

绝对音高加工的认知神经机制^{*}

侯建成¹ 宋 蓓^{2,3} 周加仙² 孙长安⁴ 朱海东⁵

(¹ 威斯康星大学麦迪逊分校医学与公共健康学院放射学系, 麦迪逊 53726, 美国)

(² 华东师范大学心理与认知科学学院, 上海 200062) (³ 哈尔滨音乐学院音乐学系, 哈尔滨)

(⁴ 苏州科技大学教育与公共管理学院, 苏州 215009) (⁵ 石河子大学心理学系, 石河子 832003)

摘要 绝对音高(absolute pitch, AP)是一种比较罕见的音高加工能力, 具有特殊的认知和神经机制。事件相关电位研究表明 AP 音乐家进行音高命名时, 工作记忆参与较少但涉及多个认知策略。功能神经成像研究发现左侧额叶背侧后部和左侧颞叶平面对 AP 音乐家非常重要, 而准 AP 音乐家(quasi-AP)的某些右侧脑区的参与则反映其增加的音高加工负荷和难度。结构神经成像研究发现 AP 音乐家具有特殊的灰质结构形态及白质连接。未来研究有待将 AP 能力进一步分为“具有相对音高能力”与“没有相对音高能力”两类并观察相应的认知神经机制, 并通过影像基因组学来探索基因多态性对 AP 能力的影响, 以及有必要观察以声调语言为母语的音乐家进行音高加工的神经机制。

关键词 绝对音高; 功能相关; 结构相关

分类号 B842

绝对音高(absolute pitch, AP, 也称固定音高或绝对音感)指在没有任何音高提示或参照的情况下对听到的实际音高进行识别, 即判断并说出(或唱出)音高的具体音名和唱名的能力(Deutsch, 2013; Hou, Chen, & Dong, 2015; Hou et al., 2014; Levitin, 1999; Parncutt & Levitin, 2001; 侯建成, 董奇, 2011)。关于 AP 的研究历史可追溯到 1876 年皇家音乐协会学报中的《音乐中耳朵对于音感的敏感度和音感的变化》一文(陈芳, 刘沛, 李姐娜, 2009)。实际上, AP 能力拥有者的数量极少, 据估计西方人群中每 1500~10000 里约有 1 人拥有 AP 能力(Bachem, 1955; Hirose et al., 2002); 在具有专业音乐训练经验的音乐家中(含职业音乐家

和音乐学院学生), AP 能力者的比例为 10%~15% (Baharloo, Johnston, Service, Gitschier, & Freimer, 1998; Gregersen, Kowalsky, Kohn, & Marvin, 1999, 2001; Hirose et al., 2002)。与之对应, 大多数人(含音乐家和非音乐家)拥有相对音高能力。相对音高(relative pitch, RP)是指在有外部参照的情况下, 识别或唱出一个指定音高的能力。一般认为, AP 能力者在头脑中具备一个固定的音高模板(tonal template), 能将每一个音高与其音名或唱名建立固定的联系, 而 RP 能力者具有移动的音高模板, 通过音高距离的判断(即音程)来加工音高(侯建成, 董奇, 2011)。现有研究已表明, AP 音乐家在进行音高加工时存在相对特殊认知神经机制。本文对此进行了归纳和论述, 并提出有必要继续研究的方向。

1 绝对音高的功能相关性研究

1.1 事件相关电位研究

事件相关电位(Event-related potentials, ERP)是指一种特定的刺激作用于感觉系统或大脑的某一部位, 以及当某种心理因素出现时在脑区所产生的电位变化(Blackwood & Muir, 1990; 魏景汉, 罗跃嘉, 2002)。许多研究通过听觉 oddball 范式观

收稿日期: 2017-02-26

* 中国博士后科学基金第 58 批面上资助项目《绝对音高能力与执行功能的关系研究》(项目编号: 2015M580303); 黑龙江省哲学社会科学研究规划一般项目《普通话与闽南语对音高识别能力的影响研究》(项目编号: 16YYB09); 教育部人文社会科学研究一般项目(项目编号 10YJAZH139)。

通讯作者: 宋蓓, E-mail: songpei2010@163.com;
周加仙, E-mail: jxzhou@psy.ecnu.edu.cn

察了 AP 音乐家、非 AP 音乐家以及非音乐家进行音高加工时的神经机制，发现三者均诱发了 P3 成分，但 AP 音乐家的 P3 波幅和潜伏期显著低于后两者(Crummer, Walton, Wayman, Hantz, & Frisina, 1994; Klein, Coles, & Donchin, 1984; Renninger, Granot, & Donchin, 2003; Wayman, Frisina, Walton, Hantz, & Crummer, 1992)。P3 反映了大脑对刺激进行编码、分类、识别等认知功能状态，也是工作记忆保持和更新的神经表现(Hirose et al., 2002; 海棠, 周临舒, 蒋存梅, 2017)，同时工作记忆与 P3 波幅呈负相关而与潜伏期呈正相关(Brown, Clarke, & Barry, 2007; Polich, 2007; Rawdon et al., 2013; Steiner, Barry, & Gonsalvez, 2013)。与此同时，AP 音乐家能将头脑中固定的音调模板(a fixed tonal template)与外界呈现的音高频率建立对应关系来加工音高，因而有关音高的工作记忆参与较少(Hirose et al., 2002; Levitin & Rogers, 2005; Siegel, 1974; Takeuchi & Hulse, 1993)。而非 AP 音乐家和非音乐家则需比较音程的关系、再对单个音高进行加工，这增加了其负载度及难度，进而表现出较高的 P3(侯建成, 董奇, 2011)。

根据当前的研究结果，AP 者进行音高加工时至少存在两个独立的阶段：第一个阶段是早期音高编码阶段，其加工源位于大脑听觉皮层(也称作“听觉记忆”阶段，pitch memory stage)；第二个阶段依赖于条件性联想记忆(conditional associative memory mechanism)，即建立音高与言语标签(verbal labels)或其他的抽象代码(abstract codes)之间的联系，其加工源位于大脑额叶和中央区(也称作“音高标签”阶段，pitch labeling stage)(Deutsch, Kuyper, & Fisher, 1987; Levitin, 1994; Levitin & Rogers, 2005; Rogenmoser, Elmer, & Jäncke, 2015; Schulze, Mueller, & Koelsch, 2013; Zatorre, 2003; Zatorre & Beckett, 1989)。Elmer, Sollberger, Meyer 和 Jäncke (2013)通过行为学方法发现，与非 AP 音乐家相比，AP 音乐家的音高加工准确率较高且反应时较短；与此同时，他们通过电生理研究方法发现 AP 和非 AP 音乐家的听觉皮层区没有出现显著的 N1/P2 波，即在音高编码阶段(第一阶段)没有差异；而在音高标签阶段(第二阶段)，AP 音乐家在中央区、右中央区和顶区出现显著的 N400，同时在中央区后部(central-posterior scalp)出现显著的晚期正波成分(late positive component, LPC)。

