

## 体育锻炼促进认知功能的脑机制

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**摘 要** 不同类型的体育锻炼对各种群体的多种认知功能均具有促进作用, 而相关的生理机制也在不同水平得到研究。在微观水平, 体育锻炼有利于脑细胞的营养供给和能量代谢, 并且能促进神经元的存活和突触生成。在宏观水平, 体育锻炼不仅能够提升海马和小脑等脑结构的体积, 还影响脑区激活水平和脑区间功能连接。值得注意的是, 体育锻炼对认知的促进效应受到诸多因素的影响, 比如个体差异、时间, 以及体育锻炼和认知刺激的相互作用等, 这些影响因素也为在两个水平上系统地阐明体育锻炼促进认知的脑机制提供了新的视角。

**关键词** 体育锻炼; 认知增强; 脑成像; 脑源性营养因子; 突触生成

**分类号** B845

体育锻炼(如, 跑步和游泳等)涉及肌肉对骨骼的拉伸和能量的消耗, 是一种旨在促进健康、提升运动技能, 且具有计划性和重复性的身体活动(Kylasov & Gavrov, 2011; Louis, Erickson, & Liu-Ambrose, 2013)。研究表明, 体育锻炼是保证身心健康的重要手段, 能够减少身体疾病(如, 心血管疾病和肥胖等)和心理疾病(如, 抑郁和焦虑等)的发病率(Huxley et al., 2014; Vankim & Nelson, 2013)。此外, 行为学研究也表明体育锻炼能够促进认知能力(Etnier et al., 1997)。从锻炼群体的角度讲, 体育锻炼能够促进包括未成年(Etnier, Labban, Piepmeier, Davis, & Henning, 2014)、成年人(Cox et al., 2016)以及老年人(Wong, 2017)等各类群体的认知功能。从锻炼特征的角度讲, 不同类型(如, 耐力训练、协调训练和拉伸训练)、强度以及持续时间的体育运动均能够促进认知能力(Etnier et al., 1997; Piepmeier, 2015)。从训练效果角度来讲, 体育锻炼也能提升不同类型的认知功能(如, 视觉记忆、听觉记忆、问题解决能力和认知控制能力等), 且促进效果能够在锻炼结束后维持一段时间(Chang, Labban, Gapin, & Etnier, 2012; Piepmeier, 2015)。

在行为层面, 研究包含的被试群体、锻炼类型和认知能力种类繁多, 因此需要元分析对结果进行统合(Hindin & Zelinski, 2012; Piepmeier, 2015)。一项元分析在纳入了近 200 项研究后发现体育锻炼能够正向预测认知能力。其中, 认知测验的类型和被试群体等因素能够对训练效果起到调节作用(Etnier et al., 1997)。进一步的, Chang 等(2012)的元分析探究了运动特征对认知功能的影响, 并发现当体育运动的强度非常剧烈, 且运动时间在 11 分钟以上时, 体育锻炼对认知功能的促进效果最强。

除了行为学和元分析的研究外, 也有研究借助生化学和影像学等技术, 从不同层面考察体育锻炼促进认知功能的脑机制。微观层面的研究多以实验动物为主, 不仅考察了体育锻炼对脑细胞内环境稳态(如, 营养摄入和能量代谢)和生化反应的影响, 也探究了体育锻炼对神经胶质细胞生成、神经元存活和突触发生(synaptogenesis)的影响(Leckie et al., 2014; Thomas, Dennis, Bandettini, & Johansen-Berg, 2012)。宏观层面的研究则多利用形态解剖和无创脑成像技术, 探究体育锻炼对脑结构(如, 灰质和白质体积等)和脑功能(如, 脑区激活水平和功能连接)的影响(Cotman, Berchtold, & Christie, 2007; Voss, Vivar, Kramer, & van Praag,

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2013)。本文将在简介行为学研究的基础上,重点介绍体育锻炼对认知功能影响的微观和宏观机制。

