

· 理论与史 ·

# 基底神经节在语言理解中的作用\*

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**摘要** 基底神经节的功能研究已超越传统运动调控范畴, 在语言加工领域取得重要进展。早期研究侧重其与言语产出的关系, 最新研究则揭示了其在语言理解中的作用及核团的功能特异性。研究发现, 尾状核与壳核广泛参与语义、句法与语用加工, 其中壳核对语音加工有独特贡献; 苍白球与丘脑底核主要与言语产出相关, 但也参与语言理解。此外, 基底神经节内的儿茶酚胺能系统通过皮层-基底神经节通路影响语言理解。现有语言模型提示, 未来研究需进一步探讨基底神经节不同核团及儿茶酚胺能系统在语言理解中的具体机制, 特别是其调控作用是否具有语言特异性。

**关键词** 基底神经节 语言理解 儿茶酚胺能系统 语言特异性

## 1 引言

基底神经节 (basal ganglia) 是大脑皮层下一组神经核团组成的功能整体, 与大脑皮层存在广泛连接 (Graybiel, 2000)。在解剖结构上 (见图 1), 基底神经节主要包括纹状体 (striatum)、苍白球 (globus pallidus, GP)、丘脑底核 (subthalamic nucleus, STN) 和黑质 (substantia nigra, SN)。其中, 背侧纹状体包括尾状核 (caudate) 和壳核 (putamen), 腹侧纹状体则由伏隔核 (nucleus accumbens, NAc) 构成。基底神经节与大脑皮层、丘脑和脑干相连, 构成复杂的神经网络。作为基底神经节的主要信息输入结构, 纹状体接收来自大脑皮层和丘脑等脑区的兴奋性输入, 这些信息通过直接和间接通路传递至其他核团, 如苍白球和黑质。在直接通路中, 信号从纹状体传递至内侧苍白球 (globus pallidus internus, GPi), 通过减少内侧苍白球对丘脑-皮层通路的抑制性输出, 从而增强皮层活动, 促进运动行为和认知加工; 间接通路同样起始于纹状体, 通过外侧苍白球 (globus pallidus externus, GPe) 和丘脑底核影响内侧苍白球活动, 增加对丘脑-皮层通

路的抑制性输出, 从而减少皮层的兴奋性作用。丘脑将调控后的信息反馈至多个大脑区域, 包括额下回、背外侧前额叶皮层、扣带回、后顶叶皮层、左侧颞中回、楔前叶以及辅助运动区等, 从而形成完整的神经环路。

基底神经节通过复杂而精细的环路结构参与运动和多种认知功能 (Graybiel, 2000)。早期研究主要聚焦于其在运动控制中的作用, 揭示了基底神经节参与运动准备、动作控制、动作选择和运动学习等过程 (Graybiel et al., 1994)。近二十年来, 越来越多的证据表明, 基底神经节在更广泛的认知功能中发挥着重要作用, 尤其在注意 (van Schouwenburg et al., 2015)、序列加工 (Liu et al., 2021)、执行控制 (Wei & Wang, 2016) 和语言加工 (Copland et al., 2021; Snijders et al., 2010) 等功能上至关重要。来自基底神经节病变患者、脑深部刺激 (DBS) 和心理药理学的研究提供了其在语言加工中的因果性证据, 改变了传统的、以皮层为中心的语言模型。

基底神经节在语言加工中的研究起源于对基底

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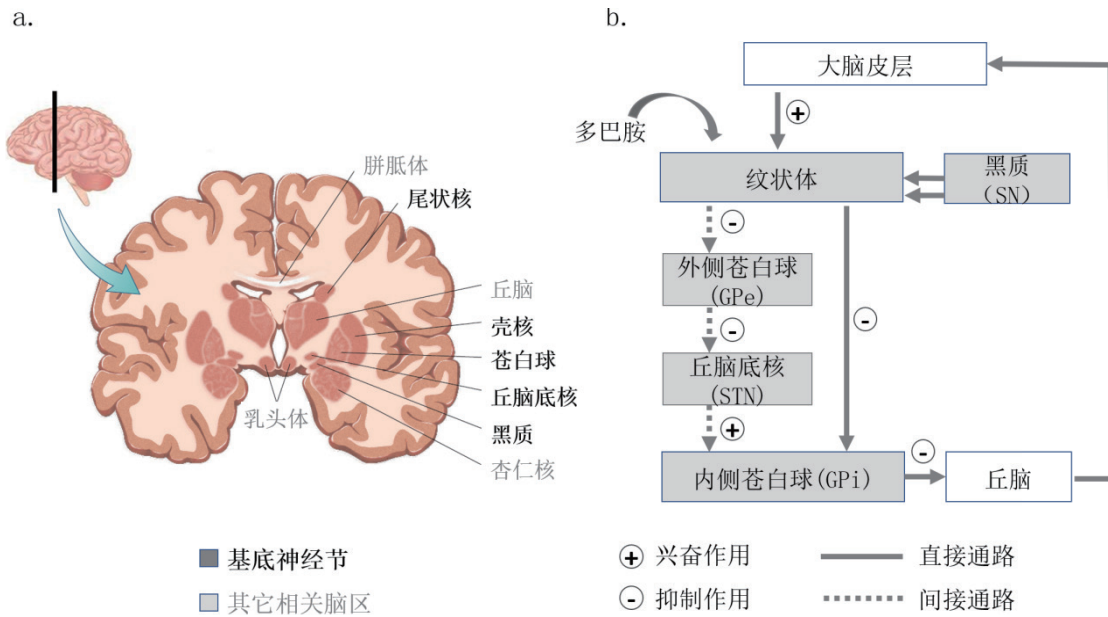


