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Hans汉斯

汉语声调加工的神经基础：来自半球偏侧化证据的启示

周伟琳

西南大学心理学部，重庆

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摘 要

汉语声调在汉字(如单音节字)加工中起重要作用。功能假设认为言语加工偏向于左半球，而音乐加工偏向于右半球。声学假设则认为声音时间信息加工偏向于左半球，而音高(由声音频率决定)信息的加工偏向于右半球。由于汉语声调同时具有与音高相关的声学特征和与语言相关的音韵特征，所以大脑对汉语声调不同特征的加工会表现出不同的半球偏侧化效应。本文从半球偏侧化的视角综述了来自神经心理学、神经影像学、电生理学和行为学关于汉语声调加工的证据。未来研究可以从汉语声调相比声母和韵母加工的差异、汉语声调在语境加工中的作用、发展性阅读障碍儿童和二语习得者加工汉语声调的神经基础、音乐经验对汉语声调加工的影响方面探讨汉语声调加工的神经基础。

关键词

汉语声调，半球偏侧化，功能性神经影像，事件相关电位，双耳分听

The Neural Basis of Chinese Lexical Tone Processing: Insights from Evidence on Hemispheric Lateralization

Weilin Zhou

Faculty of Psychology, Southwest University, Chongqing

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Abstract

Chinese lexical tone plays an important role in the processing of Chinese characters (i.e., mono-

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syllables). The functional hypothesis proposes that speech processing is lateralized to the left hemisphere and that musical processing is lateralized to the right hemisphere. Alternatively, the acoustic hypothesis points out that acoustic temporal processing is lateralized to the left hemisphere and that pitch (depended on the frequency of sounds) processing is lateralized to the right hemisphere. Because Chinese lexical tones have both low-level acoustic features (related to pitch) and higher-order phonological features (related to linguistic knowledge), the processing of different features in the brain tends toward different hemispheric lateralization. A series of evidence from neuropsychological, functional neuroimaging, electrophysiological, and behavioral studies is reviewed from the perspective of the hemispheric lateralization. Future research on the understanding of the neural bases of Chinese lexical tone concerns with the differences between tones, consonants, and vowels in the processing of Chinese characters, the role of Chinese lexical tone in the processing of semantic contexts, the neural underpinnings of Chinese lexical tone processing in developmental dyslexia and second-language learners, as well as the effects of musical experience on Chinese lexical tone processing.

Keywords

Chinese Lexical Tone, Hemispheric Lateralization, Functional Neuroimaging, Event-Related Potentials, Dichotic Listening

1. 引言

言语知觉是重要的认知功能，它提供了沿听觉通路进入大脑皮层的窗口，使具有物理属性的声学信息转换成大脑中的言语表征(Poeppel & Assaneo, 2020)。音高是承载言语的最重要信息成分之一。Yip (2002)根据音高信息在语义表达中所起的作用，将世界语言分为三种类型：声调语言(如汉语)、语调语言(如英语)和音高－口音语言(如日语)。由于声调语言在音节水平上具有特殊的音素状态，其为研究音高在言语知觉中的神经机制提供了优势。例如，汉语(如普通话)作为一种声调语言，除了声母和韵母外，还有四种不同的声调：阴平(一声)、阳平(二声)、上声(三声)和去声(四声)。在声学属性上，汉语词语声调是语音的基频(f0)，基频的变化主要由汉语的韵律决定(Li et al., 2014; Shuai & Gong, 2014)。音高知觉对理解声调语言非常重要，它利用音高模式来区分词语含义，故汉语声调在汉字语义理解中起重要作用(Ho et al., 2019)。例如，在汉语普通话中，由相同声母和韵母构成的音节，其与不同的声调相组合能够表达完全不同的意思：yi1“衣”(阴平/一声)；yi2“姨”(阳平/二声)；yi3“椅”(上声/三声)；yi4“易”(去声/四声)。

在声调语言中，声调通常被认为是音素的超音段形式，称为声调音素：一方面，声调作为音素来承载词语语义；另一方面，它在一个音节上变化音高的水平和轮廓，并由喉部的运动驱使，这类似于韵律(Chao, 1968)。虽然词语声调中声音与语音信息之间的加工差异引发了对其神经机制进行研究的广泛兴趣，但仍然存在争议(Gandour, 2006; Jongman et al., 2006)。争论之一在于脑半球的不对称性。功能假设(functional hypothesis)认为，当声调作为语音单位(如语言)被加工时，其偏向左半球；而当其作为纯声音信息(如音乐)被加工时，其偏向右半球(Van Lancker, 1980; Wong, 2002)。由于汉语声调同时包含声音信息和语音信息，所以功能假设认为汉语声调加工涉及分别对这两种信息进行不同加工的两个半球。相比之下，声学假设(acoustic hypothesis)认为，声调加工的大脑偏侧化取决于声音的听觉属性：声调中包含的频

