

婴儿语言和情绪加工的大脑偏侧化^{*}

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摘要 自胎儿时期起, 大脑左右半球不对称和偏侧化就已开始出现, 这一过程对语言和情绪等核心认知功能的特异性发展至关重要。研究婴儿大脑偏侧化不仅能为理解该现象的早期发展提供重要证据, 揭示人类复杂认知功能的发展神经机制, 也对自闭症等神经发育性疾病的早期筛查具有重要意义。现有研究表明, 婴儿语言加工表现出明显的左半球优势, 而情绪加工则主要表现为右偏侧化。然而, 与语言加工领域已确立的左半球优势效应相比, 婴儿情绪加工的右半球偏侧化模式尚未获得学界共识, 现有证据体系尚不完善。婴儿大脑偏侧化的发现与成人类似, 但部分研究结果和结论具有发展的独特性。

关键词 婴儿 新生儿 大脑偏侧化 语言 情绪

1 引言

与感觉皮层处理对侧身体感觉输入、运动皮层控制对侧身体运动的“对侧化”加工不同, “偏侧化”是一个相对的概念, 指大脑在处理特定认知功能时某侧半球更占优势, 而另一侧半球虽参与加工, 但并不处于主导地位 (Mazoyer et al., 2014; Zhen et al., 2015)。偏侧化是人脑功能组织的基本特征 (Kong et al., 2018), 早在新生儿期, 大脑就开始采用偏侧化方式工作 (Ratnarajah et al., 2013)。这一特征有助于婴儿在语言加工 (Wang et al., 2019)、情绪处理 (Watling & Damaskinou, 2020)、注意 (Mengotti et al., 2020) 以及算术 (Artemenko et al., 2020) 等认知发展中缩短执行时间, 提高整体工作效率 (Karolis et al., 2019)。

婴儿左右半球的结构和静息态功能网络不对称是大脑功能偏侧化的重要原因 (Dubois et al., 2009; Liu et al., 2022; Neubauer et al., 2020; Williams et al., 2023)。结构不对称主要表现为半球和局部脑区体积 (Esteves et al., 2019; Penhune et al., 1996)、皮层厚度与表面积 (Kong et al., 2018) 以及褶皱 (Chiarello et al., 2016) 的差异; 静息态功能网络不对称体现为半球功能网络在不同范围和层次 (如节点效率、局部网络效率和全球网络效率) 的信息传递效率存在差异 (Cai et al., 2018, 2019; Ratnarajah et

al., 2013)。值得注意的是, 此类不对称在胎儿期就已显现, 并于婴儿期随着左右半球灰质与白质的异速生长 (Andescavage et al., 2017; Matsuzawa et al., 2001) 持续演变 (Li et al., 2014; Liu et al., 2022)。然而, 尽管已经存在“苗头”, 婴儿期的大脑偏侧化程度远不如成人稳定: 其大脑激活模式更为弥散, 任务表现或脑活动模式在不同研究或不同月龄婴儿间存在较大波动, 而非成熟、固化的模式 (Bisiacchi & Cainelli, 2022)。但随着后天经验的积累、神经发育的逐渐完善, 语言及情绪加工等高级认知功能快速提升, 促使大脑半球分工逐渐明确 (Corballis, 2017)。

大脑偏侧化是中枢神经健康发展的重要生物标记 (Mazoyer et al., 2014)。研究发现, 孤独症 (Postema et al., 2021)、强迫症 (Kong et al., 2020) 和精神分裂症 (Damme et al., 2020) 等神经和精神障碍均与大脑偏侧化异常有关。更有证据表明, 这些疾病有望通过婴儿时期大脑异常偏侧化来预测 (Eyler et al., 2012; Finch et al., 2017; Liu et al., 2019)。因此, 聚焦婴儿期偏侧化的形成和发展, 不仅对揭示大脑发展规律具有重要理论价值, 而且考虑到大脑在早期发育阶段的高度可塑性, 也为相关疾病的早期筛查和干预提供了潜在的实践意义。