图 1 基底神经节核团的基本结构及其主要连接通路

注：(a)基底神经节及其相关结构<sup>①</sup>。(b)基底神经节主要连接通路简要示意图<sup>2</sup>。直接通路中，纹状体接收来自大脑皮层和丘脑的兴奋性输入，信号传递至内侧苍白球（GPi），减少对丘脑的抑制，增强兴奋性作用。间接通路则通过外侧苍白球（GPe）和丘脑底核（STN）增加对丘脑的抑制，从而降低丘脑对皮层的兴奋性作用。丘脑将调控后的信息反馈至大脑多个区域，形成完整的神经环路。

神经节损伤患者言语产出障碍的观察。言语产出依赖于发声器官的精细协调，而这些运动由运动皮层和基底神经节等区域调控（Silveri, 2021）。基底神经节损伤，如帕金森病（Parkinson's disease, PD）和亨廷顿氏病（Huntington's disease, HD），常伴随构音障碍、发音困难、流畅性下降，甚至严重重复性言语（Benke et al., 2000; Moro-Velazquez et al., 2021）。最近的元分析研究表明，这些言语产出障碍不仅源于基底神经节在运动控制中的缺陷，更关键的是，它们反映了基底神经节-皮层网络在概念/词汇选择中的调控功能障碍（Camerino et al., 2024）。这挑战了传统的 Broca-Wernicke-Geschwind 语言模型，强调基底神经节在语言加工中的重要作用。有研究者提出，纹状体是语言处理的关键脑区，尤其支持语法规则的加工（Copland et al., 2021）。

但迄今为止，有关基底神经节在语言理解中的研究较为有限。语言理解作为语言认知的重要组

成部分，与语言产出共享部分神经资源，但二者涉及的认知神经机制并不完全相同（Giglio et al., 2024）。相较语言产出的自上而下运动控制，语言理解涉及更多自下而上的信息加工过程，依赖语义激活、句法整合以及语用推理的动态协作（Meyer et al., 2016），这些过程与基底神经节的潜在关系尚不明确。此外，基底神经节并非单一功能结构，其不同核团在语言加工中的角色可能各不相同。另一方面，基底神经节的调控机制是否具有语言特异性仍存在争议。基底神经节与核心语言网络（如左前额叶和颞叶）的协作可能表现出一定的语言特异性，对语言加工进行直接调控（Snijders et al., 2010）；同时，作为多需求网络的一部分，基底神经节可能通过调节执行控制功能影响包括语言在内的更广泛的认知任务（Copland et al., 2021）。因此，探究基底神经节不同核团在语言理解中的功能分工及其在多任务场景下的动态调控机制，不仅能深化对语言理解与言语产出之间认知神经机制差异的认识，还能拓展现有语言加工模型的解释力，并为基底神经

<sup>①</sup>改编自周晓林, 高定国等译(2023)《认知神经科学: 关于心智的生物学》(第五版, 图 2.33)[M]. 北京: 中国轻工业出版社. 2 参考 Graybiel, A. M. (2000). *The basal ganglia*. *Current Biology*, 10(14), R509-R511.

节相关语言障碍的诊断与干预提供新的理论视角与临床路径。

本综述系统整合基底神经节参与语言理解的神经机制研究,围绕三个关键议题展开讨论:首先,核团功能特异性问题—基底神经节不同核团(如纹状体、苍白球)在语言理解不同层面(语音、语义、句法、语用)上的功能分化及其与皮层网络的动态协同机制;其次,神经递质调节问题—广泛分布于基底神经节内的儿茶酚胺能系统(如多巴胺、去甲肾上腺素),如何通过基底神经节-皮层通路调节语言理解;最后,语言特异性调控作用争议—基底神经节在语言理解中的作用究竟反映领域一般性的认知控制(如执行控制、冲突监控),还是语言特异性的计算需求。本文最后提出未来的研究方向,指出需要结合神经心理学、神经成像及心理药理学等多维度证据,建立计算神经模型,统一解释基底神经节在语言理解中的动态调控/调节角色。