率变异信息优先于右半球加工，而声母或韵母中包含的时间变异信息则优先于左半球加工(Zatorre & Belin, 2001; Zatorre et al., 2002)。因此，声学假设认为汉语声调变化的声音对比和语音对比都是频率变异，且频率信息优先于右半球加工，故汉语声调的加工偏向于右半球。鉴于以上关于大脑偏侧化的观点，Gandour 等对此提出了综合假设(Gandour et al., 2000, 2004; Gandour, 2006)。其观点认为，词语声调的加工根据信息类型而涉及两个半球：对于相同的声调，左半球更多地参与语义加工，而右半球更多地参与音高信息的声学加工；右半球可能在早期对声学加工有更重要的作用，而左半球在晚期的语言加工中更占主导地位。本文从神经心理学、功能性神经影像学、电生理学以及行为学方面的实证研究回顾汉语声调加工的神经特异性是由低水平的声学属性特征和高水平的语言知识共同决定的。

2. 神经心理学和功能性神经影像学证据

有关汉语失语症研究的早期证据表明，汉语失语者左半球的损伤使母语词语声调的产生与知觉受损(Naeser & Chan, 1980; Packard, 1986)，且左半球在语言功能中起重要作用。这表明与语义加工相关的左半球在词语声调加工方面占主导地位，支持了功能假设的观点。

功能性神经成像技术使得在个体内观察行为和认知任务的反应如何导致人脑中神经活动的变化成为可能(O'Shaughnessy et al., 2008)。功能性磁共振成像(functional magnetic resonance imaging, fMRI)能够测量由血流特征反映的大脑活动变化。虽然这种方法的时间分辨率很低，但具备高空间分辨率，使研究汉语声调激活的脑区成为可能。

大量关于汉语声调听觉加工的脑机制研究表明颞叶在汉语词语声调的听觉加工中起重要作用。例如，脑结构研究发现，汉语母语者右前颞叶的皮质体积比非汉语母语者更大(Crinion et al., 2009)。当泰语母语者和汉语母语者对汉语词语或泰语声调叠加到汉语音节上的合成刺激进行声调辨别任务时，两组被试在左侧颞平面均表现出对母语声调更强的反应，进而揭示了左侧颞平面在词语声调加工中的作用(Xu et al., 2006)。由于在以往的神经影像学研究中，包含极少语义信息的单音节同音异形字很多，Kwok 等(2016)因此设计了一个富含丰富语义的汉语词语声调知觉任务，要求汉语母语被试判断一个听觉呈现的汉语双音节词的两个音节是否具有相同的声调，并记录其反应的大脑活动。结果发现，左侧颞上回参与听觉刺激的初级声学分析，而右侧颞上回和左侧额下区域参与语言刺激的声调和语义加工。另外，元分析表明，双侧颞上回和双侧额下脑区参与汉语声调的听觉加工(Kwok et al., 2017)。此外，采用探照灯分类(searchlight classification)和表征相似性分析(representational similarity analysis)来研究汉语声调类别知觉的神经基础，Feng 等(2018)发现汉语词语声调加工涉及双侧颞上回和左侧顶下小叶。

将汉语作为第二语言进行学习的研究也发现颞叶(尤其是左侧)在汉语声调听觉加工中起作用。例如，对英语母语者进行汉语声调听觉训练的研究发现，汉语声调分类的习得与左侧颞上回和颞横回后部活动的增加有关(Wang et al., 2003)。当英语母语者被训练将图片与由叠加在英语音节上的汉语声调组成的单音节伪词进行匹配时，与成功的学习者相比，不成功的学习者在左侧赫氏回的灰质体积较小(Wong et al., 2008)。最近，英语单语者在六周内学习听觉汉语伪词的研究表明，训练前非语言音高和语言声调知觉的能力能够显著且正向预测新词学习结果，这与左侧赫氏回的反应模式相关(Yang & Li, 2019)。

除了听觉领域，在对汉语词语声调进行视觉加工(如阅读)的脑成像研究中，当汉语母语者对视觉呈现的汉字进行声调辨别时，左侧颞中回后部(靠近梭状回)被激活，而不是在上述听觉声调加工研究中反复发现的颞上回(Kwok et al., 2015)。在对阅读中汉语词语声调加工的功能连接分析中，Kwok 等(2019)进一步发现双侧额顶区参与汉语声调阅读，而没有涉及汉语声调听觉加工的颞区。所以，汉语声调的加工似乎是通道特异性的。