鉴于语言和情绪加工的大脑功能偏侧化最为典

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型且相关研究积累丰富，本文总结了新生儿（0~29日龄的孩子）、婴儿（30日龄~12月龄的孩子）和幼儿（13月龄~36月龄的孩子）在这两方面大脑偏侧化的研究，以更低龄的新生儿和婴儿阶段的研究发现为主。

2 语言加工的大脑偏侧化

此领域最经典的研究之一是2002年发表于《Science》的一项行为学研究，该研究发现5~12月龄的婴儿在非语言状态下嘴巴左右张开的幅度相似，而在咿呀学语（babbling）时右侧嘴巴张开幅度大于左侧，这一现象提示婴儿语言加工存在大脑左偏侧化（Holowka & Petitto, 2002）。

脑成像研究进一步证实，婴儿语言加工的脑结构存在左侧化优势。这种优势尤其体现在连接核心语言区 Broca 区（位于额下回）和 Wernicke 区（位于颞上回）的白质通路——弓状束上。研究发现，1~6月龄婴儿左半球弓状束体积更大、发育更成熟（Dubois et al., 2009, 2016）、结构更复杂（Adibpour et al., 2020）。同时，新生儿左侧弓状束的发育水平可预测其12月龄时的语言理解能力，而右侧弓状束则无此预测作用（Sket et al., 2019）。此外，新生儿尾状核神经元密度的左偏侧化程度同样可以预测其幼儿时期的语言能力（Tan et al., 2021）。在全脑结构层面，新生儿语言相关脑网络在左半球表现出更高效的结构性连接（Ratnarajah et al., 2013），且涉及语言感知-运动脑区（颞上和额下脑区）的皮层面积和厚度等指标也均呈左侧化优势（Li et al., 2014）。

语言加工的偏侧化，本质上是大脑功能的偏侧化，因此其核心证据来源于脑功能观测研究。现有研究已在婴儿的语音感知（包括母语和外语句子）和语音要素分辨（包括音素、音节和音节序列）等方面，验证了语言加工的左偏侧化。

在婴儿语音感知研究中，研究者通常采用正序和逆序播放的语音作为实验材料（Wang et al., 2024; Wu et al., 2022; Zhang et al., 2022），以控制声学特征对结果的干扰（Ramus et al., 2000）。经典研究包括：Dehaene-Lambertz 等人（2002）利用功能性核磁共振成像（functional magnetic resonance imaging, fMRI）发现，相较于静息态，2~3月龄婴儿在收听语音（正序和逆序）时左侧颞叶的激活显著强于右侧，且仅在左半球，正序语音相较逆序语音可引发角回

和楔前叶更强的激活。该课题组的后续研究也得到了相似结果（Dehaene-Lambertz et al., 2006, 2010）。由于婴儿的自我控制能力较差，功能近红外光谱成像（functional near-infrared spectroscopy, fNIRS）凭借其相较于 fMRI 具有更高的安全性、便携性及抗运动干扰能力，已在婴儿研究中得到广泛使用。fNIRS 研究显示（Peña et al., 2003），1月龄婴儿左侧颞叶对正序语音的血氧动力学响应显著强于逆序语音条件及静息基线。

除了比较正序和逆序语音外，还有 fNIRS 研究考察了婴儿对母语（相较于外语）的特异性加工，结果同样支持其母语加工的大脑左偏侧化（de Klerk et al., 2019）。有研究考察了4月龄婴儿大脑对母语、外语以及非语音刺激（环境声、猴子叫、电脑合成音）的反应，结果发现婴儿大脑在处理非语音刺激时表现为双侧或右偏侧化的激活模式，而在处理语音时表现出左偏侧化，并且左侧颞叶对母语的响应显著强于外语（Minagawa-Kawai et al., 2011）。类似，Vannasing 等人（2016）在1日龄的新生儿中观察到了母语加工的左偏侧化以及外语加工的右偏侧化。May 等人（2018）的研究为上述看似不太一致的发现提供了解释。他们发现，新生儿在母语条件下，颞叶和额叶的激活强于外语条件，且仅在母语条件下表现为左偏侧化；然而，当对比新生儿对外语和非语音刺激（口哨声）的反应时，颞叶和额叶的激活却在外语条件下表现出左偏侧化。据此，May 等人（2018）认为，新生儿出生时的母语环境（包括胎儿时期的学习经验）可能会影响婴儿将何种听觉信号处理为语言。婴儿语言加工左偏侧化的本质在于，当听觉信号被感知为语音时，颞叶和额叶会表现出左偏侧化的神经响应。