## 2 基底神经节对语言理解的调控作用

语言理解是人类大脑复杂认知功能的核心领域,涉及广泛的皮层脑区,主要包括左侧额下回的缘区和三角区以及左后侧颞中回(Fedorenko et al., 2024)。越来越多的证据表明,基底神经节也在调控语言理解的各个方面发挥关键性作用。下面我们将详细探讨基底神经节内各核团(如尾状核、壳核、苍白球和丘脑底核)在不同语言加工层次中的具体调控机制,并分析其与大脑皮层的功能性连接如何支持语音、语义、句法和语用等层面的语言加工。

### 2.1 尾状核对语言理解的调控作用

词汇-语义加工指的是词汇意义的解析与理解过程(Hagoort & Indefrey, 2014)。神经心理学研究发现,帕金森病患者的尾状核活动减弱与他们的语义理解障碍显著相关(Roesch-Ely et al., 2006; Skeel et al., 2001)。患者和健康人群中的脑功能成像研究发现,尾状核参与多种词汇语义任务,包括语义选择(Ketteler et al., 2008)、语义联想(Tiedt et al., 2022)、语义控制(Ali et al., 2010; Rabini et al., 2023)以及处理句子或语段中的语义违反(Mason & Just, 2007; Mestres-Missé et al., 2014)等。最近

的功能连接分析显示,在同义词辨别任务中,尾状核与左侧额下回及腹侧前额叶连接增强(Wu & Hoffman, 2024)。这些研究普遍支持下列看法:尾状核在词汇-语义加工过程中,通过影响丘脑对皮层语义网络(如左侧额中回、双侧额下回、右侧颞中回和双侧下顶叶)的激活,参与调控和监管语义的提取与选择,从而选择目标语义信息并抑制非目标语义信息的激活(Cocquyt et al., 2019)。然而,也有研究者认为,尾状核在语义加工中的激活可能与其在奖赏回路中的作用有关,而非直接参与语义加工。例如,Rabini等人(2023)发现,在成功检索复杂语义知识时,尾状核与眶额皮层和伏隔核共同激活,但这些区域与被试整体语义加工能力似乎并无关联。

尾状核也在句法理解、特别是复杂句法结构加工中扮演重要角色。句法结构加工是将词汇依据语法规则整合为短语或句子的过程,通常与左侧额下回的功能相关(Hagoort & Indefrey, 2014)。Ullman在2001年就提出,纹状体是语言处理的关键脑区,尤其支持语法规则的加工(Ullman, 2001)。已有研究揭示,帕金森病患者在阅读存在句法违反的句子时,其相关的脑电效应(P600效应,波幅与句法加工难度成正比)显著弱于健康对照组(Friederici et al., 2003),且患者的句法加工障碍与基底神经节受损引发的运动障碍相对独立(Johari et al., 2019; Teichmann et al., 2015)。在健康人群中,神经成像研究显示,句法加工难度增加时尾状核出现显著激活,尤其在参与处理形态句法违反(Kuperberg et al., 2008)、句法歧义(Mestres-Missé et al., 2012; Snijders et al., 2010; Snijders et al., 2009)、非典型语序句(Teichmann et al., 2005; Teichmann et al., 2008; Ye et al., 2012)以及复杂句(Thibault et al., 2021)时。Mestres-Missé等人(2012)提出,尾状核的激活模式与句法复杂度密切相关。尾状核头部的后部和前部在句法加工中的激活呈现梯度变化:后部参与处理句法歧义或违规,而前部仅在处理最为复杂的句法歧义句时显著激活。最近,研究者进一步提出,尾状核和苍白球在加工语言内部语法规则时具有特异性,它们不参与音位规则加工(Seyfried & Uddén, 2023)。综上,尾状核在抑制错误/非偏好

句法结构，并激活正确句法结构的加工过程中发挥重要作用。

近年来，一些研究者指出，尾状核在语用加工中也扮演重要角色，这可能与基底神经节在社会性加工中的作用密切相关（Adolphs, 2001）。语用加工是指在语言理解和交流中，借助语境与背景信息推断说话者意图、含义及非字面意义的过程（Levinson, 1983），包括理解言外之意、言语行为以及社会规范。帕金森病患者在语用加工上存在障碍，表现为无法使用礼貌策略、缺乏话题连贯性、难以保持对话流畅等（McNamara & Durso, 2018）。McNamara 和 Durso（2018）认为，基底神经节通过调节社交脑网络（包括纹状体、边缘系统、内侧前额叶皮层和脑岛等）支持个体在语言交流中进行社交推理、情境判断和情感互动；基底神经节损伤可能破坏这些功能，从而影响患者的语用加工能力。健康人群的神经成像研究也发现，双侧尾状核/壳核在涉及语用推理时显著激活，且与右侧额下回和双侧颞上回的连接增强（Zhan et al., 2017）。当违反语言中的预设时，双侧尾状核的激活与句子的可接受度评分相关（Dietrich et al., 2019）。这些研究表明，尾状核可能在监测、评估和调控语用加工中发挥关键作用。