N400 与视觉和听觉的语义概念加工有关(Goerlich et al., 2012)，而 LPC 与记忆有关(Chung, Tong, & McBride-Chang, 2012; Ohara, Lenz, & Zhou, 2006)。该研究表明 AP 音乐家通过概念性关联记忆(conceptual associative memory)加工音高(Elmer et al., 2013)。接下来 Rogenmoser 等(2015)研究发现，在音高命名任务中，AP 与非 AP 音乐家均没有出现显著的非匹配负波(mismatch negativity, MMN)差异，但是 AP 音乐家在额叶区出现了显著降低的 P3a 波。失匹配负波(MMN)由 Naatanen, Gaillard 和 Mäntysalo (1978)首先报道，指出 MMN 的产生是由一系列重复的、特征性质相同的“标准刺激”中，出现可辨别的“偏离刺激”诱发产生的脑电位反应，实验中用偏离刺激诱发的脑电波减去标准刺激诱发的脑电波所得到的负波就是 MMN。MMN 是一种脑认知活动的内源性成分，反映听觉皮质对刺激信息加工差异的感知能力，与信息的早期自动加工过程及感觉记忆水平的前注意控制有关(Garrido, Kilner, Stephan, & Friston, 2009; Picton, Alain, Otten, Ritter, & Achim, 2000)。而降低的 P3a 反映了较少工作记忆的参与(Berti & Roeber, 2013; Ruhnau, Wetzel, Widmann, & Schröger, 2010; Schomaker & Meeter, 2014)且与多个认知功能有关，例如语言、听觉想象及体感知觉等(Escera, Alho, Winkler, & Näätänen, 1998; Roeber, Berti, & Schröger, 2003; Schröger & Wolff, 1998; Wetzel & Schröger, 2007)。这似乎支持了一些行为学研究结论，例如 AP 音乐家通过语言编码来保持音高信息(Siegel, 1974)、通过语言编码、听觉、动觉、视觉和空间意象进行音高加工(Zatorre & Beckett, 1989)，或通过语义和情绪性信息(例如音高“F#”被编码为情绪性词语“不自然、辛酸、疼痛、痛苦的感觉”)进行音高编码(Hsieh & Saberi, 2008)。该结论已得到神经成像研究的支持(见“功能神经成像研究”部分)。另外，P3a 与音乐训练起始年龄存在正性相关(Rogenmoser et al., 2015)，表明早期音乐训练对 AP 能力形成的重要性(Baharloo et al., 1998; Gregersen et al., 1999, 2001; Levitin, 1999; Levitin & Rogers, 2005; Wilson, Lusher, Wan, Dudgeon, & Reutens, 2009; Zatorre, 2003)。因此，AP 任务加工的第二个阶段(或多维加工阶段，multidimensional stage)是 AP 与非 AP 能力差异的神经表现(Rogenmoser et al., 2015)。

1.2 功能神经成像研究

Zatorre, Perry, Beckett, Westbury 和 Evans (1998)要求 AP 和 RP 音乐家: (1)对每个独立的音高进行命名; (2)根据后面一个音高提示对前一个音高进行命名, 同时通过正电子断层扫描(positron emission tomography)进行观察, 发现 AP 音乐家的左侧额叶背侧后部(left posterior dorsolateral frontal cortex, LPDLF, 接近于初级运动皮层区, BA 8/6)的大脑血流量(cerebral blood flow, CBF)在两个任务中均显著增加, 而 RP 音乐家则没有变化。这也得到其他研究结果的支持(Bermudez & Zatorre, 2005; Ohnishi et al., 2001; Schulze, Gaab, & Schlaug, 2009; Wengenroth et al., 2014; Zatorre, Chen, & Penhune, 2007)。额叶背侧后部是条件性联想记忆(conditional associative memory)的重要加工脑区(Halsband & Freund, 1990; Petrides, 1995; Petrides, Alivisatos, Evans, & Meyer, 1993), 有研究者认为额叶背侧后部的激活在一定程度上反映了音乐能力的高低, 因为它不但负责条件性联想记忆, 还负责音乐信息的储存、监测和检索等加工(Kostopoulos & Petrides, 2003; Owen, Milner, Petrides, & Evans, 1996; Petrides et al., 1993; 侯建成, 董奇, 2011)。需要指出, 当 RP 音乐家判断音程时才会激活左侧额叶背侧后部, 因为将特定的音程联系至特定的名称(如小三度或大三度)也是条件性联想记忆。

除了左侧额叶背侧后部, Zatorre 等还发现其他脑区也出现激活, 例如颞叶中回和下回、额叶中回和下回、枕叶等区域。如前所述, AP 者加工音高时涉及多个认知功能或策略: 颞叶中回和下回负责视觉、听觉及语言加工(Bogousslavsky, Miklossy, Deruaz, Regli, & Assal, 1986; Heywood, Gaffan, & Cowey, 1995; McGuire et al., 1995; Onitsuka et al., 2004; Platel, Baron, Desgranges, Bernard, & Eustache, 2003); 额叶下回负责语义(Platel et al., 2003), 同时对音高空间信息的联觉发挥作用(Ishai, Haxby, & Ungerleider, 2002); 额叶中回涉及听觉信息的体感知觉(Wan & Schlaug, 2010); 枕叶区负责视知觉以及视觉想象(Schmithorst, 2005) (音乐音高能引发相关的视觉表象, 参见侯建成, 刘昌, 2008)。另有研究发现枕叶的视觉联合区, 特别是初级视觉皮质中枢(枕叶纹状区)能将视觉、听觉及其他感觉信息进行整合(Schürmann, Raij, Fujiki, & Hari,

2002)。Zatorre 等的研究结果也说明左侧额叶背侧后部与其他脑区之间可能存在一定的功能连接网络, 而左侧额叶背侧后部或许是连接其它脑区的关键部位, 因为该部位受损后导致了行为障碍(Petrides, 1990; Petrides et al., 1993)。

另外, 位于颞叶上回后部的颞叶平面(planum temporale, PT)对 AP 能力也发挥重要作用(Clark, Boutros, & Mendez, 2010)。功能成像研究发现 AP 音乐家的左侧颞叶平面的激活程度与 AP 测验成绩呈正性相关(Ohnishi et al., 2001; Wilson et al., 2009; Zatorre et al., 1998)。颞叶平面与听觉加工的音素感知(音素是语音单位)有关(Altarelli et al., 2014; Delisi, Hoff, Neale, & Kushner, 1994; Griffiths & Warren, 2002), 而语音的音素类别与音乐音高类别大致相同(Burns & Campbell, 1994), 这对于 AP 能力很重要。

需要注意的是, AP 音乐家的左侧颞叶平面和左侧额叶背侧后部可能组成了一个神经功能连接网络: 颞叶平面(或者颞叶上回后部)是听觉皮层, 能将听觉信息直接投射到额叶背侧后部(Petrides & Pandya, 1988), 两者与其它脑区也发生相互作用(Zatorre et al., 1998; Ohnishi et al., 2001; Petrides & Pandya, 1988)。同时颞叶平面和额叶背侧后部之间的功能网络也可能源于两者之间潜在的结构网络(例如皮层厚度或白质纤维结构连接), 因为大脑结构网络能影响局部或整体的功能网络(Wang, Dai, Gong, Zhou, & He, 2015)。

事实上, AP 是一个连续变量, 即 AP 群体内部也存在高低之分。有研究观察了准 AP 能力(Quasi-AP, QAP; 或伪绝对音高, pseudo-AP)*音乐家的音高加工机制。在一项目音高命名任务中, QAP 音乐家具有显著的右侧半球网络激活, 包括右侧颞叶上回和中回, 以及右侧前额叶背外侧皮层(Wilson, Lusher, Wan, Dudgeon, & Reutens, 2006)。颞叶上回和中回负责语义记忆(Binder, Desai, Graves, & Conant, 2009), 而前额叶背外侧皮层负责工作记忆(Schwenzer & Mathiak, 2011)。另一个有关 QAP 音乐家的音高命名研究发现除了左侧半球, 右侧半球网络的激活与听觉工作记忆有关,

* 准 AP 能力(或伪 AP 能力): 与 AP 能力者相比, 准 AP 者在音高加工时具有较低的准确率。例如: 与其它音相比, 准 AP 音乐家对 C、G、A 三个音的识别正确率较高且加工音高时使用了参考音(reference tones) (参见 Wilson et al., 2009)。