除语音加工外，婴儿在分辨更为底层的语音要素，包括音素（分为元音和辅音两类）、音节（元音和辅音的组合）和音节序列等时，同样表现出左偏侧化（陈钰，张丹丹，2020）。例如，fNIRS 研究显示（Altvater-Mackensen & Grossmann, 2016），6月龄婴儿在加工匹配的元音-面孔刺激对时，其左侧额下回的血氧响应显著强于不匹配条件，表明该脑区在早期语音-视觉信息整合中起关键作用。研究还发现，随着发育，婴儿语言加工的左偏侧化程度增强且涉及脑区范围扩大：6月龄和12月龄婴儿在收听音节时，其左脑事件相关电位（event-related potential, ERP）振幅显著高于右脑，且此差异随年

龄增加而逐渐扩大 (Maitre et al., 2014); Cai 等人 (2024) 关于婴儿人工语法学习的研究则发现, 新生儿期前额叶已表现出左偏侧化, 至 6~7 月龄时, 缘上回、颞上回和额下回均表现出显著的左偏侧化。

目前仅发现一项支持婴儿语言加工右偏侧化的研究: Daneshvarfard 等人 (2019) 的脑电研究发现, 胎龄 7~8 月的早产儿在收听以 1.6 Hz 重复呈现的音节时, 其听觉频率诱发响应在多个脑区呈右偏侧化。这可能与两方面因素有关: 一方面, 该研究采用调制频率较低的听觉刺激材料, 而大脑 (包括新生儿) 对此类低频信息的加工可能类似于语音韵律加工, 主要依赖右半球 (李思瑾等, 2023; 张丹丹等, 2019; 2023; Telkemeyer et al., 2009; Zhang et al., 2019)。另一方面, 生命早期, 右脑对语言加工具有重要作用, 而该作用随个体发展逐渐减弱。这种右半球对语言加工参与程度的动态变化可能反映了神经可塑性的重要时间窗, 为解释早期左半球损伤后语言功能的代偿性恢复提供了理论依据 (Olulade et al., 2020)。

尽管如此, 目前绝大多数研究均支持婴儿语言加工存在左偏侧化。而这一特征可能具有早期筛查孤独症等疾病的潜力。孤独症是幼儿时期最常见的神经发育性疾病 (Hirota & King, 2023; Zeidan et al., 2022), 常伴随明显的语言发展障碍 (Belteki et al., 2022)。元分析发现, 孤独症患者大脑功能偏侧化的变异程度高于健康人群, 涉及语言、运动和知觉等多个领域 (Li et al., 2023)。特别地, 患者在语言加工时常表现出左偏侧化减弱或消失 (Lindell, 2020), 甚至在核心语言区 (颞上回、额下回) 呈右偏侧化 (Herringshaw et al., 2016)。针对婴幼儿孤独症的研究同样发现, 孤独症高风险婴幼儿 (有哥哥或姐姐被确诊为孤独症) 缺乏典型的语言加工左偏侧化。现有证据表明, 孤独症高风险婴儿在 1.5 月龄时即表现出左侧弓状束连通性减弱和右侧增强的特征性改变, 且该结构偏侧化模式与 3 岁时的孤独症症状表现存在显著关联 (Liu et al., 2019)。脑功能研究发现, 3 岁时确诊的孤独症幼儿, 在其 12 月龄进行辅音辨别任务时被诱发的失匹配反应 (mismatch response, MMR; 成人失匹配负波的早期形态) 表现出与正常婴儿相反的右偏侧化 (Finch et al., 2017); 2~3 岁孤独症幼儿在收听语音时, 右侧额叶激活强于左侧 (Redcay & Courchesne, 2008)。纵向追踪研究发现, 后期确诊的高风险幼儿, 表现