以上关于汉语声调加工的脑成像研究表明声调包含的语义和声学特征信息是由大脑两半球相关的脑区共同参与的，既支持功能假设，也支持声学假设。

3. 电生理学证据

与血流动力学方法相比，电生理记录(尤其是脑电图记录)因高时间(较差的空间)分辨率而提供了了解大脑加工时间进程的窗口(Teplan, 2002)。由听觉被动 Oddball 范式引发的失匹配负波(mismatch negativity, MMN)是一种事件相关电位(event-related potentials, ERPs)，在刺激开始后约 150~250 ms 呈额中分布(Näätänen et al., 1978)。受语言经验的影响，MMN 能反映自动的、前注意加工时期的语音辨别(Näätänen, 2001)。所以在电生理学上，MMN 是研究汉语声调加工的一个重要神经指标(Yue et al., 2014)。

听觉汉字声调在大脑中的音韵加工约起始于刺激呈现后 110 ms (Yue et al., 2017)。有研究证据支持在音高加工的早期阶段半球偏侧化是由声学假设理论所解释的(Poeppel, 2003; Zatorre & Belin, 2001)。例如，汉语词语声调在汉语母语者右半球引起的 MMN 反应比左半球更强(Luo et al., 2006; Ren et al., 2009)，而声母的 MMN 反应则相反(Luo et al., 2006)。声母和声调分别以快速变化的时间变异和缓慢变化的频率变异为特征。这与认为左半球倾向加工时间信息和右半球倾向加工频率信息的声学假设理论相符合。进一步证据表明，汉语词汇声调早期听觉加工的半球偏侧化取决于音高水平和音高轮廓：音高水平的听觉加工偏向右半球，而音高轮廓的听觉加工偏向左半球，这反映了词汇声调加工的一个潜在半球间交互机制(Wang et al., 2013)。汉语声调加工的半球不对称结果表明，音高的早期皮层加工主要由声学特征决定，然后在晚期可能反映到语义特征上。这个推测最近被一项同时采用 Oddball 范式和双耳分听任务的 ERPs 研究所检验(Wang et al., 2021)。其中，反映早期听觉加工的大脑反应指标(MMN)和反映晚期语义加工的行为学指标(反应时：对差异刺激进行反应)同时得到测量。结果表明，汉语母语者对汉语声调的早期听觉加工呈现出右半球优势效应(MMN 在右半球的幅值比左半球大)，而晚期加工则呈现出左半球优势效应(右耳对词语声调的偏差刺激的反应时比左耳短)。即汉语母语者在汉语词汇声调的听觉加工中表现出了从右到左的脑半球优势变化的趋势。这证实了声学假设理论和功能假设理论不是相互排斥的，而是各自在听觉加工的不同时间阶段上起到不同的作用：听觉加工早期依赖于声学线索，支持声学假设；而晚期依赖于语义功能，支持功能假设。然而，Shuai 和 Gong (2014)进行的一系列 ERPs 实验(双耳分听，音韵启动下的词语判断，以及语义违反任务)发现，对声调中音高变化的听觉加工，作为自下而上加工，引起更大的右半球激活；相比之下，词语声调的语言加工，作为自上而下加工，引起更大的左半球激活。并且，这两种类型的加工同时发生在早期(约 200 ms)和晚期(约 300~500 ms)，表明汉语词语声调加工是一种并行模型。这一发现与上述表明汉语词语声调加工的序列模型的证据相反。

此外，汉语声调类别知觉的 ERPs 研究表明，声学信息(类别内词语声调刺激)和音韵信息(类别间词语声调刺激)可以在 MMN 时间窗内同时得到加工(Xi et al., 2010)。并且，类别内和类别间的词语声调偏差刺激都在右半球引发了稍大的 MMN，可能反映了其在感觉加工中的作用，符合声学假设观点。类别间汉语词语声调的偏差刺激比类别内偏差刺激在左半球产生更大的 MMN，这可能反映了更多基于记忆的语言加工，符合功能假设观点。进一步支持功能假设的证据表明，类别间汉语声调加工的左半球优势效应并未在对汉语词语声调类别知觉有缺陷的阅读障碍儿童中观察到(Zhang et al., 2012b)。在注意的条件下，只有类别间汉语词语声调偏差刺激在左半球产生更大的 N2b 和 P3b 反应，而类别内偏差刺激在两个半球引起相似的 N2b 和 P3b 反应(Zhang et al., 2012a)。其结果反映了类别间汉语词语声调加工的左半球优势也能在有意识的注意条件下观察到，符合功能假设观点。