这包含右侧颞叶上回的前部和后部、右侧额叶中回和下回，以及右侧小脑(Wilson et al., 2009)。额叶中回负责运动和体感知觉(Wan & Schlaug, 2010)，额叶下回负责语义加工(Platel et al., 2003)，小脑负责早期听觉编码(Schulze et al., 2009)、工作记忆(Baddeley, 2003)以及多模态信息编码(Stewart et al., 2003)，同时语义、运动、体感知觉以及多模态信息编码对 QAP (和 AP)音乐家的音高加工策略非常重要(Hsieh & Saberi, 2008; Wilson et al., 2009; Zatorre & Beckett, 1989)。这两个神经成像研究支持了其行为实验结果，即 QAP 音乐家也采用诸如音色感知、语义加工、肢体和视觉想象等多个认知策略进行音高命名(Wilson et al., 2009)，这与 AP 音乐家类似。另外，这两个研究也指出与 AP 音乐家相比(加工音高时左侧半球优势)，略低水平 AP 能力(如 QAP)的右侧半球激活则反映增加的音高加工负荷及难度。

综上所述，左侧额叶背侧后部对 AP 音乐家的音高加工非常重要，这与条件性联想记忆有关。左侧颞叶平面也负责其音高加工，同时音乐训练的起始年龄也决定颞叶平面的活动强度。这两个脑区之间可能具有潜在的功能网络或结构网络。其它脑区负责音高加工的多个认知功能或策略。QAP 音乐家进行音高加工时也借助了多个认知策略，同时其右侧半球也参与了音高加工。

2 绝对音高的结构相关性研究

结构神经成像是探索 AP 神经机制的另一种方法。大脑结构可以反映脑区之间如何相互作用，以及如何形成多样的结构神经网络。研究者已通过形态学测量方法(morphologic measures)研究了大脑结构形态(如灰质体积和密度、皮层厚度、皮层表面积)，以及通过非侵入性扩散成像技术(如弥散张量成像, diffusion tensor imaging, DTI)观察了白质纤维结构。

2.1 大脑结构形态研究

研究表明，AP 音乐家的左侧颞叶平面表面积显著高于其右侧(Altarelli et al., 2014; Delisi et al., 1994; Griffiths & Warren, 2002; Schlaug, Jancke, Huang, & Steinmetz, 1995)，而这种不对称也可能是较小的右侧而非左侧较大的颞叶平面表面积所致(Keenan, Thangaraj, Halpern, & Schlaug, 2001)。Zatorre 等(1998)以及 Worsley, Marrett, Neelin 和

Evans (1996)观察了 AP 和 RP 音乐家的大脑结构，发现 AP 音乐家的颞叶平面的体积(volume)也呈现显著的双侧不对称，即左侧体积显著大于右侧，而 RP 音乐家的双侧体积则没有差异。相关分析表明在 AP 音乐家中，音高识别正确率的高低与左侧颞叶平面体积呈显著正相关，即左侧颞叶平面体积较大则音高识别正确率较高。由于颞叶平面与听觉加工和语言音素感知有关(Griffiths, Johnsrude, Dean, & Green, 1999; Griffiths & Warren, 2002)，Zatorre 等(1998)认为左侧颞叶平面可能涉及提取和操控词语和声调等信息加工。神经语言学研究发现颞叶平面是大脑外侧裂语言区(包括颞叶平面、顶下小叶和额叶语言区)的一个重要部位，负责音调、词汇、语法、听觉信号加工(例如选择和监控音高感知和发声)等，而且在自我听觉监控过程中发挥非常重要的作用(Foundas, Bollich, Corey, Hurley, & Heilman, 2001)。Zatorre 等(1998)还认为颞叶平面可看作 AP 能力的一个重要标记，因为左侧颞叶平面大小与 AP 能力高低呈正相关。与此同时，位于听觉联合皮质区的颞叶平面比初级听觉皮层要相对高级、但又低于产生意识加工的额叶；颞叶平面的神经元能将音高信息投射至两侧额叶背侧区后部，而左脑颞叶平面负责语义联结，与较高级的额叶一起对 AP 能力发挥作用(Zatorre et al., 1998; 蔡振家, 2004, 2014)。

Bermudez, Lerch, Evans 和 Zatorre (2009)通过基于体素的形态测量学(voxel-based morphometry, VBM)观察 AP 与非 AP 音乐家的大脑结构差异，发现 AP 音乐家的整体皮层厚度比非 AP 音乐家要薄，但仅在左侧前距状列(left peri-calcarine)、左侧距状裂外周皮层(left pericalcarine cortex)的皮层较厚且与 AP 能力呈正相关。研究还发现 AP 音乐家的灰质体积也比非 AP 音乐家要低，例如右侧横向中央沟、右侧中央前回和后回、右侧顶上小叶、左侧额叶上回等，同时 AP 音乐家的音高测验结果与左侧距状裂外周皮层、颞叶上回和中回的灰质密度呈正相关，而与左侧额上回、左侧眶额皮质、右侧额叶下回和右侧扣带回的灰质密度呈负相关。该结果与普通音乐家与非音乐家的大脑结构研究结果有所不同(音乐家的皮层厚度和灰质密度大多显著高于非音乐家，参见 Bermudez et al., 2009)。两种研究结果的差异反映了 AP 具有特殊的神经加工机制(例如神经细胞的大小、数量、

连接程度及髓鞘化程度等因素, 参见 Bermudez et al., 2009), 且 AP 音乐家较低的皮层厚度和灰质体积可能反映其加工音高时拥有较高的工作效率和一定程度的自动化加工机制。因为有研究发现音乐家较低的灰质密度与音乐认知的自动化加工程度有关, 这有助提升音乐认知加工效率(James et al., 2014)。Dohn 等(2015)却发现 AP 音乐家许多脑区的皮层厚度(如双侧颞叶上回、左侧额叶下回、右侧缘上回、右侧海马旁回、双侧前扣带回等)均高于非 AP 音乐家。这与 Bermudez 等的结果不同, 可能与不同被试有关(Dohn 的被试中男性偏多: 28/34; 而 Bermudez 的较多被试中女性偏多: 47/71。参见 Dohn et al., 2015)。

研究表明, 大脑的多个区域以度分布(degree distribution)、集群系数(clustering coefficient)、局部有效性(local efficiency)等方式组成了庞杂的神经网络, 并通过相互作用完成各种认知功能。近些年来, 结合基于图论(graph theory)的复杂网络理论, 研究者发现通过结构和扩散磁共振成像数据构建的脑结构网络以及通过脑电图/脑磁图数据和功能磁共振成像数据构建的脑网络具有很多重要的拓扑性质, 如“小世界网络”(small-world network)属性(Bullmore & Sporns, 2009; Loui, Zamm, & Schlaug, 2012; 梁夏, 王金辉, 贺永, 2010)。Jäncke, Langer 和 Hänggi (2012)通过图论分析方法观察了 AP 音乐家是否与非 AP 音乐家及非音乐家在小世界网络属性上存在差异, 发现前者在外侧裂语言区具有显著增加的结构性局部连接网络, 包括右侧赫氏回(Heschl's gyrus), 右侧颞叶平面(PT), 右侧颞叶上回(superior temporal gyrus), 右侧三角部(pars triangularis, Broca 区的一部分)、左右侧极平面(planum polare, 位于赫氏回后部)、左侧颞叶上沟(superior temporal sulcus)以及左侧岛盖部(pars opercularis), 这些区域涉及高阶(higher-order)听觉信息、工作记忆及语义记忆的加工。该研究支持了 ERP 和功能神经成像的研究结果。

2.2 弥散张量成像研究

弥散张量成像(diffusion tensor imaging, DTI)通过测量大脑组织内水分子的弥散特性来获得水分子弥散的方向、量级和各向异性等信息, 进而探测出大脑组织的微观结构, 尤其表现了神经白质纤维束轨迹等信息。与非 AP 音乐家相比, AP 音乐家在连接左侧颞叶上回后部和颞叶中回后部