出左半球对语言反应不足且右侧颞叶反应异常增强, 此右偏侧化模式在 1 至 4 岁间进行性加剧 (Eyler et al., 2012); 在 6~12 月龄的追踪期间, 孤独症高风险婴儿收听音节时的脑电慢波未发展出典型的左偏侧化 (Seery et al., 2013); 在加工音节序列时, 其左半球语言区功能连接在 3~12 月龄期间逐渐减弱, 至 12 月龄时已显著弱于健康对照组 (Keehn et al., 2013)。总之, 上述研究一致发现: 孤独症高危婴儿缺乏典型的语言左偏侧化, 且这种异常偏侧化与其发展后期孤独症状密切相关。因此, 追踪婴儿语言加工偏侧化的发展, 有望为孤独症风险个体的早期识别和预警提供依据。

综上, 婴儿语言加工的大脑左偏侧化已获得行为学、脑结构和脑功能等多层面研究的广泛验证。该特征不仅反映了大脑功能偏侧化在早期发展中的重要性, 更可能作为潜在的神经标记物, 为孤独症等神经发育性疾病的早期识别提供客观依据。

3 情绪加工的大脑偏侧化

除语言加工外, 婴儿对情绪信息的识别与处理在其认知发展中同样重要 (McIntosh et al., 2021; Tanner & Dounavi, 2021)。情绪加工偏侧化的主流理论是右半球假说 (Demaree et al., 2005), 主张情绪的产生与加工主要由大脑右半球主导。结构 MRI 研究为此提供了初步证据: 新生儿情绪加工相关脑区在右半球表现出更高效的连接 (Ratnarajah et al., 2013), 且关键脑区 (如颞上沟) 存在右侧化的结构优势 (Li et al., 2014)。但除新生儿期外, 目前支持婴儿情绪加工右偏侧化的脑结构证据仍较缺乏。成人研究从情绪韵律 (雷震等, 2021; Ukaegbe et al., 2022) 和面孔表情 (Sato et al., 2019) 等方面为右半球假说提供了丰富证据。鉴于情绪韵律与面孔表情在婴幼儿情绪发展中的重要作用 (莫李澄等, 2024), 婴儿情绪加工偏侧化的研究也主要聚焦于这两个领域。

语音的韵律特征是情绪信息的重要载体之一 (Frühholz & Grandjean, 2013), 新生儿甚至胎儿时期, 大脑就已具备加工语音中情绪性韵律的能力 (张丹丹等, 2019; 2023; Blasi et al., 2011; Zhang et al., 2019)。已有研究发现, 婴儿对韵律的加工呈现右偏侧化 (Martinez-Alvarez et al., 2023)。例如, 一项采用 oddball 范式的新生儿脑电研究 (Cheng et al., 2012) 以恐惧和快乐韵律音节为偏差刺激, 中

性音节为标准刺激，结果发现：恐惧和快乐韵律音节仅在右侧额叶诱发出 MMR，且恐惧韵律引起的 MMR 幅度更大。婴儿情绪语音加工的经典研究来自 Grossmann 等人（2010），他们采用 fNIRS 发现，7 月龄婴儿在加工快乐和愤怒韵律词语时，右侧额叶的激活显著高于中性韵律条件，而左侧额叶却未发现此差异。Zhang 等人通过系列 fNIRS 研究考察了新生儿对情绪韵律语音的反应，发现其主要依赖右侧额上回、角回和额下回等脑区加工情绪性韵律，且这些脑区对正负性情绪韵律的激活均强于中性韵律（张丹丹等，2023；Zhang et al., 2017, 2019）。此外，Homae 等人（2006）的 fNIRS 研究同样发现，3 月龄婴儿的右侧额顶区对富含韵律的语音比对平铺直叙的语音的激活更强，而左侧脑区则无此差异。最后，孤独症领域鲜有婴儿情绪加工偏侧化异常的报道。目前仅一项观测性研究发现（Blasi et al., 2015），4~7 月龄孤独症高风险婴儿对悲伤哭声的敏感性降低，且其右侧梭状回（典型的社会性情绪加工脑区）的激活弱于健康对照组。这提示孤独症婴儿可能存在情绪加工右偏侧化的减弱。