## 1 体育锻炼促进认知功能的微观机制

在微观层面上,营养的获得和能量的利用是神经元进行生命活动的必要前提(Bedi et al., 2003; Bélanger, Allaman, & Magistretti, 2011)。在充分营养供给和能量稳定代谢的基础上,细胞将高效地完成各类生化反应,合成维持神经元存活、突触建立所必须的神经递质和蛋白质等其他物质(Thomas et al., 2012)。体育锻炼能够影响上述的细胞活动过程,例如脑源性神经营养因子的研究表明体育锻炼能够对细胞内的生化反应产生影响(Piepmeyer, 2015)、而血管促进和脑疾病相关的研究则表明体育锻炼能够对细胞的营养供给和能量代谢产生影响(Carusio et al., 2015; Thomas et al., 2012)。

### 1.1 脑源性神经营养因子

脑源性营养因子(Brain Derived Neurotrophic Factor, BDNF)在体育锻炼促进认知能力的过程中起到促进作用。研究表明, BDNF 大量存在于海马和大脑皮层等负责高级认知功能(如,学习和记忆)的脑区(Hyman et al., 1991),能够通过如下两条途径促进认知功能。首先, BDNF 能够通过影响神经胶质细胞促进神经元的功能。例如, Xiong 等(2015)的研究发现, BDNF 能够提升小神经胶质细胞的健康水平。由于小神经胶质细胞在稳定神经元的物理网络结构方面具有重要的作用(Streit, 2002)。因此, BDNF 可能通过稳定和重塑神经元的物理结构提升认知能力。其次,在维持已有神经元存活的同时促进突触再塑。具体来讲, BDNF 能够通过影响包括钙调素激酶 II (calcium-calmodulin kinase II) 和丝裂原活化蛋白激酶(mitogen activating protein kinase)在内的细胞内信号转导系统促进环磷酸腺苷反应元件结合蛋白(cAMP responsive element-binding protein, CREB)的合成(Vaynman, Ying, Wu, & Gomez-Pinilla, 2006)。由于 CREB 在维持神经元存活以及突触可塑性(synaptic plasticity)的过程中至关重要(Dhar et al., 2014; Landeira et al., 2016),因此 BDNF 能够通过促进 CREB 的合成促进认知功能。

作为一种与脑可塑性密切相关的高分子蛋白, BDNF 的合成过程受到体育锻炼的影响(Piepmeyer, 2015)。基因层面的研究表明,体育锻炼能够通过影响能量代谢相关的神经调控因子 PGC-1 $\alpha$  调节

鸢尾素基因 FNDC5 的表达,最终促进 BDNF 的合成(Wrann et al., 2013)。而动物实验的结果表明,长期跑步训练能够诱发大鼠 BDNF 的合成,并通过提升神经胶质细胞的健康水平促进大鼠的空间记忆能力(Xiong et al., 2015)。最后,来自人类的研究发现,剧烈的体育锻炼或长期的散步均能够通过促进 BDNF 的合成提升中央执行功能、记忆和学习能力,而且年龄起到正向调节作用(Leckie et al., 2014; Piepmeyer, 2015)。因此,无论是对于实验动物还是人类,多种类型的体育锻炼均能够促进 BDNF 的合成,在对神经胶质细胞和神经元产生积极影响的同时提升认知功能。

### 1.2 血管促进

体育锻炼能够促进血管健康并增加脑血流量,在为大脑带来充足营养和能量的同时提升脑可塑性(Thomas et al., 2012)。以动物为对象的形态解剖学研究发现,相对于非运动组小鼠,运动组小鼠的脑皮层血管更加丰富(van der Borght et al., 2009),结果表明体育锻炼能够促进大脑血管生成。而影像学的研究也证明体育锻炼能够提升单位时间内流经大脑的血液总量(Gligoroska & Manchevska, 2012)。充足的血液供给不仅提供了细胞代谢所需的能量,还带来了丰富的营养物质。由于丰富的营养物质是某些脑再塑相关神经递质(如,去甲肾上腺素、肾上腺素和 5-羟色胺等)合成的必要前体物质(Brudzynski & Gibson, 1997; Girard & Garland, 2002; Meeusen et al., 1997)。因此体育锻炼能够通过改善细胞的血流环境,使神经元高效地进行生化反应,并最终促进神经元的存活和突触连接的建立。

