看问题是什么样子的)。要更改视角就需要禁止(或停用)以前的视角,并将不同的视角作为当前任务,激活工作记忆(Johann et al., 2020)。因此,认知转换需要并建立在抑制控制和工作记忆的基础上。认知转换的另一个方面涉及改变人们对事物的看法(跳出固有思维)。此外还包括足够的灵活性以适应变化的需求或优先级,如承认自己当前的行为是错误的,并能够利用突然出现的、意想不到的机会(Diamond, 2013)。

认知灵活性可以通过对个体是否可以灵活地进行任务转换(task switching)来测定。在完成当前任务时,任务信息会整合成一个抽象的任务设置(task set),这个任务设置通常包含了知觉、注意、记忆、反应等多个成分(Sakai, 2008)。在转换过程中,相对于重复先前的任务,转换加工需要认知控制系统重新配置

合适的心理资源,针对当前任务目标建立一个新的任务设置(Monsell, 2003)。实验室研究中,任务转换范式(task-switching paradigm)常被用来探究认知灵活性的内在机制。此范式需要被试在两种或两种以上的任务间不停地转换,当前任务与先前任务相同时称作任务重复(repeat)试次,当前任务与先前任务不同时称作任务转换(switch)试次。研究发现相比重复试次,被试在转换试次反应时更长、正确率更低(Meiran, 1996; Monsell, 2003; Rogers & Monsell, 1995)。任务转换与任务重复之间的这种差异被称作转换代价(switchcost),其主要通过转换试次的反应时(或正确率)与重复试次的反应时(或正确率)之差来测量(Rogers & Monsell, 1995)。转换代价也被认为是为新任务重置认知系统这一执行控制过程所需的时间。

一项元分析研究指出,知觉转换,反应转换和上下文转换(perceptual, response, context switching)三种转换类型任务都普遍激活了额顶网络,尤其是额下回和后顶叶,说明这两个脑区在任务转换中可能起着一般性的作用(Kim et al., 2012; Mofrad et al., 2020; Sdoia et al., 2020)。另一项元分析研究显示,背外侧前额叶(DLPFC; BA9, 46)、扣带回(cingulate; BA 32, 24)、上顶叶(superior parietal lobe; BA 7)和下顶叶(inferior parietal lobe; BA 40)等脑区在认知灵活性任务中普遍激活(Niendam et al., 2012; Tsumura et al., 2021; Vallesi et al., 2022)。

3. 执行功能的评估方式

根据现有研究,研究者们主要采用量化评估的方式来测量和评估执行功能,其中包括实验评估和测量评估两大类。实验评估包括神经生理学实验和心理学实验,而测量评估主要以量表评估为主。

3.1. 实验评估

3.1.1. 神经生理实验

研究者常用事件相关电位(Event Related Potentials, ERP)任务和眼跳任务(Saccade tasks)对个体执行功能进行测量评估。ERP 是一种能够以毫秒级别的精度检测时间潜在信号的神经生物学研究方法,其结果十分精确可靠,当个体开展执行功能相关活动时,ERP 可以对大脑在不同时间段的活动进行准确而有效的监控,从而使其成为有效测量执行功能的一种方法(邢强等, 2017; Clayson et al., 2021; Jiao et al., 2020)。

3.1.2. 心理学实验

(1) 抑制控制

研究者常用 Stop-signal 任务、Stroop 范式、Flanker 任务、Go/No-Go 任务、Simon 任务等来测量抑制控制能力。Stop-signal 任务要求被试在实验中快速而准确地执行一个反应(反应任务)或停止已形成的反应冲动(停止任务)。它是一个迫选反应时任务,在停止任务中,可以测量出被试对停止信号的反应速度与成功抑制率,从而综合评估其抑制能力(Jia et al., 2021; Li et al., 2022)。经典 Stop-signal 任务过程如图所示:屏幕中央首先呈现注视点“+”,固定时长后呈现一个反应信号(如方形或圆形)。要求被试在看到反应信号后迅速做出选择性反应(如方形按左反应键,圆形按右反应键)。若在反应信号出现后伴随有一个听觉信号(“滴”)——即停止信号,那么实验要求被试在本次试验中抑制住原有的按键冲动,不做任何按键反应(Logan, 1994)。