总之，关于汉语声调在大脑加工中时间进程的研究表明，由于汉语声调同时具有与音高相关的声学属性和与语言相关的音韵属性，且声学信息和音韵信息在汉语声调加工中有不同作用(Yu et al., 2014)，所

以大脑对不同属性的加工涉及相应的时间段并表现出不同的半球偏侧化效应。

4. 行为学证据

汉语声调行为学研究的实验范式通常采用双耳分听的形式，即同时在被试的左右耳中呈现不同的听觉刺激。由于右耳主要通过对侧通路连接到左半球，而左耳主要通过对侧通路连接到右半球，因此研究中经常发现母语为声调语言者在声调加工中表现出与语言相关的右耳优势效应(right ear advantage, REA)，即左半球优势效应。

例如，Wang 等(2001)采用双耳分听任务研究了汉语母语者和英语母语者对汉语词语声调加工的半球优势效应。结果发现，汉语母语者表现出了 REA，而英语母语者没有表现出耳优势效应。这说明，拥有声调语言经验的汉语母语者对汉语词语声调的加工偏向于左半球，而无声调语言背景的英语母语者对其加工倾向于双侧化趋势，符合功能假设的观点。Wang 等(2004)通过操纵被试群体的语言背景进一步研究了语言经验对汉语词语声调加工半球偏侧化的影响。实验同样采用双耳分听任务让四组被试(汉语母语者、英－汉双语者、挪威母语者和英语母语者)判断每只耳中听到的声调。结果发现，汉语母语者和英－汉双语者都表现出 REA (左半球优势)，而挪威母语者和英语母语者没有表现出耳优势效应。结果同样表明，只有当汉语声调作为个体语言系统的一部分时，才会出现对其加工的左半球偏侧化，同样符合功能假设的观点。尽管上述研究发现左半球在汉语声调加工中具有优势，但右半球也有参与加工的可能，因为 REA 在被试间的变化程度不同(Wang et al., 2001, 2004)。因此，汉语声调加工中的半球偏侧化只是一种趋势，因为一个半球的“优势”并不排除另一半球的活动。

最近一项采用双耳分听范式研究汉语声调加工半球优势效应的研究发现汉语声调加工的半球优势效应受到言语内容的影响(Mei et al., 2020)。具体而言，没有语言信息的嗡嗡声声调用作刺激时，表现出左耳优势效应(右半球优势)，符合声学假设的观点。然而，当声调刺激中逐渐增加音韵和语言信息时，左耳优势效应变得不稳定，逐渐表现出右耳优势效应，即左半球更多地参与词语声调加工。这支持了功能假设，即双耳分听中的耳优势效应是受言语功能的半球偏侧化影响的。

5. 总结与展望

由于汉语声调同时具有在物理属性上与音高相关的特征以及在语言功能上与语义相关的特征，当大脑加工这些信息时会表现出不同的半球偏侧化效应。未来关于汉语声调加工的研究可以考虑以下几个方向：1) 汉语声调加工相比声母、韵母加工的差异(Huang et al., 2018; Li et al., 2010; Yu et al., 2022; Zhang et al., 2021)。2) 汉语声调在语境加工中的作用，如成语(Hu et al., 2012)和句子(Zou et al., 2020)。3) 与同龄正常儿童相比，汉语发展性阅读障碍儿童加工汉语声调的神经基础。例如，已有证据表明汉语发展性阅读障碍儿童的听觉颞叶皮层在汉语声调加工中表现出缺损(Wang et al., 2019)，以及其对汉语声调意识加工方面的缺陷(Wang et al., 2020)。4) 将汉语作为第二语言进行学习的二语习得者加工汉语声调的神经基础。例如，非汉语母语被试通过训练后对汉语声调知觉加工能力的提升表现在声调辨别能力的增强(Lu et al., 2015)，但即使对汉语很熟练的二语习得者仍表现出对汉语声调加工的困难(Pelzl et al., 2020)。又如，学习汉语的英语被试在汉语声调类别知觉加工中表现出更大的 P300，即可能分配更多注意资源(Shen & Froud, 2018)。5) 音乐经验对汉语声调加工的影响。例如，法语音乐家比非音乐家更容易觉察汉语声调的变异(Marie et al., 2011)。音乐经验对汉语声调类别知觉加工产生影响，如有音乐经验者在类别内汉语声调加工时产生的 MMN 波幅强于无音乐经验者(Zhu et al., 2021)。

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