体育锻炼能够促进脑血管生成,改善脑细胞的营养供给和能量代谢过程,并最终提升脑可塑性。但值得注意的是,血管生成并不能完全解释体育锻炼促进认知功能的全部机制。Colcombe 等(2004)的研究表明,虽然耐力训练能够直接提升血管的健康水平,但拉伸训练、协调能力训练等几乎不会影响血管生成的低强度运动同样能够促进认知功能。因此, Hötting 和 Röder (2013)指出在讨论体育锻炼促进认知功能的机制时,应考虑除了血管促进外的其它因素,并作出综合解释。

### 1.3 疾病干预

运动能够通过干预破坏内稳态的疾病起到保护脑可塑性和认知功能的作用(Hötting & Röder,

2013)。由于与新陈代谢相关的能量供给和与血液循环相关的营养供给是细胞进行生化反应的生理基础(Cotman et al., 2007), 因此代谢类疾病和循环系统疾病能够阻碍神经元的存活和突触的建立, 并进一步引发认知功能障碍(Stranahan & Mattson, 2012; Zochodne, 2014)。一项大样本的研究发现, 高血压、心血管疾病、心脏病以及其他类型的循环系统类疾病能够强烈预测认知功能的衰退; 而糖尿病这种代谢类疾病不仅能够导致认知功能的衰退, 还能提升阿尔兹海默症的患病风险(Haring et al., 2013)。

体育锻炼能够有效减少慢性炎症反应, 通过降低糖尿病和心血管疾病的发病风险保护认知功能(Espeland et al., 2017; Pedersen, 2017), 起到“防患于未然”的作用。相反, 减少体育锻炼不仅会提高罹患心血管疾病的风险, 还会进一步导致认知功能的衰退(Alosco et al., 2014)。另外, 对于已经罹患相关疾病的个体, 体育锻炼也能够起到“亡羊补牢”的作用。同样均患有二型糖尿病的个体, 经常运动的一组在认知测试中不仅拥有更好的成绩(Colberg, Somma, & Sechrist, 2008), 而且认知衰退的速度更慢(Caruso et al., 2015)。对于心血管病患者而言, 疾病对认知功能的影响也受到有氧运动的调节(Hayes, Alosco, & Forman, 2014)。相对于控制组, 进行了两周有氧运动的实验组患者表现出了更高水平的注意和中央执行功能(Tanne et al., 2005)。因此, 运动能够对认知能力起到“防患于未然”和“亡羊补牢”的双重保护作用。

## 2 体育锻炼促进认知功能的宏观机制

生化学研究从基因的翻译和转录、脑营养的供给和神经递质的合成等微观层面解释体育锻炼促进认知功能的生理机制(Leckie et al., 2014; Piepmeier & Aaron, 2015), 而形态解剖学和脑成像技术则能够从更宏观的层面描绘大脑特征。利用解剖学手段, 能够直接观察突触密度和皮层厚度等解剖学特征(Voss et al., 2013)。而利用影像学技术, 不仅能够对脑结构和脑激活模式进行无创观测(Friston, Frith, Liddle, & Frackowiak, 1993), 还能够利用大尺度脑网络分析等方法对全脑活动模式进行分析(Wang, Kang, Kemmer, & Guo, 2016)。

### 2.1 脑结构

体育锻炼对实验动物和人类的脑结构均有影

响(Voss et al., 2013)。来自啮齿动物的研究表明, 体育锻炼不仅能够提升海马齿状回中神经元树突棘的密度(Stranahan, Khalil, & Gould, 2007), 还能提升运动皮层的厚度(Anderson, Eckburg, & Relucio, 2002)及其血管总量(Swain et al., 2003)。对于人类而言, 难以使用形态解剖学手段对人脑进行观测, 但无创脑成像技术(如, 基于体素的形态学分析和弥散成像技术)提供了探索脑结构特征的有效途径(Ashburner & Friston, 2000; Pierpaoli, Jezzard, Basser, Barnett, & Di Chiro, 1996)。