## 2.2 壳核对语言理解的调控作用

壳核是背侧纹状体的另一组成部分，在感觉运动协调、强化学习和言语产出中发挥重要作用（Viñas-Guasch & Wu, 2017）。在言语产出过程中，（左侧）壳核在发声、复述、命名等任务中显著激活（Desai et al., 2006）。壳核前部和后部在言语产出中可能具有不同功能——前部负责处理伪词和不规则单词的发音计划和语音编码，而后部主要参与基于记忆的熟悉语音输出的运动协调（Oberhuber et al., 2013）。

壳核在语言理解的多个方面也发挥作用（Ullman et al., 2024）。首先，壳核对语音理解起关键调控作用。尽管壳核与尾状核经常在语言理解任务中共同激活，然而，与尾状核在语义、句法和语用加工中的主导作用不同，壳核在多项研究中表现出与语音理解的密切联系（Booth et al., 2007; Cherodath et al., 2017; Wang et al.,

2019）。语音理解涉及识别、分辨和处理语言声音结构，这一过程需要多个皮层结构的协调，包括左侧颞上回、前额叶皮层、辅助运动区和脑岛等（Hickok & Poeppel, 2004）。Booth 等人（2007）发现，左侧壳核在韵律判断任务中显著激活，并与语音加工相关的皮层结构存在单向输出，表明壳核可以向大脑皮层发送信号，协调语音加工相关的脑区活动。儿童研究发现，双侧壳核在韵律判断任务中的激活显著高于拼写判断任务，进一步支持了壳核在语音理解中的独特作用（Bitan et al., 2007）。基于发展性语言障碍的证据显示，患者的壳核体积以及壳核与其它皮层区域的结构连接，相比健康对照组存在异常（Pigdon et al., 2019; Ullman et al., 2020），表明壳核的结构与功能变化可能是语音加工障碍的重要神经基础。

壳核在词汇-语义和句法加工中也发挥重要作用（Abutalebi & Green, 2016）。相比健康人群，帕金森病患者加工动作动词时，壳核与基底神经节内其它核团的连接显著减弱，且壳核体积减少与其对替代性通路（内侧扣带回和扣带旁回）的依赖程度成正相关（Abrevaya et al., 2016），表明帕金森病患者通过激活非运动网络补偿受损的基底神经节功能。Viñas-Guasch 和 Wu（2017）的元分析结果显示，左侧壳核的前部在词汇语义提取、理解和产出中起关键作用，且主要与左半球语言加工脑区（如额下回、额中回、颞上沟、楔前叶）以及语言控制脑区（如左侧扣带回、苍白球和前运动皮层）协同激活。左侧壳核的后部则主要参与句法语义加工，与左侧额中回、颞中回以及左半球语言加工脑区的右侧同源区域、右岛叶及双侧小脑协同激活。相比之下，右侧壳核在语言处理中的作用较为次要，但与左侧壳核协同参与语言的理解和产出。右侧壳核除了与语言加工核心脑区协同激活，还与左侧梭状回共同激活，参与字形识别和正字法信息整合。

## 2.3 苍白球和丘脑底核对语言理解的调控作用

苍白球和丘脑底核均在运动控制中起重要作用（Klostermann et al., 2008; Manes et al., 2018），常作为脑深部刺激（DBS）手术的主要靶点。而现有证据表明，这两个核团也在言语产出中扮演重要角

色。电刺激过度活跃的苍白球和丘脑底核可显著改善运动症状（Deep-Brain Stimulation for Parkinson's Disease Study Group, 2001），但 DBS 也可能导致语言流畅性下降和语言切换障碍等问题（Cai et al., 2024; Manes et al., 2014; Vos et al., 2021）。

然而，关于苍白球与丘脑底核是否参与语言理解过程，目前尚无定论。一些研究认为，苍白球与丘脑底核在语言理解的多个方面发挥作用。Bahlmann 等人（2008）发现，左侧苍白球和双侧尾状核参与加工人工句法，且无论句法是否正确左侧苍白球均有激活。也有研究发现，丘脑底核在语义（De Letter et al., 2020; Tiedt et al., 2017）和语用（Brück et al., 2011）加工过程中发挥作用。Tiedt 等人（2017）记录了被试在语音或语义启动范式下基底神经节的 EEG 信号，发现丘脑底核在启动词阶段显著激活，而在目标词阶段没有显著激活，表明它在语言理解中参与行为准备和执行控制。De Letter 等人（2020）的 DBS 研究显示，帕金森病患者在加工动作动词时，丘脑底核的局部场电位对动作动词（如“扔”）的反应强于心理动词（如“希望”），说明丘脑底核在语言理解中帮助快速识别与动作相关的线索。此外，Péron 等人指出，丘脑底核在辨别语音中的情绪信息时发挥重要作用（Péron et al., 2016; Péron et al., 2017）。