之间的纤维束有显著增加, 同时双侧颞叶(包括颞叶上回后部和颞叶中回后部)也具有显著增加的白质纤维束体积, 表明 AP 音乐家的颞叶上回具有音高分类功能(Loui, Li, Hohmann, & Schlaug, 2011)。这在一定程度上支持了功能神经成像的研究结论, 即左侧颞叶上回是负责音高分类的重要区域(Loui et al., 2012; Schulze et al., 2009)。

与此同时, AP 音乐家的左侧半球纤维量也显著增加, 即比非 AP 音乐家和非音乐家有较大的纤维超链接(hyperconnectivity) (Loui et al., 2011)。具体而言, 颞叶上回和颞叶中回通过弓状纤维束(arcuate fasciculus, AF, 其属于上纵束<superior longitudinal fasciculus, SLF>的一个部分)均与额叶(尤其是额叶下回)存在结构性连接, 而上纵束是连接颞叶和额叶的白质纤维束(Catani & Mesulam, 2008; Loui, Alsop, & Schlaug, 2009)。颞叶上回和颞叶中回的纤维连接负责音乐感知行为, 而颞叶中回和额叶下回的纤维连接负责音高的“产生-感知”(production-perception)配对。重要的是, 颞叶上回-颞叶中回-额叶下回三者组成了一个重要的三节点网络, 负责听觉感知及音高刺激分类(Loui et al., 2009, 2011)。

上纵束(SLF)主要连接颞叶(负责音乐和语言听觉加工)和额叶(负责执行功能, 例如工作记忆)(Friederici, 2009; Glasser & Rilling, 2008; Oechslin, Imfeld, Loenneker, Meyer, & Jäncke, 2010), 同时顶叶与颞叶和额叶也各有连接(与额叶连接时顶叶负责运动调节, 与颞叶连接时顶叶负责视觉和空间加工)(Makris et al., 2005)。与非 AP 音乐家和非音乐家相比, AP 音乐家具有增强的上纵束结构, 其各向异性值(fractional anisotropy, FA)较高, 同时 AP 音乐家的音高识别正确率与左侧上纵束存在显著正相关(Oechslin et al., 2010)。因此, 左侧的弓状纤维束或上纵束能够从结构网络的角度为功能网络(例如额叶下回和颞叶上回之间的功能连接)研究提供一定依据, 因为大脑结构网络能对局部以及整体性功能网络产生影响(Wang et al., 2015)。

Dohn 等(2015)也通过基于纤维束示踪的空间统计分析(Tract-Based Spatial Statistics, TBSS)方法研究 AP 音乐家的大脑白质结构, 发现其右侧的额枕下束(right inferior fronto-occipital fasciculus)、钩束(uncinate fasciculus)和下纵束(inferior longitudinal fasciculus)的各向异性分数(fractional anisotropy, FA)显著高于非 AP 音乐家。额枕下束不但包含额

叶(含 Broca 区及临近区域)和枕叶的连接, 还包含前额叶及(颞叶)听觉皮层, 以及颞叶和顶叶后部的连接(Dohn et al., 2015; Kier, Staib, Davis, & Bronen, 2004)。钩束通过颞干(temporal stem)将额叶的语言功能区(如岛盖部、三角部、额眶部)和颞叶的语言功能区(如 Wernicke 区)联系起来(Dohn et al., 2015; Kier et al., 2004; Parker et al., 2005)。下纵束连接了枕叶的视觉加工区和颞叶中前部区域, 且其侧支(lateral branches)与右侧颞叶的上(superior)、中(middle)、下回(inferior gyrus)存在连接, 而其内支(medial branches)则与钩回(uncus)和海马旁回(parahippocampal gyrus)存在连接(Dohn et al., 2015; Wakana, Jiang, Nagae-Poetscher, van Zijl, & Mori, 2004)。最后, 右侧海马旁回(parahippocampal gyrus)的皮层厚度和 FA 呈显著正相关。结合大脑语言区的较高 FA 与皮层厚度具有正性相关(Phillips et al., 2011)以及音高感知功能归于大脑右侧(Loui, Li, & Schlaug, 2011)等研究结论, 推测右侧海马旁回负责音高标签的记忆编码功能(memory encoding) (Dohn et al., 2015)。

需要指出, 与 Loui 等和 Oechslin 等发现的白质结构左侧优势结论不同, Dohn 等发现 AP 音乐家存在白质右侧优势, 一方面可能与样本量不同有关, 另一方面是 Dohn 使用了基于全脑 FA 的 TBSS 研究方法, 而 Loui 和 Oechslin 使用了基于感兴趣区(region-of-interest)的纤维束(tractography)成像技术(Dohn et al., 2015)。

3 有待研究的问题

首先, 根据上述研究, AP 音乐家的右侧颞叶平面表面积和体积比非 AP 音乐家要小, 以及 AP 音乐家的 P3 波幅和潜伏期低于非 AP 音乐家, 据此有研究者认为这提供了一个逆向思考的观点, 即 AP 能力虽被视为一种罕见的音乐禀赋*, 但可

能也缺少了某些音乐能力(例如 RP 能力); 有些 AP 音乐家无法很快地说出音程而必须根据固定唱名来推算(Miyazaki, 1993, 1995)。但也有一部分 AP 音乐家兼具 RP 能力且在加工音程时不存在困难(例如有 AP 音乐家加工音程时出现了显著 P3 且反应速度较快、正确率也较高, 参见 Renninger et al., 2003)。这似乎还可将 AP 能力进一步分为“具有 RP 能力”与“没有 RP 能力”两类, 因而 AP 和 RP 能力似乎是并存的(蔡振家, 2004, 2014)。蔡振家(2004, 2014)认为, 拥有 AP 没有弊端, 关键在于是否过分依赖 AP 进行音乐信息加工, 例如在辨别音程与和弦时“不是去掌握声音的整体感觉, 而是先记下各个绝对音名、再推算音程或和弦, 这就是过分依赖绝对音高且这种方式会弱化相对音高”。另外, 许多亚洲的音乐专业学生通过 AP 将每个音听出来, 而传统的欧洲音乐教育反而更重视 RP 训练, 强调音程与和弦等内容的听辨能力, 进而理解其在乐曲中的功能(蔡振家, 2004)。因此在实际音乐教学和训练中也要重视 RP 的训练。

其次, 尽管 AP 能力受到早期音乐训练因素的影响, 但遗传因素显得更为重要(Chin, 2003; Deutsch et al., 1987; Ross, Olson, & Gore, 2003; Ross, Olson, Marks, & Gore, 2004)。Profita, Bidder, Optiz 和 Reynolds (1988)选取 19 个家庭并通过分离分析(segregation analysis)**发现了 35 名 AP 能力者, 说明 AP 能力存在显著的家族遗传性, 同时女性更常见且表现为垂直传递(vertical transmission)的遗传规律。在一項家族研究中, Gregersen 和 Kumar (1996)估算出 AP 能力的遗传可能性为 20, 即 AP 能力者的兄弟姐妹(siblings)同样存在 AP 能力的概率是普通家系的 20 倍。Gregersen 等(1999, 2001)进行的两项家系聚集性研究(familial aggregation study)发现 AP 能力者的兄弟姐妹同样具有 AP 能力的相对概率分别是普通家系的 8.3 倍和 12.2 倍。另外, Theusch, Basu 和 Gitschier (2009)通过全基因组连锁分析(linkage analysis)观察到 AP 能力可能存在种族差异, 染色体 8q24.21 和

* 有研究认为, AP 比 RP 更为高级, 这个假说得到动物实验的验证(如鸟类研究, 参见 Hulse & Cynx, 1985; 猴子研究, 参见 D'Amato, 1988; 狼的研究, 参见 Tooze, Harrington, & Fentress, 1990)。这些动物在听音时倾向 AP 感知, AP 在某些动物社群活动中扮演重要角色, 参见 Hulse & Page, 1988), 同时在婴儿行为实验中也得到佐证, 例如 8 个月大的婴儿倾向于 AP 感知, 而成年人则倾向于 RP 感知, 所以绝大部分婴儿可能都具有 AP 能力, 但此能力在学习语言过程中终会被 RP 所取代(参见 Saffran & Griepentrog, 2001)。