Stroop 范式由 1935 年美国心理学家 Stroop 提出,其发现对颜色的命名,总会受到颜色词本身词义的干扰而导致颜色命名时间延长,如用蓝色墨水书写“红”字时,字义本身会干扰对蓝色的命名(Stroop, 1935)。这种同一刺激的颜色信息(蓝)和字义信息(红)发生干扰的现象被称为 Stroop 效应或 Stroop 干扰效应。

Go/No-Go 任务也是抑制控制能力测量常用的方法。在此任务中,要求被试对实验任务中出现的刺激类型进行判断并做出反应(Han et al., 2020),当出现的是“目标刺激”时,需要进行按键反应,即“Go”反应;反之,当出现的是“非目标刺激”时,则不需要进行按键反应,即“No-Go”反应(Xie et al., 2022)。Go/No-Go 任务适用于各个年龄阶段的抑制控制能力测试(Wiebe et al., 2012)。

Simon 任务常采用向上或向下的箭头(↑或↓)作为实验材料务(Holmes et al., 2009)。在每一个实验试

次中, 电脑屏幕中央首先呈现注视“+”300 ms, 空屏300 ms后在电脑屏幕左侧部分或右侧部分呈现箭头刺激500 ms, 最后呈现1000 ms的空屏(Grandjean et al., 2023)。被试的任务是判断箭头的朝向而不是空间(左右)位置。若箭头朝上则按左键, 若箭头朝下则按右键, 或者反之; 左右手按键在被试间平衡。记录反应时和正确率。

(2) 认知灵活性

研究者常用威斯康星卡片分类测验(Wisconsin Card Sorting Test, WCST)测量认知灵活性(Hommel et al., 2022; Miles et al., 2021)。在威斯康星卡片分类测验任务中, 要求被试根据卡片的颜色、数量或形状进行分类堆放, 让被试通过对分类堆放后获得的反馈发现规则。在连续进行10次正确分类后, 改变分类规则。该任务共有4张位于屏幕上方的刺激卡片和128张反应卡片, 每张卡片的大小为8 cm * 8 cm, 卡片上分别以红、绿、蓝、黄4种颜色, 画有1~4个三角形、星形、十字形或圆形。其中4张刺激卡分别画有1个红三角、2个绿星、三个黄十字、4个蓝圆的图片, 按上述顺序放于卡片盒上方。分类原则由计算机设定(颜色、数量或形状), 需要被试不断尝试、分析、推理找到计算机设定的分类原则。

(3) 工作记忆

在测量工作记忆的任务中, 研究者常用的任务范式有: 图片工作记忆任务(Picture Working Memory Task)、倒背任务(Backward Task)、N-back任务、科西块任务(Corsi Block Task)等(Best & Miller, 2010)。图片工作记忆任务是测量工作记忆的经典任务之一。任务进行过程中, 需要根据主试的要求在图画题册的题目页中正确指出任务页(题目页前一页)中曾出现的所有目标图案, 随着目标图案的增加, 任务难度也逐渐增加。倒背任务需要被试在头脑中对已有信息重新进行组织后再表达出来, 以考察被试的工作记忆(Zhang et al., 2019)。N-back任务要求被试将刚刚出现过的刺激(字母、位置或图形)同前面出现的第n个刺激相比较, 通过控制当前刺激与目标刺激间隔的刺激个数(n)来操纵记忆负荷(Frost et al., 2021)。科西块任务需要被试观察主试触摸一系列色块, 然后被试按相同的顺序触摸这些色块(Milner, 1971), N-back测试任务与科西块任务已经有结构化良好的计算机版本用于实验室实验。

3.2. 量表评估

执行功能行为评定量表(Behavior Rating Inventory of Executive Function, BRIEF)是目前应用较为广泛的评定个体执行功能问题的量表, 量表包含抑制(Inhibition)、转移(Shift)、情绪控制(Emotional Control)、工作记忆(Working Memory)和计划/组织(Plan/Organize)等5个分量表, 每个分量表都反映了执行功能的一个特定亚成分。针对不同的年龄段, 量表分别开发出学龄前儿童版(教师/父母评定)、学龄儿童版(教师/父母评定)及青少年成人版本(自我评定), 能够对不同年龄段的个体进行标准化执行功能评定(Gioia et al., 2002)。国内研究者对其进行翻译修订后将量表用于执行功能的评定中, 发现执行功能行为评定量表中文版在我国文化背景下同样适用并具有较好的信度及效度。