但另一些 DBS 研究并未发现苍白球与丘脑底核对语言理解的影响（Tremblay et al., 2015; Wahl et al., 2008）。例如，Wahl 等人（2008）同时记录了病人在进行语言理解时基底神经节和大脑皮层上的电信号，虽然在大脑皮层与丘脑腹侧中间核上都观察到了语义（N400）与句法（ELAN, P600）加工的经典 ERP 效应，但内侧苍白球和丘脑底核上却没有相关的 ERP 效应，表明二者可能并不直接参与丘脑-皮层网络的语义/句法加工。Tremblay 等人（2015）发现，DBS 刺激丘脑底核可以显著提高帕金森患者的运动能力，但对他们的语义和语用加工没有显著影响。综上，尽管当前以 DBS 和磁共振为主的实验手段揭示了苍白球和丘脑底核在语言理解过程中的潜在作用，但由于实验任务和被试群体的差异，它们的具体功能仍存在争议。

#### 2.4 儿茶酚胺能系统在语言理解中的作用

为了更系统地理解基底神经节在语言理解中的作用，研究不仅要关注各个核团的功能，还需深入探讨儿茶酚胺（Catecholamine, CA）能系统的调节作用。儿茶酚胺，包括多巴胺和去甲肾上腺素，在结构和功能上与基底神经节密切相关。其中，多巴胺主要合成于中脑黑质与腹侧被盖区，传递至纹状体、前额叶皮层等多个脑区，通过影响纹状体-大脑皮层的功能连接强度，调节运动、奖惩、语言等认知功能（Cools & D'Esposito, 2011）；去甲肾上腺素主要合成于脑桥蓝斑，传递至纹状体、小脑等多个脑区，调节注意、记忆和反应抑制等认知功能（Unsworth & Robison, 2017），并进一步对语言加工产生影响。

近年来，CA 能系统在语义理解中的调节作用成为一个重要研究方向。早期关键证据来自帕金森病患者，患者因黑质多巴胺能神经元丢失导致多巴胺水平下降，表现出语义激活速度减慢（Angwin et al., 2007）、歧义词加工困难（Ketteler et al., 2014）和语义抑制受损（Copland et al., 2009）等障碍。此后，心理药理学研究发现，CA 促进剂（如左旋多巴）能提高词汇层面对高频语义信息的加工，抑制低频语义信息的加工，从而增强语义激活的集中性（Andreou et al., 2014; Kischka et al., 1996; Roesch-Ely et al., 2006），这一过程与左侧颞中回的激活增强和前扣带回和背侧前额叶皮层的抑制相关（Copland et al., 2009）。Tan 和 Hagoort（2020）进一步揭示，CA 促进剂可促进句子层面的语义理解，增强被试对语义违反的敏感度。

CA 能系统对句法加工也有调节作用。帕金森病患者在处理复杂句法结构时存在困难（Bocanegra et al., 2015; Colman et al., 2011）；服用 CA 促进剂后，患者的复杂句理解能力显著改善（Grossman et al., 2001）。Novakova 等人（2023）发现，在加工复杂句法时，健康人群右侧纹状体与辅助运动区的功能连接强度与理解正确率正相关，而帕金森病患者的连接强度与理解正确率负相关，表明多巴胺能神经元的丧失可能影响了纹状体-额叶通路在句法理解中的功能。

CA 能系统在语用加工中的作用也备受关注。帕金森病患者在理解间接回答以及非字面意义

(Monetta et al., 2009) 时存在加工障碍。例如, 帕金森病患者难以理解影响言外之意 (Holtgraves & McNamara, 2010), 在幽默、隐喻和反讽理解中表现不佳 (Baraldi et al., 2021; Chahine et al., 2021; Humphries et al., 2019; Montemurro et al., 2019; Tremblay et al., 2015)。

综上所述, 已有证据初步显示, 基底神经节通过 CA 能系统对语言理解多个方面产生显著调节作用。然而, 目前关于这些神经递质具体如何参与语言加工以及它们与基底神经节之间功能交互的细节仍有待更深入的探索与验证。未来研究应更加系统地整合神经成像、临床病例及心理药理学等手段, 明确儿茶酚胺能系统在语言加工中的精细作用机制。

### 3 基底神经节在语言理解中的作用：语言特异性还是领域一般性？

已有的实验研究和模型说明, 基底神经节的功能不仅包含传统的运动协调, 也涉及语言理解的各个方面。一个重要的问题是, 基底神经节在语言理解中的调控作用是语言特异性 (language-specific) 的, 还是领域一般性 (domain-general) 的? 语言特异性观点认为, 纹状体对语言有区别于对其它认知功能的特殊调控机制 (Jacquemot & Bachoud-Lévi, 2021); 而领域一般性观点认为, 基底神经节采用同样的机制, 在语言任务和其它非语言任务中管理信息流动与认知资源分配 (Copland et al., 2021)。近年来, 大样本脑成像研究表明, 大脑的核心语言网络 (如左前额叶和颞叶) 对语言加工具有特异性; 而多需求网络 (双侧前额叶, 顶叶, 扣带回, 岛叶等区域) 则呈现出领域一般性 (domain-general), 参与包括语言加工、记忆、注意在内的多种认知任务 (Blank & Fedorenko, 2017; Fedorenko et al., 2012; Fedorenko et al., 2024)。然而, 基底神经节在语言理解中是否具有特异性尚不明确。对这一问题的考察有助于回应心理语言学长久以来的核心争议——语言加工是依赖领域一般性的神经计算资源, 还是具有独特的神经基础 (Caplan & Waters, 1999; Hsu et al., 2021; Tan et al., 2017)。