** 分离分析(segregation analysis)是遗传学的经典分析方法, 以孟德尔的分离定律为理论基础, 主要通过家系调查对基因的分离行为进行遗传学分析, 借助分离分析可确定某一性状的遗传方式。

8q21.11 均与德裔犹太人及印度血统家系的综合数据集(combined dataset)存在强连锁(LOD 值分别为 2.330 和 2.069), 而染色体 8q24.21 的 rs3057 位点与欧洲家系存在强连锁(LOD 值为 3.464, 表明该连锁区域内至少存在一个易感基因使欧洲家系出现 AP 能力的概率更大), 这也支持了遗传异质性(genetic heterogeneity)*对 AP 能力的重要作用。Gregersen 等(2013)对 53 个 AP 能力家系和 36 个联觉能力家系进行全基因组连锁分析, 探讨 AP 和联觉之间的遗传关系(即 AP 能力与多个认知功能的关系, 参见 Loui et al., 2012), 发现 126 位 AP 能力者中有 28 位兼具联觉能力, 然而仅有 8 位联觉能力者兼具 AP 能力(且分别来自 8 个家系); 对数据集单独进行非参数连锁分析后, 发现了一些与 AP 和联觉能力连锁的重叠区域(LOD 值均大于 2), 尤其是在 2 号染色体和 6 号染色体。人类的很多行为表现均可由遗传因素来解释(Moldin & Gottesman, 1997), 而人的行为又主要由神经系统所控制。因此基因的效应并非直接表达在行为水平, 而是通过它们的分子和细胞效应为中介, 进而影响大脑的结构与功能以及影响脑内的信息加工, 进而最终影响行为(何清华, 2010)。目前许多的认知神经科学的研究已将“基因-脑-行为”三者整合起来, 以一种整合的思路来研究行为, 这种思路被称为影像基因组学(Imaging Genetics; 何清华, 2010)。在 AP 研究中, 研究者可通过影像基因组学来探索和评估大脑内表达的基因多态性的功能特征并进一步考察其对 AP 能力的潜在影响。

另外, AP 与语言存在密切联系。Schön, Magne 和 Besson (2004)强调了语言的声调与 AP 能力密切相关, 特别是汉语的普通话(Mandarin)和广东话(Cantonese)对 AP 能力的发展和形成发挥重要作用, 因为这些语言的声调都通过不同的音高来表达出各种不同的意义。Deutsch, Henthorn 和 Dolson (2004), Deutsch, Henthorn, Marvin 和 Xu (2006), Deutsch, Dooley, Henthorn 和 Head (2009) 的研究为 AP 能力和声调语言的关系提供了一定论据, 即语言的音高与音乐的音高具有相似或相

关, 如越南语(Vietnamese language)和普通话均能表现出一种显著、准确且稳定的 AP 特征, 因此研究者假设 AP 本身也具有某些语言特征(如元音特征等)。Sohn 发现东亚地区的 AP 能力的差异比例非常小, 因为汉语、韩语和日语均通过语言的音高(声调)来通达词汇意义, 即音高在获取词义方面具有重要作用(Henthorn & Deutsch, 2007)。迄今为止, 许多研究观察了以非声调语言(如英语和法语)为母语的 AP 音乐家加工音高的神经机制, 但今后也有必要观察以声调语言为母语的 AP 音乐家加工 AP 的神经机制。

参考文献

- 蔡振家. (2004). 绝对音感的认知心理学研究. *关渡音乐学刊*, (1), 77–92.
- 蔡振家. (2014). 音乐认知心理学 (第二版, pp. 46–53). 台北: “国立”台湾大学出版中心.
- 陈芳, 刘沛, 李妲娜. (2009). 绝对音高现象的研究现状及展望. *星海音乐学院学报*, (4), 96–101.
- 海棠, 周临舒, 蒋存梅. (2017). 绝对音高者对音乐的加工及其神经机制. *心理科学*, 40(1), 51–57.
- 何清华. (2010). 情绪在风险决策加工中的重要性: 基因-脑-行为的多角度研究 (博士学位论文). 北京师范大学.
- 侯建成, 董奇. (2011). 音乐绝对音高信息加工的脑机制. *心理科学进展*, 19(9), 1306–1312.
- 侯建成, 刘昌. (2008). 国外有关音乐活动的脑机制的研究概述——兼及“莫扎特效应”. *中央音乐学院学报*, (1), 110–118.
- 梁夏, 王金辉, 贺永. (2010). 人脑连接组研究: 脑结构网络和脑功能网络. *科学通报*, 55(16), 1565–1583.
- 魏景汉, 罗跃嘉. (2002). 认知事件相关脑电位教程 (pp. 101–105). 北京: 经济日报出版社.
- Altarelli, I., Leroy, F., Monzalvo, K., Fluss, J., Billard, C., Dehaene-Lambertz, ... Ramus, F. (2014). Planum temporale asymmetry in developmental dyslexia: Revisiting an old question. *Human Brain Mapping*, 35, 5717–5735.
- Bachem, A. (1955). Absolute pitch. *The Journal of the Acoustical Society of America*, 27, 1180–1185.
- Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, 4, 829–839.
- Barharloo, S., Johnston, P. A., Service, S. K., Gitschier, J., & Freimer, N. B. (1998). Absolute pitch: An approach for identification of genetic and nongenetic components. *American Journal of Human Genetics*, 62, 224–231.
- Bermudez, P., Lerch, J. P., Evans, A. C., & Zatorre, R. J.

* 遗传异质性(genetic heterogeneity)是指不同的突变引起相同的或相似的表型, 包括等位基因异质性(allelic heterogeneity), 即同一基因座上不同的突变; 以及基因座异质性(locus heterogeneity), 即不同基因座上的突变。