除情绪性韵律外，婴儿的面孔表情加工同样表现出显著的右偏侧化（Safar & Moulson, 2020）。例如，一项 fNIRS 研究发现，5 月龄婴儿仅右侧额叶对恐惧和快乐面孔的激活存在差异，具体表现为对恐惧表情的激活强于快乐表情（Di Lorenzo et al., 2019）。进一步地，还有研究表明 7 月龄婴儿对动态与静态面孔表情（中性、快乐和恐惧）的加工存在差异：静态面孔诱发的脑电中央区负成分（negative central component, Nc）波幅在情绪间无显著差异，而动态快乐和恐惧表情相比中性表情，仅在右侧中央区诱发更大的 Nc 波幅（Quadrelli et al., 2019）。后续研究在相同月龄婴儿中重复验证了这一右偏侧化模式（Quadrelli et al., 2021）。

尽管右半球假说已得到大量研究支持，但也有研究发现大脑在加工积极和消极情绪时存在不同方向的偏侧化模式（Pralus et al., 2020）。对此，有研究者提出了效价假说，认为消极情绪的产生、体验和调控主要依赖右半球，而积极情绪则主要由左半球负责（Palomero-Gallagher & Amunts, 2022）。当前一些婴儿情绪性听觉和视觉加工的研究为效价假说提供了证据。听觉方面，有研究发现，快乐韵律语音在 2 月龄婴儿左侧额顶皮层引起的激活强于中性和愤怒韵律语音（Shekhar et al., 2019）。视觉方

面，Fox 团队发现，10 月龄婴儿在观看演员展示快乐和悲伤面孔表情的录像片段时，快乐面孔表情会引发左侧额叶更强的激活，而悲伤面孔表情则会引发右侧额叶更强的激活（Davidson & Fox, 1982）。Nakato 等人（2011）也发现，7 月龄婴儿的左侧额叶对快乐面孔表情有更强激活，而右侧额叶则对愤怒表情有更强激活。除面孔表情加工外，身体姿态加工的研究同样发现，快乐的身体姿态会引发 8 月龄婴儿左侧额叶更强的激活，而悲伤的身体姿态会引发右侧额叶更强的激活（Missana & Grossmann, 2015）。此外，Fox 和 Davidson（1987, 1988）还考察了 10 月龄婴儿面部情绪的表达，发现婴儿表达喜悦情绪时左侧额叶的激活强于右侧额叶。

综上，婴儿在情绪性语音韵律和面孔表情加工中表现出显著的大脑右偏侧化，为情绪加工的右半球假说提供了有力证据。效价假说也得到了部分婴儿研究结果的支持，表现为左脑在积极情绪加工中更具优势，而右脑在消极情绪加工中更具优势。

4 总结和展望

语言和情绪是两种关键且复杂的认知功能，其偏侧化现象是大脑功能特异性的表现。上述研究表明，人类大脑结构和功能的半球不对称从胎儿时期就已开始发展，至婴儿期初步形成（Kong et al., 2018）。特别是与语言和情绪加工相关的脑区（额叶、颞叶），在婴儿期就已存在显著的左右半球结构和功能不对称。在语言加工方面，婴儿不仅在语言相关脑结构上呈左偏侧化，还在感知语音和语音要素时表现出功能的左偏侧化，而孤独症或高风险婴幼儿群体则表现出大脑左偏侧化减弱甚至右偏侧化。在情绪加工方面，目前存在右半球假说和效价假说两种不同的观点，现有婴儿研究发现更倾向于支持前者。其中，情绪性语音韵律加工的证据可早至新生儿阶段，而视觉性情绪面孔加工最早证据来自 5 月龄婴儿，因为此时他们的视觉精细加工能力才开始成熟。值得注意的是，目前缺乏婴儿情绪右偏侧化的脑结构证据（例如成人研究一致表明了社会情绪脑区——颞上沟的右偏；Leroy et al., 2015）。总之，与语言加工较为明确的左偏侧化不同，婴儿情绪加工右偏侧化结论尚未得到一致性地认可，相关证据仍不完整。