影像学的研究表明, 体育锻炼能够对人类运动相关脑区的结构产生影响。最初的研究表明, 仅仅是规律性的散步就能提升辅助运动区(supplementary motor area)的脑体积(Colcombe et al., 2006)。后来, 研究开始关注体育锻炼、脑结构变化和运动相关认知能力的关系。例如, Ji等(2017)的研究发现, 6周的有氧运动能够提升老年人手部运动皮层、纹状体和小脑的灰质体积。由于纹状体可能和体育运动过程中的中央执行功能(如, 注意和加工运动相关的信息)相关(Ji et al., 2017), 且小脑和运动中的动作习得和精确化相关(Schonewille et al., 2011), 因此可以推测体育锻炼能够通过改变大脑结构促进个体运动相关的认知能力。

除了运动相关的脑区, 体育锻炼也能够对海马和新皮层等脑区的结构产生影响(Fabel et al., 2003; Hötting, Schauenburg, & Röder, 2012; Klempin et al., 2013; Köbe et al., 2016)。一些研究利用弥散张量成像(diffusion tensor imaging, DTI)技术, 对脑白质纤维束的体积进行估计, 结果发现有氧训练能够使海马体积提升2%~16%(Erickson et al., 2011; Pajonk et al., 2010)。此外, 一些研究利用体素形态学分析法(voxel-based morphometry, VBM), 在全脑水平对体素类型做判断, 结果发现6个月的有氧训练和拉伸训练均能提升老年人脑灰质和白质的体积(Colcombe et al., 2006), 降低背侧前扣带皮层、背外侧前额叶皮层、左侧颞叶(Voss et al., 2013; Ziegler et al., 2012)和顶叶(Ho et al., 2011)区域脑组织的流失速率。因此, 基于多方法的影像学研究均表明, 体育锻炼能够通过改变大脑结构促进认知功能。

### 2.2 脑活动模式

脑活动模式的改变是大脑发生重塑的重要指标之一, 意味着潜在的脑结构变化和认知能力的

改变(Hohenfeld et al., 2016; Hötting & Röder, 2013)。通过功能性磁共振技术(functional magnetic resonance imaging, fMRI), 不仅能够探测特定脑区在执行认知任务时的血氧依赖水平(blood oxygenation level dependent, BOLD), 还能探测多个脑区 BOLD 信号时间序列的相关水平, 即脑功能连接模式(Friston et al., 1993; Greicius, Krasnow, Reiss, & Menon, 2003)。

### 2.2.1 脑激活水平的改变

体育锻炼能够对运动相关脑区的激活水平产生影响。一项利用低频震荡技术(amplitude of low-frequency oscillation function, ALFF)的研究表明, 相对于锻炼前, 体育锻炼后被试脑岛、小脑和纹状体的活动水平显著提升(Ji et al., 2017)。由于脑岛、小脑和纹状体在运动控制和运动学习的过程中发挥重要作用(Fink, Frackowiak, Pietrzyk, & Passingham, 1997; Schonewille et al., 2011), 因此可以推测体育锻炼能够通过改变运动相关脑区的活动模式, 提升运动相关的认知能力。

除了运动相关脑区, 体育锻炼也能够对高级认知功能相关脑区的激活水平产生影响(Prakash, Voss, Erickson, & Kramer, 2015)。首先, 有些研究发现体育锻炼能够降低一些脑区的激活水平。例如, 有氧运动能够降低老年人前扣带回和儿童前额叶的激活水平, 并提升中央执行功能(Chaddock-Heyman et al., 2013; Colcombe et al., 2004)。而背后的机制则可能是体育锻炼能够通过提升突触连接效率(An, Zagaar, & Alkadhi, 2015; Christie et al., 2008), 使这些脑区在完成同样强度认知任务的同时消耗更少的能量, 并表现出较低的激活水平。其次, 有些研究发现体育锻炼能够增强某些脑区的激活水平(Holzschneider, Wolbers, Röde, & Hötting, 2012)。例如, 有氧训练能够提高青少年双侧顶叶(Chen, Zhu, Yan, & Yin, 2016)和老年人左侧枕叶、右侧颞上回等脑区的激活水平(Hsu et al., 2018)。而背后的机制则可能是有氧运动能够通过提升血管健康和脑血液供给使皮层激活水平增强(Holzschneider et al., 2012)。值得注意的是, 对于同一脑区, 体育锻炼对激活水平影响的方向存在跨研究的一致性(Chaddock-Heyman et al., 2013; Ji et al., 2017)。但对于不同脑区, 激活方向将可能由于作用机制的不同而存在差异。