- (2009). Neuroanatomical correlates of musicianship as revealed by cortical thickness and voxel-based morphometry. *Cerebral Cortex*, 19, 1583–1596.
- Bermudez, P., & Zatorre, R. J. (2005). Conditional associative memory for musical stimuli in nonmusicians: Implications for absolute pitch. *Journal of Neuroscience*, 25, 7718–7723.
- Berti, S., & Roeber, U. (2013). Encoding into visual working memory: Event-related brain potentials reflect automatic processing of seemingly redundant information. *Neuroscience Journal*, 2013, Article ID 172614.
- Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, 19, 2767–2796.
- Blackwood, D. H., & Muir, W. J. (1990). Cognitive brain potentials and their application. *The British Journal of Psychiatry*, 157, 96–101.
- Bogousslavsky, J., Miklossy, J., Deruaz, J. P., Regli, F., & Assal, G. (1986). Unilateral left paramedian infarction of thalamus and midbrain: A clinico-pathological study. *Journal of Neurology, Neurosurgery, and Psychiatry*, 49, 686–694.
- Brown, C. R., Clarke, A. R., & Barry, R. J. (2007). Auditory processing in an inter-modal oddball task: Effects of a combined auditory/visual standard on auditory target ERP. *International Journal of Psychophysiology*, 65, 122–131.
- Bullmore, E., & Sporns, O. (2009). Complex brain networks: Graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience*, 10(3), 186–198.
- Burns, E. M., & Campbell, S. L. (1994). Frequency and frequency-ratio resolution by possessors of absolute and relative pitch: Examples of categorical perception? *Journal of the Acoustical Society of America*, 96, 2704–2719.
- Catani, M., & Mesulam, M. (2008). The arcuate fasciculus and the disconnection theme in language and aphasia: History and current state. *Cortex*, 44, 953–961.
- Chin, C. S. (2003). The development of absolute pitch: A theory concerning the roles of music training at an early developmental age and individual cognitive style. *Psychology of Music*, 31, 155–171.
- Chung, K. K. H., Tong, X. H., & McBride-Chang, C. (2012). Evidence for a deficit in orthographic structure processing in Chinese developmental dyslexia: An event-related potential study. *Brain Research*, 1472, 20–31.
- Clark, D. L., Boutros, N. N., & Mendez, M. F. (2010). *The brain and behavior: An introduction to behavioral neuroanatomy* (p. 62). Cambridge: Cambridge University Press.
- Crummer, G. C., Walton, J. P., Wayman, J. W., Hantz, E. C., & Frisina, R. D. (1994). Neural processing of musical timbre by musicians, nonmusicians, and musicians possessing absolute pitch. *The Journal of the Acoustical Society of America*, 95, 2720–2727.
- D'Amato, M. R. (1988). A search for tonal pattern perception in cebus monkeys: Why monkeys can't hum a tune. *Music Perception*, 5, 453–480.
- Delisi, L. E., Hoff, A. L., Neale, C., & Kushner, M. (1994). Asymmetries in the superior temporal lobe in male and female first-episode schizophrenic patients: Measures of the planum temporale and superior temporal gyrus by MRI. *Schizophrenia Research*, 12, 19–28.
- Deutsch, D. (2013). Absolute pitch. In D. Deutsch (Ed.), *The psychology of music* (3rd ed., pp. 141–182). San Diego, CA: Academic Press.
- Deutsch, D., Dooley, K., Henthorn, T., & Head, B. (2009). Absolute pitch among students in an American music conservatory: Association with tone language fluency. *Journal of the Acoustical Society of America*, 125, 2398–2403.
- Deutsch, D., Henthorn, T., & Dolson, M. (2004). Absolute pitch, speech, and tone language: Some experiments and a proposed framework. *Music Perception*, 21(3), 339–356.
- Deutsch, D., Henthorn, T., Marvin, E., & Xu, H. S. (2006). Absolute pitch among American and Chinese conservatory students: Prevalence differences, and evidence for a speech-related critical period. *The Journal of the Acoustical Society of America*, 119, 719–722.
- Deutsch, D., Kuypers, W. L., & Fisher, Y. (1987). The tritone paradox: Its presence and form of distribution in a general population. *Music Perception*, 5(1), 79–92.
- Dohn, A., Garza-Villarreal, E. A., Chakravarty, M. M., Hansen, M., Lerch, J. P., & Vuust, P. (2015). Gray- and white-matter anatomy of absolute pitch possessors. *Cerebral Cortex*, 25(5), 1379–1388.
- Elmer, S., Sollberger, S., Meyer, M., & Jäncke, L. (2013). An empirical reevaluation of absolute pitch: Behavioral and electrophysiological measurements. *Journal of Cognitive Neuroscience*, 25(10), 1736–1753.
- Escera, C., Alho, K., Winkler, I., & Näätänen, R. (1998). Neural mechanisms of involuntary attention to acoustic novelty and change. *Journal of Cognitive Neuroscience*, 10, 590–604.
- Foundas, A. L., Bollich, A. M., Corey, D. M., Hurley, M., & Heilman, K. M. (2001). Anomalous anatomy of speech-language areas in adults with persistent developmental stuttering. *Neurology*, 57, 207–215.
- Friederici, A. D. (2009). Allocating functions to fiber tracts: Facing its indirectness. *Trends in Cognitive Sciences*, 13,

- 370–371.
- Garrido, M. I., Kilner, J. M., Stephan, K. E., & Friston, K. J. (2009). The mismatch negativity: A review of underlying mechanisms. *Clinical Neurophysiology*, 120, 453–463.
- Glasser, M. F., & Rilling, J. K. (2008). DTI tractography of the human brain's language pathways. *Cerebral Cortex*, 18, 2471–2482.
- Goerlich, K. S., Witteman, J., Schiller, N. O., van Heuven, V. J., Aleman, A., & Martens, S. (2012). The nature of affective priming in music and speech. *Journal of Cognitive Neuroscience*, 24, 1725–1741.
- Gregersen, P. K., Kowalsky, E., Kohn, N., & Marvin, E. W. (1999). Absolute pitch: Prevalence, ethnic variation, and estimation of the genetic component. *The American Journal of Human Genetics*, 65, 911–913.
- Gregersen, P. K., Kowalsky, E., Kohn, N., & Marvin, E. W. (2001). Early childhood music education and predisposition to absolute pitch: Teasing apart genes and environment. *American Journal of Human Genetics*, 98, 280–282.
- Gregersen, P. K., Kowalsky, E., Lee, A., Baron-Cohen, S., Fisher, S. E., Asher, J. E., ... Li, W. T. (2013). Absolute pitch exhibits phenotypic and genetic overlap with synesthesia. *Human Molecular Genetics*, 22(10), 2097–2104.
- Gregersen, P. K., & Kumar, S. (1996). The genetics of perfect pitch. *American Journal of Human Genetics*, 59(Suppl.), A179.
- Griffiths, T. D., Johnsrude, I., Dean, J. L., & Green, G. G. R. (1999). A common neural substrate for the analysis of pitch and duration pattern in segmented sound? *NeuroReport*, 10, 3825–3830.
- Griffiths, T. D., & Warren, J. D. (2002). The planum temporale as a computational hub. *Trends in Neurosciences*, 25, 348–353.
- Halsband, U., & Freund, H. J. (1990). Premotor cortex and conditional motor learning in man. *Brain*, 113, 207–222.
- Henthorn, T., & Deutsch, D. (2007). Ethnicity versus early environment: Comment on 'Early childhood music education and predisposition to absolute pitch: Teasing apart genes and environment' by Peter K. Gregersen, Elena Kowalsky, Nina Kohn, and Elizabeth West Marvin [2000]. *American Journal of Medical Genetics Part A*, 143A (1), 102–103.
- Heywood, C. A., Gaffan, D., & Cowey, A. (1995). Cerebral achromatopsia in monkeys. *European Journal of Neurology*, 7, 1064–1073.
- Hirose, H., Kubota, M., Kimura, I., Ohsawa, M., Yumoto, M., & Sakaihara, Y. (2002). People with absolute pitch process tones with producing P300. *Neuroscience Letters*, 330, 247–250.
- Hou, J. C., Chen, C. S., & Dong, Q. (2015). Resting-state functional connectivity and pitch identification ability in non-musicians. *Frontiers in Neuroscience*, 9, 7.
- Hou, J. C., Chen, C. S., Wang, Y. P., Liu, Y. Y., He, Q. H., Li, J., & Dong, Q. (2014). Superior pitch identification ability is associated with better executive functions. *Psychomusicology: Music, Mind, and Brain*, 24(2), 136–146.
- Hsieh, I., & Saberi, K. (2008). Dissociation of procedural and semantic memory in absolute-pitch processing. *Hearing Research*, 240, 73–79.
- Hulse, S. H., & Cynx, J. (1985). Relative pitch perception is constrained by absolute pitch in songbirds (*Mimus*, *Molothrus*, and *Sturnus*). *Journal of Comparative Psychology*, 99, 176–196.
- Hulse, S. H., & Page, S. C. (1988). Toward a comparative psychology of music perception. *Music Perception*, 5, 427–452.
- Ishai, A., Haxby, J. V., & Ungerleider, L. G. (2002). Visual imagery of famous faces: Effects of memory and attention revealed by fMRI. *NeuroImage*, 17(4), 1729–1741.
- James, C. E., Oechslin, M. S., van De Ville, D., Hauert, C. A., Descloux, C., & Lazeyras, F. (2014). Musical training intensity yields opposite effects on grey matter density in cognitive versus sensorimotor networks. *Brain Structure and Function*, 219, 353–366.
- Jäncke, L., Langer, N., & Hänggi, J. (2012). Diminished whole-brain but enhanced peri-sylvian connectivity in absolute pitch musicians. *Journal of Cognitive Neuroscience*, 24, 1447–1461.
- Keenan, J. P., Thangaraj, V., Halpern, A. R., & Schlaug, G. (2001). Absolute pitch and planum temporale. *NeuroImage*, 14, 1402–1408.
- Kier, E. L., Staib, L. H., Davis, L. M., & Bronen, R. A. (2004). MR imaging of the temporal stem: Anatomic dissection tractography of the uncinate fasciculus, inferior occipitofrontal fasciculus, and Meyer's loop of the optic radiation. *American Journal of Neuroradiology*, 25, 677–691.
- Klein, M., Coles, M. G. H., & Donchin, E. (1984). People with absolute pitch process tones without producing a P300. *Science*, 223, 1306–1309.
- Kostopoulos, P., & Petrides, M. (2003). The midventrolateral prefrontal cortex: Insights into its role in memory retrieval. *European Journal of Neuroscience*, 17, 1489–1497.
- Levitin, D. J. (1994). Absolute memory for musical pitch: Evidence from the production of learned melodies. *Perception & Psychophysics*, 56, 414–423.
- Levitin, D. J. (1999). Absolute pitch: Self-reference and human memory. *International Journal of Computing*