量表评估法因其简便易行而受到研究者的喜爱, 尤其对于那些不适合采用实验室实验测量评定技术来评定个体心理成就水平或能力时, 更是首选之一, 但是被试在作答量表时由于社会期望、自身认知水平等因素可能会出现自我掩饰、作答不认真等情况, 他评量表由于作答者观察角度等可能会出现作答偏差, 无法真实测量个体心理能力水平高低。

3.3. 前沿技术评估

3.3.1. 沉浸式虚拟现实任务

Kirkham 等人(2024)基于19篇文献的综述表明, 沉浸式虚拟现实(VR)范式在评估执行功能方面存在潜力。但作者认为, 当前的证据仍然存在局限性, 对诸如晕动症等不良影响的监测频率较低, 样本量存

在显著差异,可能限制解释并阻碍心理测量评估。

3.3.2. 基于无线脑电图和三维步态分析的双任务范式

Arpaia 等人(2024)探索出一种基于无线脑电图和三维步态分析的双任务范式,来评估执行功能的可行性。研究重点关注了抑制和工作记忆这两种核心执行功能,并设置了渐进难度水平的认知任务。

4. 当前执行功能评估存在问题及展望

4.1. 存在问题

4.1.1. 缺少标准化的执行功能评估方法和评价标准

当前采用的执行功能检测任务多种多样,不同的任务所评估的执行功能的核心成分又不相同,即便是同一任务又存在不同的版本和相应的常模,造成不同执行功能研究的结果难以横向比较。此外,一些执行功能评估任务,包含较多的执行功能以外的认知成分,对执行功能检测的特异性较差,异常的检测成绩有多大成分归结于执行功能障碍难以确定。

4.1.2. 国内缺少软件化的、打包成套的执行功能检测任务

比较全面的执行功能评估需要采用尽量多的覆盖执行功能各个核心成分的检测任务,但是这样做耗时长且患者难以充分配合,临床可行性较差。在众多的核心成分检测任务中,选择哪些检测任务进行组合,既达到广覆盖,又不至于过于冗长,需要进行大样本的在正常人群中进行的测试和不断调试。而国内目前正缺少国产化的、软件化的执行功能检测任务。

4.2. 进一步展望

在行业协会的组织下,进行多中心、大样本的包括执行功能在内的各种认知功能的常模研究,尽快建立本土化的常模,以便于指导国内的临床工作。针对国内目前还缺少国产化的、软件化的执行功能检测任务,应加强与信息技术行业的合作,在这一领域迎头赶上。

未来研究应加强心理学、神经科学、计算机科学等多学科的交叉合作,推动执行功能评估向智能化、个性化方向发展。例如,利用机器学习算法分析多模态数据(行为、脑影像、生理信号),构建个体化的执行功能认知图谱,为实现“精准神经心理学”评估与干预提供支持。

具体来说:(1) 组建全国 EF 评估联盟。建议由相关专业委员会牵头,联合多家医院、高校及科技企业,在三年内统一任务 SDK、数据格式与质量控制流程,发布涵盖三大核心成分的评估工具包,并适配 PC 与移动双平台。(2) 开展多中心常模建设。采用分层整群抽样,覆盖年龄 6 至 85 岁、城乡与多民族区域,样本量不少于两万例。评估工具采用 VR-N-back 与手机 Stroop 双通道,数据实时上传至共享平台,两年内发布含文化校正系数的百分位常模,并开放接口供合规调用。(3) 开发深度学习辅助诊断开源模型。在两年内完成轻量化模型,支持移动设备离线推理,输出可解释报告。目标指标:对注意缺陷多动障碍筛查灵敏度与特异度均达到 0.80 以上,并通过公平性审计。(4) 推广虚拟现实居家评估。在三年内完成短时“VR-EF 体检”应用开发,适配主流头显,使用手部追踪与瞳孔直径实时采集,数据经加密存储,患者获得可追溯的“EF 健康护照”。

综上,目前执行功能及其亚成分的测量评估范式形式多样并受到广泛应用,但是,并不存在通用、普适的实验任务,因此在研究任务的选择上研究者也要考虑被试年龄阶段、能力发展特点等因素,选取符合被试身心发展规律的研究任务进行施测,以获得准确、客观的测量评估结果。

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