### 2.2.2 功能连接的改变

复杂的认知任务不仅需要某些特定脑区的参

与, 也需要多脑区的协同配合(Burdette et al., 2010; Voss et al., 2010)。体育锻炼能够对运动相关脑区和高级认知功能相关脑区的功能连接产生影响(Chirles et al., 2017; Rajab et al., 2014; Voss et al., 2010)。

体育锻炼能够促进感觉运动相关脑区的功能连接, 并最终提升负责运动学习相关的认知能力(Rajab et al., 2014)。例如, Rajab 等(2014)的研究表明, 体育锻炼不仅能够促进静息状态下次级躯体感觉皮层(secondary somatosensory cortex)的本土连接水平, 使个体表现出更好的触觉注意力; 还能促进丘脑基底核本土连接的水平, 使个体更好地在运动学习过程中对奖赏做出反馈。

除了感觉运动相关的脑区, 体育锻炼还能促进高级认知功能相关脑区的功能连接。以中央执行功能为例, 相对于不进行运动的控制组, 运动组被试的纹状体和多个脑区(如, 丘脑、扣带回、颞叶、顶叶和枕区)的功能连接水平均有所提升, 其中纹状体和丘脑的功能连接程度能够正向预测运动组被试的中央执行功能(Ji et al., 2017)。此外, 体育锻炼也能对脑网络激活水平产生影响(Rajab et al., 2014)。例如, Voss 等(2010)的研究表明体育锻炼能够改变默认脑网络(default mode network)和额叶执行网络(frontal executive network)的激活模式, 并使老年人表现出较高的中央执行功能。而 Ji 等(2017)的研究也表明, 体育锻炼能够提高听觉相关脑网络活动的同步性(Rajab et al., 2014)。

## 3 宏观和微观机制研究的不足

### 3.1 微观机制

目前来讲, 虽然有大量研究探究了体育锻炼促进认知功能的微观生理机制, 但仍存在需要解决的问题。首先, 体育锻炼促进认知功能的具体机制仍需深入探讨(Erickson, Hillman, & Kramer, 2015)。在血管促进方向, 虽然有研究发现体育锻炼能够通过促进血管生成提升认知功能(Kim, Jeong, Won, Ka, & Oh, 2014; Roelofs, Smithryan, Trexler, Hirsch, & Mock, 2016)。但充足的血液供给能够通过提供丰富的营养促进脑可塑性的观点仍停留在理论推测阶段。未来需要更多研究考察营养供给、神经递质合成在脑血管生成和脑可塑性间发挥的作用。此外, 在疾病干预方向, 虽然 Espeland 等(2017)和 Pedersen (2017)从流行病学和行为测量

的角度明确了体育锻炼、疾病和认知衰退的关系,且 Anazodo、Shoemaker、Suskin 和 Lawrence (2013) 也证明疾病对脑结构的损伤程度会因运动程度的不同而存在差异,但运动在疾病和脑生化反应间的调节作用仍不明确。不同程度的运动如何调节患者大脑的营养供给和能量代谢过程,并最终影响脑结构和脑功能,需要在未来做进一步探究。

其次,现有研究结果尚待进一步统合。例如,虽然研究发现锻炼诱发的 BDNF 能够促进中央执行功能和记忆(Lee et al., 2014; Skriver et al., 2014),但 Tsai 等(2014)的研究发现锻炼诱发的 BDNF 不能够影响中央认知功能。不一致的研究结果可能由锻炼时长、强度和种类的不同引发,也有可能由被试群体和认知能力测量方式的不同所致,未来需做进一步整合。

最后,以人类为被试的基因学和生化学研究数量较少,且测量方式也不够直接。例如,虽然 Heyman 等(2012)的研究通过检测血浆中内源性大麻酚(endocannabinoids)的含量间接推测了人脑中 BDNF 的含量,但并未对 BDNF 的含量进行直接测量。因此,未来的研究应在伦理道德许可的条件下,设计更加巧妙的实验,对这一问题做深入的探讨。