- Anticipatory Systems*, 4, 255–266.
- Levitin, D. J., & Rogers, S. E. (2005). Absolute pitch: Perception, coding, and controversies. *Trends in Cognitive Sciences*, 9, 26–33.
- Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: A new disconnection syndrome? *Journal of Neuroscience*, 29, 10215–10220.
- Loui, P., Li, H. C., Hohmann, A., & Schlaug, G. (2011). Enhanced cortical connectivity in absolute pitch musicians: A model for local hyperconnectivity. *Journal of Cognitive Neuroscience*, 23, 1015–1026.
- Loui, P., Zamm, A., & Schlaug, G. (2012). Enhanced functional networks in absolute pitch. *NeuroImage*, 63, 632–640.
- Makris, N., Kennedy, D. N., McInerney, S., Sorensen, A. G., Wang, R. P., Caviness, V. S., Jr., & Pandya, D. N. (2005). Segmentation of subcomponents within the superior longitudinal fascicle in humans: A quantitative, *in vivo*, DT-MRI study. *Cerebral Cortex*, 15, 854–869.
- McGuire, P. K., Silbersweig, D. A., Wright, I., Murray, R. M., David, A. S., Frackowiak, R. S., & Frith, C. D. (1995). Abnormal monitoring of inner speech: A physiological basis for auditory hallucinations. *The Lancet*, 346, 596–600.
- Miyazaki, K. (1993). Absolute pitch as an inability: Identification of musical intervals in a tonal context. *Music Perception*, 11, 55–71.
- Miyazaki, K. (1995). Perception of relative pitch with different references: Some absolute-pitch listeners can't tell musical interval names. *Perception and Psychophysics*, 57, 962–970.
- Moldin, S. O., & Gottesman, I. I. (1997). Genes, experience, and chance in schizophrenia—Positioning for the 21st century. *Schizophrenia Bulletin*, 23(4), 547–561.
- Naatanen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42, 313–329.
- Oechslin, M. S., Imfeld, A., Loenneker, T., Meyer, M., & Jäncke, L. (2010). The plasticity of the superior longitudinal fasciculus as a function of musical expertise: A diffusion tensor imaging study. *Frontiers in Human Neuroscience*, 3, 76.
- Ohara, S., Lenz, F., & Zhou, Y. D. (2006). Sequential neural processes of tactile-visual crossmodal working memory. *Neuroscience*, 139, 299–309.
- Ohnishi, T., Matsuda, H., Asada, T., Aruga, M., Hirakata, M., Nishikawa, M., ... Imabayashi, E. (2001). Functional anatomy of musical perception in musicians. *Cerebral Cortex*, 11, 754–760.
- Onitsuka, T., Shenton, M. E., Salisbury, D. F., Dickey, C. C., Kasai, K., Toner, S. K., ... McCarley, R. W. (2004). Middle and inferior temporal gyrus gray matter volume abnormalities in chronic schizophrenia: An MRI study. *American Journal of Psychiatry*, 161, 1603–1611.
- Owen, A. M., Milner, B., Petrides, M., & Evans, A. C. (1996). Memory for object features versus memory for object location: A positron-emission tomography study of encoding and retrieval processes. *Proceedings of the National Academy of Sciences of the United States of America*, 93, 9212–9217.
- Parker, G. J. M., Luzzi, S., Alexander, D. C., Wheeler-Kingshott, C. A. M., Clecarelli, O., & Ralph, M. A. L. (2005). Lateralization of ventral and dorsal auditory-language pathways in the human brain. *NeuroImage*, 24, 656–666.
- Parncutt, R., & Levitin, D. J. (2001). Absolute pitch. In S. Sadie (Ed.), *The new grove dictionary of music and musicians* (pp. 37–39). London, England: MacMillan.
- Petrides, M. (1990). Nonspatial conditional learning impaired in patients with unilateral frontal but not unilateral temporal lobe excisions. *Neuropsychologia*, 28, 137–149.
- Petrides, M. (1995). Functional organization of the human frontal cortex for mnemonic processing: Evidence from neuroimaging studies. *Annals of the New York Academy of Sciences*, 769, 85–96.
- Petrides, M., Alivisatos, B., Evans, A., & Meyer, E. (1993). Dissociation of human mid-dorsolateral from posterior dorsolateral frontal cortex in memory processing. *Proceedings of the National Academy of Sciences of the United States of America*, 90, 873–877.
- Petrides, M., & Pandya, D. N. (1988). Association fiber pathways to the frontal cortex from the superior temporal region in the rhesus monkey. *The Journal of Comparative Neurology*, 273, 52–66.
- Phillips, O. R., Clark, K. A., Woods, R. P., Subotnik, K. L., Asarnow, R. F., ... Narr, K. L. (2011). Topographical relationships between arcuate fasciculus connectivity and cortical thickness. *Human Brain Mapping*, 32, 1788–1801.
- Pickton, T. W., Alain, C., Otten, L., Ritter, W., & Achim, A. (2000). Mismatch negativity: Different water in the same river. *Audiology and Neurotology*, 5, 111–139.
- Platel, H., Baron, J. C., Desgranges, B., Bernard, F., & Eustache, F. (2003). Semantic and episodic memory of music are subserved by distinct neural networks. *NeuroImage*, 20, 244–256.
- Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, 118, 2128–2148.
- Profità, J., Bidder, T. G., Optiz, J. M., & Reynolds, J. F. (1988). Perfect pitch. *American Journal of Medical Genetics*, 29, 763–771.