#### 3.1 基底神经节的领域一般性作用

现有研究普遍支持基底神经节在语言理解中具有领域一般性功能观点, 认为其在语言与非语言任务中功能相似, 均通过调控个体执行控制功能, 影响被试的任务表现 (Crescentini et al., 2008; Dominey et al., 2009; Hervais-Adelman et al., 2015; Ludlow et al., 1987; Thibault et al., 2021)。例如, Thibault 等人 (2021) 发现, 句法理解与工具使用激活了相似的神经网络, 包括额顶叶网络和基底神经节 (左侧尾状核、双侧内侧苍白球和壳核), 且这一重叠并不能单纯用工作记忆或运动控制来解释。工具使用与句法训练之间的双向迁移效应进一步支持了共享认知神经机制的存在。双语研究也发现, 语言切换任务与非语言切换任务激活了共同的脑区, 如左侧额下回、丘脑、尾状核和壳核 (Abutalebi & Green, 2016; Sulpizio et al., 2020; Tao et al., 2021)。

基于这些证据, Copland 等人 (2021) 提出一个语言加工的皮层-纹状体通路调控模型 (corticostriatal regulation of language functions)。该模型认为, 纹状体与脑岛、额叶协同工作, 在完成高负荷语言加工时 (如语言学习、多语切换、句法歧义) 发挥领域一般性 (而非语言特异性) 的调控作用, 即这个调控作用是通过影响一般性的认知控制功能, 包括处理不确定性、解决备选项之间的竞争以及对信息进行排序和选择, 从而影响语言加工。模型强调皮层-纹状体通路的调控机制具有动态特性, 会随着认知控制需求的增加而更加活跃, 以适应任务的认知负荷与不确定性。纹状体在不同任务中分工明确: 尾状核负责选择和监控, 壳核则负责执行控制。这一假设得到了神经成像、临床人群以及心理药理学研究的支持, 这些研究共同发现, 纹状体在语言加工和非语言执行控制任务中都与丘脑、前额叶皮层共同激活 (Korb et al., 2017; Mestres-Missé et al., 2017; Snijders et al., 2009)。

#### 3.2 基底神经节的语言特异性作用

然而, 也有研究认为, 基底神经节对语言加工的影响可能具有语言特异性 (Chan et al., 2013; Crescentini et al., 2008)。一些研究发现, 基底神经节病变患者的语言理解障碍与其一般性认知控制能力的损伤程度缺乏关联 (Grossman et al., 1992;

Sambin et al., 2012; Troyer et al., 2004)。例如, Grossman 等 (1992) 发现, 帕金森患者的语言理解障碍与他们的记忆力、注意等认知功能测验成绩无显著相关; Sambin 等 (2012) 发现, 亨廷顿病患者的句子理解困难并非源于记忆负荷损伤。此外, Chan 等人 (2013) 的 fMRI 研究表明, 前额叶-纹状体通路在语言任务中的敏感性高于非语言任务, 进一步支持基底神经节对语言加工的特异性调控作用。

基于这些证据, Jacquemot 和 Bachoud-Lévi (2021) 提出了语言加工解剖-功能整合模型 (anatomico-functional integrative model of language)。该模型强调纹状体在语言加工 (包括语言理解与言语产出) 中的核心作用: 首先, 纹状体作为中心节点, 与多个语言皮层区域连接, 参与调控形态、词汇语义、句法和语音各个层面的语言加工; 其次, 纹状体通过与前额叶皮层的连接, 调控执行控制和注意力等认知资源, 从而间接影响复杂语言加工的效率 and 流畅度; 最后, 左侧尾状核负责资源分配和语言内容的跟踪, 左侧壳核则与运动皮层共同激活, 参与言语产出和理解。该模型强调语言加工过程与工作记忆等认知功能的交互作用; 更重要的是, 该模型提出纹状体在调控认知资源时具有语言特异性, 某些特定方面似乎专门服务于语言, 这种专门化表现为独立的额叶-纹状体网络, 支持语言特定的执行功能, 并在语言任务中表现出比其他任务更高的调控精确性和复杂性 (Ali et al., 2010; Stanc et al., 2024)。