### 3.2 宏观机制

宏观机制的研究也存在一些不足。首先,体育锻炼为什么对不同脑区激活程度的影响存在方向性差异,目前尚无定论。虽然研究发现体育锻炼可能以提升突触连接效率、减少神经元能耗的方式降低前额叶和前扣带回等脑区的激活水平(Chaddock-Heyman et al., 2013; Christie et al., 2008; Colcombe et al., 2004),也可能以促进脑血管生成的方式提升枕叶和颞叶等脑区的激活水平(Hsu et al., 2018; Holzschnieder et al., 2012)。但并没有研究关注为什么在不同的脑区,体育锻炼对脑激活水平的影响遵循了不同的机制。未来,需要综合脑血管生成、突触连接生成和神经元能量消耗等因素,对该问题做进一步探讨。

其次,不同特征的体育锻炼对脑结构和脑功能的影响仍不明确。行为学的研究提示,体育锻炼的特征会对认知功能的促进效果产生影响。相对于每次锻炼 20 分钟,每次 40 分钟的锻炼对认知能力的促进效果更强(Davis et al., 2011)。对于老年人而言,相对于每周锻炼一次,只有每周锻炼

一次以上才对认知功能有促进效果(Liu-Ambrose, Nagamatsu, Voss, Khan, & Handy, 2012)。虽然 Voelcker-Rehage 和 Niemann (2013)的梳理了不同类型体育锻炼对脑结构和脑功能的影响,但较少研究考察体育锻炼其他特征的作用。未来应结合形态解剖学和无创脑成像技术考察体育锻炼的频率、持续时间和强度对大脑的影响。

最后,体育锻炼对脑功能连接影响的研究仍处在起步的阶段(Hötting & Röder, 2013)。从被试群体的角度讲,大多数脑网络的研究样本仅局限于非健康个体(如,多发性硬化症和癫痫患者等)和老年人(Flodin et al., 2015; Ji et al., 2017; Koirala, Lee, Eom, Kim, & Kim, 2017),较少有研究以健康成年人和未成年人为被试。从功能连接类型的角度讲,目前关注的脑网络种类也较为单一,虽然 Voss 等(2010)的研究表明体育锻炼能够对默认脑网络和中央执行脑网路产生影响,但较少研究关注体育锻炼对全脑网络的功能整合和信息交换效率的影响。因此,未来的研究不仅应纳入更多类型的群体,还应结合大尺度脑网络分析等方法深入探讨体育锻炼对脑功能连接的影响。

## 4 总结与展望

### 4.1 总结

该部分旨在对体育锻炼促进认知功能的机制做出梳理。具体来讲,体育锻炼对认知功能的机制研究分为微观和宏观两个部分(图 1)。在微观层面上,体育锻炼对认知功能影响的生理机制涉及到内环境稳态、生化反应、神经元的存活和突触连接的建立(Prakash et al., 2015)。首先,体育锻炼能够改善神经元生存的环境(Caruso et al., 2015; Thomas et al., 2012)。血管促进和疾病干预的研究均认为,体育锻炼能够通过促进血管生成以及降低干扰内环境稳态的疾病,使神经元的营养供给和能量代谢处于稳定状态。其次,在稳定内环境的基础上,体育锻炼将促进细胞的内生化反应(Piepmeyer, 2015)。脑源性神经营养因子的研究表明,体育锻炼能够通过调节细胞内能量利用和基因转录等过程,促进 BDNF、CREB 等与脑再塑过程相关物质的合成。最后,在保证高效且稳定进行生化反应的基础上,体育锻炼将促进神经元的存活和突触的建立(Gligoroska & Manchevska, 2012; Xiong et al., 2015)。