- Rawdon, C., Murphy, J., Blanchard, M. M., Kelleher, I., Clarke, M. C., Kavanagh, F., ... Roche, R. A. P. (2013). Reduced P300 amplitude during retrieval on a spatial working memory task in a community sample of adolescents who report psychotic symptoms. *BMC Psychiatry*, 13, 125.
- Renninger, L. B., Granot, R. I., & Donchin, E. (2003). Absolute pitch and the p300 component of the event-related potential: An exploration of variables that may account for individual differences. *Music Perception*, 20, 357–382.
- Roeber, U., Berti, S., & Schröger, E. (2003). Auditory distraction with different presentation rates: An event-related potential and behavioral study. *Clinical Neurophysiology*, 114, 341–349.
- Rogenmoser, L., Elmer, S., & Jäncke, L. (2015). Absolute pitch: Evidence for early cognitive facilitation during passive listening as revealed by reduced p3a amplitudes. *Journal of Cognitive Neuroscience*, 27, 623–637.
- Ross, D. A., Olson, I. R., & Gore, J. C. (2003). Absolute pitch does not depend on early musical training. *Annals of the New York Academy of Sciences*, 999, 522–526.
- Ross, D. A., Olson, I. R., Marks, L. E., & Gore, J. C. (2004). A nonmusical paradigm for identifying absolute pitch possessors. *The Journal of Acoustical Society of America*, 116(3), 1793–1799.
- Ruhnau, P., Wetzel, N., Widmann, A., & Schröger, E. (2010). The modulation of auditory novelty processing by working memory load in school age children and adults: A combined behavioral and event-related potential study. *BMC Neuroscience*, 11, 126.
- Saffran, J. R., & Griepentrog, G. J. (2001). Absolute pitch in infant auditory learning: Evidence for developmental reorganization. *Developmental Psychology*, 37(1), 74–85.
- Schlaug, G., Jäncke, L., Huang, Y., & Steinmetz, H. (1995). In vivo evidence of structural brain asymmetry in musicians. *Science*, 267, 699–701.
- Schmithorst, V. J. (2005). Separate cortical networks involved in music perception: Preliminary functional MRI evidence for modularity of music processing. *NeuroImage*, 25, 444–451.
- Schomaker, J., & Meeter, M. (2014). Novelty detection is enhanced when attention is otherwise engaged: An event-related potential study. *Experimental Brain Research*, 232, 995–1011.
- Schön, D., Magne, C., & Besson, M. (2004). The music of speech: Music training facilitates pitch processing in both music and language. *Psychophysiology*, 41, 341–349.
- Schröger, E., & Wolff, C. (1998). Attentional orienting and reorienting is indicated by human event-related brain potentials. *Neuroreport*, 9, 3355–3358.
- Schulze, K., Gaab, N., & Schlaug, G. (2009). Perceiving pitch absolutely: Comparing absolute and relative pitch possessors in a pitch memory task. *BMC Neuroscience*, 10, 106.
- Schulze, K., Mueller, K., & Koelsch, S. (2013). Auditory Stroop and absolute pitch: An fMRI study. *Human Brain Mapping*, 34, 1579–1590.
- Schürmann, M., Raji, T., Fujiki, N., & Hari, R. (2002). Mind's ear in a musician: Where and when in the brain. *NeuroImage*, 16(2), 434–440.
- Schwenzer, M., & Mathiak, K. (2011). Numeric aspects in pitch identification: An fMRI study. *BMC Neuroscience*, 12, 26.
- Siegel, J. A. (1974). Sensory and verbal coding strategies in subjects with absolute pitch. *Journal of Experimental Psychology*, 103, 37–44.
- Steiner, G. Z., Barry, R. J., & Gonsalvez, C. J. (2013). Can working memory predict target-to-target interval effects in the P300? *International Journal of Psychophysiology*, 89, 399–408.
- Stewart, L., Henson, R., Kampe, K., Walsh, V., Turner, R., & Frith, U. (2003). Brain changes after learning to read and play music. *NeuroImage*, 20, 71–83.
- Takeuchi, A., & Hulse, S. H. (1993). Absolute pitch. *Psychological Bulletin*, 113, 345–361.
- Theusch, E., Basu, A., & Gitschier, J. (2009). Genome-wide study of families with absolute pitch reveals linkage to 8q24.21 and locus heterogeneity. *The American Journal of Human Genetics*, 85(1), 112–119.
- Tooze, Z. J., Harrington, F. H., & Fentress, J. C. (1990). Individually distinct vocalizations in timber wolves, *Canis lupus*. *Animal Behaviour*, 40, 723–730.
- Wakana, S., Jiang, H. Y., Nagae-Poetscher, L. M., van Zijl, P. C. M., & Mori, S. (2004). Fiber tract-based atlas of human white matter anatomy. *Radiology*, 230, 77–87.
- Wan, C. Y., & Schlaug, G. (2010). Music making as a tool for promoting brain plasticity across the life span. *The Neuroscientist*, 16, 566–577.
- Wang, Z. J., Dai, Z. J., Gong, G. L., Zhou, C. S., & He, Y. (2015). Understanding structural-functional relationships in the human brain: A large-scale network perspective. *The Neuroscientist*, 21(3), 290–305.
- Wayman, J. W., Frisina, R. D., Walton, J. P., Hantz, E. C., & Crummer, G. C. (1992). Effects of musical training and absolute pitch ability on event-related activity in response to sine tones. *The Journal of the Acoustical Society of America*, 91, 3527–3533.
- Wengenroth, M., Blatow, M., Heinecke, A., Reinhardt, J., Stippich, C., Hofmann, E., & Schneider, P. (2014).

- Increased volume and function of right auditory cortex as a marker for absolute pitch. *Cerebral Cortex*, 24, 1127–1137.
- Wetzel, N., & Schröger, E. (2007). Modulation of involuntary attention by the duration of novel and pitch deviant sounds in children and adolescents. *Biological Psychology*, 75, 24–31.
- Wilson, S. J., Lusher, D., Wan, C. Y., Dudgeon, P., & Reutens, D. C. (2006). Imaging the neurocognitive components of pitch naming: Insights from quasi-absolute pitch. In M. Baroni, A. R. Addessi, R. Caterina, & M. Costa (Eds.), *Proceedings of 9th international conference on music perception and cognition* (pp. 825–833). Liege, Belgium: The Society for Music Perception & Cognition (SMPC).
- Wilson, S. J., Lusher, D., Wan, C. Y., Dudgeon, P., & Reutens, D. C. (2009). The neurocognitive components of pitch processing: Insights from absolute pitch. *Cerebral Cortex*, 19, 724–732.
- Worsley, K. J., Marrett, S., Neelin, P., & Evans, A. C. (1996). Searching scale space for activation in PET images. *Human Brain Mapping*, 4, 74–90.
- Zatorre, R. J. (2003). Absolute pitch: A model for understanding the influence of genes and development on neural and cognitive function. *Nature Neuroscience*, 6, 692–695.
- Zatorre, R. J., & Beckett, C. (1989). Multiple coding strategies in the retention of musical tones by possessors of absolute pitch. *Memory and Cognition*, 17, 582–589.
- Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory-motor interactions in music perception and production. *Nature Reviews Neuroscience*, 8, 547–558.
- Zatorre, R. J., Perry, D. W., Beckett, C. A., Westbury, C. F., & Evans, A. C. (1998). Functional anatomy of musical processing in listeners with absolute pitch and relative pitch. *Proceedings of the National Academy of Sciences of the United States of America*, 95, 3172–3177.

The cognitive and neural mechanisms of absolute pitch

HOU Jiancheng¹; SONG Bei^{2,3}; ZHOU Jiaxian²; SUN Chang'an⁴; ZHU Haidong⁵

(¹ Department of Radiology, School of Medicine and Public Health, University of Wisconsin-Madison, Madison 53726, USA)

(² School of Psychology and Cognitive Science, East China Normal University, Shanghai 200062, China)

(³ Music Conservatory of Harbin, Harbin, China)

(⁴ School of Education and Public Administration, Suzhou University of Science and Technology, Suzhou 215009, China)

(⁵ Department of Psychology, Shihezi University, Shihezi 832003, China)

Abstract: Absolute pitch (AP) is a rare ability to process music pitch; it also has the special cognitive and neural basis. The studies by event-related potentials showed that AP musicians use less working memory but with multiple cognitive strategies during AP processing. Functional neuroimaging studies showed that the left posterior dorsolateral frontal cortex and the left planum temporale are very important to AP musicians, but the involvements in some right cerebral regions indicate the increased load and difficulty during pitch processing in quasi-AP musicians. Structural neuroimaging studies showed the special morphometry of the left planum temporale as well as the white matter structure in AP musicians. Future research needs to further divide AP ability into “with relative pitch ability” and “without relative pitch ability” together with their cognitive and neural basis, and investigate the effect of gene polymorphism on AP ability through imaging genomics, and also necessarily examine the neural basis of pitch processing in the musicians with native tonal language.

Key words: absolute pitch; functional correlate; structural correlate