总之, 纳入基底神经节的语言模型均强调语言加工 (未区分理解与产出) 与执行控制之间的密切互动。尽管大量证据支持基底神经节主要通过领域一般性的认知控制功能参与语言加工, 但其在特定任务 (如句法加工) 中仍表现出更为精细的调控能力。然而, 这些模型存在一定的局限: 首先, 纹状体通过执行控制影响语言加工的具体机制仍不明确; 其次, 其研究焦点集中于纹状体-前额叶通路, 忽略了基底神经节其他核团 (如苍白球、丘脑底核) 的潜在作用。未来研究需进一步解析基底神经节在语言加工中的具体作用机制, 明确其对语言理解与言语产出中的差异化调控, 并深入探讨其与其他认知过程的交互关系。

#### 4 总结与展望

本综述整合了基底神经节病变患者、神经成像以及心理药理学研究, 揭示基底神经节在语言理解中的独特作用及各核团的功能差异。结果表明, 尾状核与壳核在语义、句法和语用加工中起关键作用, 壳核则在语音加工有独特贡献。苍白球主要与句法加工和发音控制相关, 而丘脑底核则调控语义和情绪韵律的语用处理。此外, 基底神经节中的儿茶酚胺能系统也参与调节语义激活、句法加工甚至语用理解。

尽管已有研究揭示了基底神经节在语言理解中的多方面作用, 有一些问题亟待进一步探索。首先, 亟需深入探讨基底神经节不同核团在语言理解中的功能分工及其协同机制。当前研究多将基底神经节视为功能整体, 或仅关注特定核团 (尤其是尾状核、壳核) 的独立激活模式, 缺乏对核团-核团、核团-皮层交互机制的系统分析。未来研究应借助高分辨弥散成像、分层功能磁共振成像 (laminar fMRI)、颅内电生理记录以及心理药理学等技术, 揭示各核团在语音、语义、句法等层面上如何分工并通过环路协同, 从而厘清基底神经节在语言理解中的深层贡献。

其次, 需要进一步考察基底神经节在语言理解中的作用是否具有语言特异性。未来的研究需要对比更广泛的语言与非语言实验任务, 并结合毫秒级 MEG/EEG、颅内电生理记录、超高场 fMRI 与计算建模, 更精细地描绘基底神经节各个核团在语音感知、语义理解、句法理解及语用推理等任务中的时间-空间动态, 并与言语产出和理解范式直接对照。这不仅考察基底神经节介入语言理解的“特异性窗口”, 也有助于构建统一的理解-产出双向语言模型。

再次, 为深入理解基底神经节在语言理解中的调控机制, 亟需系统考察儿茶酚胺系统, 特别是多巴胺与去甲肾上腺素的功能差异及个体差异。多巴胺可通过调节认知资源分配和奖励机制参与语言相关过程, 而去甲肾上腺素则在调节唤醒水平和情绪状态方面发挥作用。这两类神经递质在神经通路和功能作用上均存在显著差异, 在复杂的语言理解任务中可能对语义激活、句法解析和语用推理等产生不同的调节效果 (Cools & Arnsten, 2022;

Ye, 2022)。此外,已有研究提出,多巴胺和去甲肾上腺素对认知功能的影响均呈倒U型曲线关系,即其浓度过高或过低都会损害认知加工效率,尤其影响前额叶皮层和纹状体的功能状态(Cools & D'Esposito, 2011)。这种非线性调节模式强调了神经递质水平、作用脑区和认知功能之间的复杂交互,提示个体间的基线差异可能显著影响语言理解过程中基底神经节的参与方式。但目前关于儿茶酚胺系统在语言理解中的功能差异及个体差异仍缺乏系统性的研究。未来研究应结合心理药理学干预、遗传学和磁共振波谱(MRS)等多模态成像手段,系统考察不同神经递质的浓度、受体分布及其对基底神经节—皮层通路连接强度和语言理解表现的影响。

最后,有必要系统考察神经可塑性在基底神经节参与语言理解过程中的作用。已有研究表明,语言经验,尤其是双语使用,可引发基底神经节结构与功能的可塑性变化,如尾状核、壳核与苍白球灰质体积的增加以及与皮层区功能连接的增强(Burgaleta et al., 2016; Gallo et al., 2024)。这些变化不仅反映了基底神经节对长期语言调控需求的适应性重组,也提示其在语言理解中的调节机制具有经验依赖性。然而,当前主流语言模型普遍忽视了这种结构—功能的动态变化。未来研究可采用纵向队列设计和多模态影像技术,结合语言能力的发展轨迹与使用习惯,揭示语言经验如何通过神经可塑性机制塑造基底神经节—皮层网络在语言理解中的功能特征,从而为构建动态、发展性的语言神经机制模型提供坚实依据。

综上,未来研究应结合多模态成像、神经调控、药物干预和计算建模等多种方法,深入探讨基底神经节不同核团在双语及多任务语言环境中的功能分工及其与语言网络的交互关系,进一步研究这些核团在健康个体与患者中的作用差异,特别是在高认知负荷语言环境下的调控机制。这些研究将为构建机制精细、解释力强的神经语言模型奠定基础,也有助于推动神经递质靶向干预在语言障碍治疗中的临床应用。

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# The Role of Basal Ganglia in Language Comprehension

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**Abstract** The basal ganglia (BG) are a group of subcortical nuclei that play critical roles in motor control, reinforcement learning, and language processing. Anatomically, the BG include the striatum, globus pallidus, subthalamic nucleus, and substantia nigra, which are closely connected to the cerebral cortex. Traditionally, the BG have been implicated primarily in motor functions. However, emerging evidence has shown that they also play important roles in language processing. Patients with BG dysfunction, such as those with Parkinson's disease or Huntington's disease, exhibit not only motor impairments but also a range of language disorders. These findings challenge traditional Broca-Wernicke-Geschwind language model, suggesting that both cortical and subcortical structures, particularly the BG, are essential for language function.