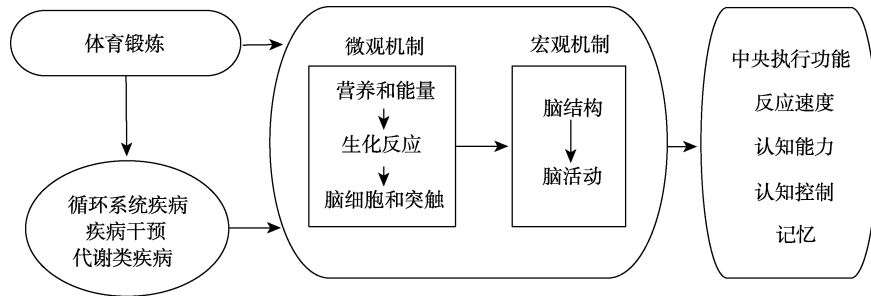


图1 体育锻炼促进认知功能的作用模式

在宏观层面上,体育锻炼引发的细胞和突触的变化将带来大脑宏观尺度的变化(Hötting & Röder, 2013)。首先,体育锻炼将引发脑结构的变化(Brown et al., 2003; Fabel et al., 2003; Köbe et al., 2016)。形态解剖和脑成像的研究均表明,体育锻炼能够减少灰质和白质这些脑组织的流失速率,并提升海马和小脑等脑区的体积。其次,脑结构的变化也将带来脑活动模式和认知功能的变化(Chaddock-Heyman et al., 2013; Chirles et al., 2017)。例如,体育锻炼不仅能够改变前扣带回、额叶等脑区的激活水平,也能够改变额叶执行网络、默认脑网络等多脑区间的功能连接水平,并最终提升中央执行功能等认知能力。

## 4.2 展望

### 4.2.1 影响锻炼效果的个体因素

体育锻炼能够提升各类群体的认知能力,但促进效果和作用机制可能因为锻炼群体(如,年龄、性别和健康水平等)的不同而不同(Etnier et al., 1997)。以年龄为例,相对于发育成熟且功能稳定的大脑,正在发育和衰老的脑更容易因为训练而发生改变(Blumen, Gopher, Steiner, & Stern, 2010; De Luca & Leventer, 2008)。研究发现,体育锻炼能够降低儿童执行注意控制任务中前额叶的激活水平(Chaddock-Heyman et al., 2013),提升青少年顶叶和左侧海马(Chen et al., 2016)以及老年人左侧枕叶、右侧颞上回等脑区的激活水平(Hsu et al., 2018),但无法促进成年人的中央执行功能(Hötting, Reich, et al., 2012)、语言记忆以及注意力(Stroth, Hille, Spitzer, & Reinhardt, 2009)。虽然有研究发现体育锻炼能够提升60岁以下中年人的记忆力(Hötting, Reich, et al., 2012),但进一步的元分析表明,相对于成年人(18~60岁),体育锻炼对未成年人(18岁以下)以及老年人(61~90岁)的促

进作用更强(Etnier et al., 1997)。

关于个体因素在体育锻炼和认知能力间的调节作用,仍是未来需要深入探讨的问题。首先,虽然充分的研究表明体育锻炼能够对未成年人和老年人的大脑产生积极影响(Blumen et al., 2010),但目前依然缺乏体育锻炼对健康成年人脑影响的影像学依据。此外,虽然行为学的研究表明性别、对运动的反应程度和健康水平等因素能够调节体育锻炼促进认知功能的效果(Etnier et al., 1997; Hötting & Röder, 2013),但同样缺乏相关影像学证据。未来也应考虑体育锻炼对大脑的影响是否会因为以上个体因素的不同而不同。

### 4.2.2 影响锻炼效果的时间因素

丰富且确凿的证据表明,体育锻炼能够促进认知功能(Gligoroska & Manchevska, 2012; Hötting & Röder, 2013)。但体育训练结束后,运动带来的认知功能提升是否能够继续保持、能够保持多久的问题同样值得关注。Rhyu等(2010)的研究发现,两个月的体育锻炼能够提升猴子大脑皮层的血管总量和学习能力,但当体育锻炼停止3个月后,皮层血管总量又会恢复至运动前水平。来自人类的研究结果与之类似,体育锻炼量降低到健康标准以下长达一年时,个体发生认知衰退的风险将会明显提升(Alosco et al., 2014)。因此,身体锻炼对认知功能的促进作用虽然是长期的,但促进效果会随着时间的流逝变小甚至消失。

关于体育锻炼对认知能力影响的长期效果,仍存在需要解决的问题。首先,虽然行为学的研究表明体育锻炼对认知能力的提升是长效的,但该后效的持续时间和伴随时间的衰减速率仍不明确。未来应纳入锻炼类型、个体特征等变量,考察不同特征的锻炼对于不同群体认知功能的长效作用。其次,在训练停止较长一段时间后,个体的