While earlier research has primarily focused on the role of the BG in speech production, recent studies have expanded the scope to encompass language comprehension. Although language comprehension and production share certain neural mechanisms, they also involve distinct processes. It remains unclear, however, whether the different BG nuclei contribute differently to various aspects of language comprehension, such as semantics, syntax, phonology, and pragmatics. This review summarizes research using methods from neuropsychology, neuroimaging, and psychopharmacology to address these questions.

Our review indicates that the dorsal striatum, composed of the caudate and putamen, is crucial for regulating almost all aspects of language comprehension. During both semantic and syntactic processing, the dorsal striatum is involved in monitoring and modulating information selection, activating goal-relevant information while inhibiting irrelevant or less-preferred ones. Neuroimaging studies reveal an anterior-posterior gradient within the dorsomedial striatum, with more anterior regions supporting complex syntactic processing. Moreover, the dorsal striatum is involved in pragmatic processing, as it coactivates with the frontal-temporal network to generate context-appropriate meanings. Studies also suggest that the putamen contributes uniquely to phonological processing. In contrast, the globus pallidus and subthalamic nucleus, which are commonly targeted in deep brain stimulation (DBS) for medical treatment, are primarily linked to speech production. Although some studies suggest their involvement in semantic and syntactic processing, others have failed to observe activation in these areas. Further research is necessary to clarify the precise role of these nuclei in language processing.

Beyond the BG nuclei themselves, the catecholaminergic (CA) system—particularly dopamine (DA) and norepinephrine (NA)—plays a crucial role in language comprehension via the fronto-striatal pathway. Closely interconnected with the basal ganglia, this system not only modulates motor function but also supports higher-order cognitive processes, including multiple aspects of language. The role of CAs in semantic processing has gained considerable attention. Patients with BG dysfunctions often exhibit deficits in semantic, syntactic, and pragmatic processing. Recent pharmacological studies in healthy individuals have shown that CA stimulants (e.g., levodopa and methylphenidate) causally enhance the semantic and syntactic unification, even when language processing per se is goal-irrelevant. These findings demonstrate that higher CA levels may further amplify the importance of language processing through modulating fronto-striatal connectivity.

A central question in current research is whether the BG support language comprehension through mechanisms that are language-specific or domain-general mechanisms. The domain-general view, supported by evidence from neuroimaging, neuropsychological, and bilingual-switching studies, proposes that the BG—particularly the caudate nucleus and putamen—modulate cognitive control processes such as selection, monitoring, and resource allocation across both linguistic and non-linguistic tasks. In contrast, the language-specific view argues that certain BG—frontal circuits are specialized for language, with some neuropsychological and fMRI studies showing comprehension deficits or heightened fronto-striatal sensitivity in language tasks independent of general executive dysfunction. While current findings largely favor a domain-general regulatory role, the BG may exert

finer-grained, potentially specialized control in specific linguistic domains, such as syntactic processing. Resolving this issue is critical for addressing a longstanding debate in psycholinguistics: whether language processing relies solely on shared neural resources or also engages dedicated neural mechanisms.

In summary, this review underscores the distinctive role of the BG in language comprehension, highlighting functional specializations among its nuclei. Several critical questions, however, remain unanswered. Future research should move beyond isolated activation patterns to systematically map the division of labor and coordination among BG nuclei, as well as their interactions with cortical language networks, using advanced techniques such as high-resolution diffusion imaging, laminar fMRI, intracranial recordings, and psychopharmacology. A central priority is to clarify whether BG regulatory functions are language-specific or domain-general by directly comparing linguistic and non-linguistic tasks with temporally precise (MEG/EEG) and spatially precise (ultra-high-field fMRI) measures. The catecholaminergic system—particularly dopamine and norepinephrine—also warrants focused investigation to disentangle their distinct and potentially non-linear contributions, integrating pharmacological, genetic, and MR spectroscopy approaches to assess neurotransmitter concentrations, receptor distributions, and connectivity effects. Finally, the role of neural plasticity, especially the bilingualism-induced structural and functional adaptations, should be incorporated into dynamic, developmentally informed models of BG–language interaction. These models should be supported by longitudinal, multimodal imaging to link language experience with functional network reorganization.

**Key words** basal ganglia, language comprehension, catecholaminergic system, language-specific mechanisms