脑结构和脑活动模式是否恢复至原有水平,哪些类型的运动能够为大脑带来更持久的变化等问题仍不明确,未来应结合生化和脑成像技术做深入探究。

#### 4.2.3 认知刺激对锻炼效果的影响

行为学的研究表明,认知刺激在体育锻炼促进认知功能的过程中起到了“锦上添花”的作用。相对于单独的认知训练或体育锻炼,联合训练对认知能力的提升作用更强,其效果也能在训练结束后保持更长的时间(Bhere et al., 2017; Heisz et al., 2017; Shatil, 2013)。Rahe等(2015)的研究表明,单独的认知训练和联合训练都能够提升老年人的记忆,但联合训练的效应量更高。在训练结束一年后,联合训练对记忆力的提升效果仍然存在,而认知训练组被试的记忆成绩和前测已无显著差异。类似的,Heisz等人(2017)也发现,相对于单独的体育锻炼或认知训练,联合训练能够更有效地促进健康成年人的记忆力。

在微观层面上,认知刺激促进锻炼效果的脑神经机制已被初步探讨。研究表明,体育锻炼能够使海马前部齿状回亚颗粒区的前体细胞快速增殖(Kempermann et al., 2010),但却不能维持新增细胞的存活和整合进已有的功能网络(Kronenberg et al., 2006)。而相对于体育锻炼,认知训练并不能促进前体细胞的激增,但却能够防止新增细胞的凋亡(Kronenberg et al., 2006),并促进新突触的生成和连接(Choo et al., 2017)。因此,联合训练能够通过提供丰富的认知刺激使体育锻炼诱发的新生细胞功能化,并最终促进认知功能的提升效果。

伴随了认知刺激的体育锻炼能够更好地促进认知功能,但相应的脑神经机制仍需进一步探讨。首先,现有微观机制的研究仅仅局限于海马脑区,额叶和扣带回等其它脑区是否遵循相同的机制,目前仍不明晰。其次,宏观机制的研究存在明显不足。虽然Holzschneider等(2012)的研究发现体育锻炼和空间记忆训练的联合训练能够提升海马等脑区的激活水平。但其他类型的联合训练对脑结构、脑区激活水平和脑区间功能连接模式的影响仍不明晰,未来需要结合影像学手段做进一步探讨。

## 5 结论

总结来说,体育锻炼对认知功能影响的研究

目前取得了丰硕的成果。来自行为学和元分析的研究表明,体育锻炼不仅能够提升身体健康水平,还能够促进记忆、中央执行功能等认知能力(Etnier et al., 1997; Piepmeyer, 2015)。除了行为层面的研究,生化学和基因学的研究从微观层面入手,讨论了体育锻炼对脑细胞生成、存活和突触连接建立的影响(Prakash et al., 2015)。最后,影像学和形态解剖学的研究也提供了体育锻炼对大脑结构和功能影响的宏观证据(Hötting & Röder, 2013)。未来,不仅应进一步探讨相关生理机制的不明晰之处,还应重点考察个体特征、时间以及认知刺激等因素在体育锻炼、脑神经活动以及认知功能间的调节作用。

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## The brain mechanisms of the physical exercise enhancing cognitive function

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**Abstract:** It has been identified that physical exercise is able to enhance cognitive functions, attracting attention to the underlying brain mechanisms. The literature shows that the enhancing effects rely basically on two distinct mechanisms, on the microscale and macroscale levels, respectively. At the microscale level, physical exercise favored synaptogenesis and the survival of neurons through better nutrient supply and metabolism. At the macroscale level, physical exercise could enhance cognition through enlarging the volume of white and grey matter, and changing the brain activity and functional connectivity. Notably, multiple factors could influence the enhancing effects of physical exercise on cognition, such as individual differences, time, and the interaction between physical exercise and cognitive stimulations. These factors provide new directions to conduct deep and systematic investigations on the brain mechanisms of enhancing effects on the two levels.

**Key words:** physical exercise; cognitive enhancement; brain imaging; brain derived neurotrophic factor; synaptogenesis