在婴儿大脑对语言和情绪加工的偏侧化领域，我们建议未来还值得在以下方面开展工作。

第一,采用非语音的情绪材料,排除混淆因素,清晰地揭示婴儿情绪加工的大脑偏侧化。现有婴儿情绪加工研究多采用情绪性语音作为实验材料,但这可能使得婴儿在处理情绪信息的同时进行语言加工。Yamane等人(2021)的研究为此提供了典型证据,他们在考察婴儿对音乐(类似于情绪性语音)的加工时发现:当仅有歌词发生改变时,12月龄婴儿的左半球激活增强;当仅有音乐旋律发生改变时,婴儿的右半球激活增强;而当歌词和旋律同时改变时,婴儿大脑则表现为双侧激活增强且左右脑激活程度无显著差异。这表明婴儿会同时对语言和情绪韵律进行加工,导致观察到的语言左偏侧化与情绪右偏侧化的结果相互混淆。为避免这一问题,未来研究可以使用非语音材料。针对视觉尚未完全发展的半岁以下婴儿,我们认为不含歌词的情绪性音乐韵律可能是研究情绪加工的理想材料;针对视觉已基本发育成熟的半岁以上婴儿,我们推荐面孔表情和身体姿态表情等视觉情绪材料。

第二,纵向追踪婴儿偏侧化的发展及其关键期。语言和情绪加工在人类出生后的第一年内发生了巨大的改变。以情绪加工为例(Missana & Grossmann, 2015),8月龄婴儿会表现出4月龄婴儿所不具备的陌生人焦虑(Braungart-Rieker et al., 2010),并能分辨4月龄婴儿无法区分的身体姿态表情(Missana & Grossmann, 2015)。此外,有研究表明新生儿的情绪加工具有正性偏向(即优先加工正性信息),但1周岁的婴儿已表现出与儿童和成人一致的负性偏向(张丹丹等,2023)。这些发现提示婴儿情绪加工及其偏侧化的发展可能存在关键期。目前仅有一项纵向研究考察了婴儿大脑情绪加工偏侧化的发展(Brooker et al., 2017),该研究分别在6月龄和12月龄时测量了婴儿对情绪信息(陌生人恐惧和躲猫猫游戏)加工的大脑偏侧化程度,结果发现婴儿额叶对消极情绪偏侧化的短期稳定性不足,而额叶和顶叶对积极情绪偏侧化的短期和长期稳定性都很低。这提示婴儿不同脑区对不同情绪加工偏侧化的发展存在差异。鉴于婴儿大脑的快速发展,未来研究应采用纵向追踪设计,通过多时间点、多指标的全面观测,系统揭示婴儿大脑偏侧化的变化规律。

第三,同时考察婴儿语言和情绪加工的大脑偏侧化。研究表明,婴儿情绪和语言加工存在相互促进的关系(Hoemann et al., 2019; Ma et al., 2020; Shablack et al., 2020)。例如,丰富的情绪性韵律信

息可促进7月龄婴儿的语音编码(Kalashnikova et al., 2018),而婴儿的语言功能也能促进其对情感概念的习得(Shablack et al., 2020)。由此可见,作为语言和情绪加工的神经基础,大脑偏侧化在发展过程中很可能存在相互作用。例如,在儿童阅读学习导致的大脑重组过程中,文字与面孔表征在左侧梭状回的竞争会导致文字与面孔识别区域出现互补的偏侧化模式:文字表征在左侧梭状回,而面孔表征转移至右侧梭状回(Dehaene et al., 2015)。在研究中同时考察婴儿语言和情绪加工的大脑偏侧化,可以推进三个层面的工作。首先,可以通过对比凸显、准确揭示语言和情绪这两大认知功能的发展特征,例如Arimitsu等人(2011)采用带有或不带韵律的日语音节材料发现,新生儿对音节改变产生左偏的脑反应,而对韵律改变则产生右偏的脑反应。其次,鉴于孤独症患儿常表现为语言加工的左偏侧化减弱或右偏侧化,情绪加工的右偏侧化减弱或左偏侧化(Lindell, 2020),将婴儿语言和情绪偏侧化相结合作为孤独症的早筛指标,有望提高该病筛查的敏感性。最后,在理论层面,有利于提出统一的大脑偏侧化理论,同时支撑语言左偏化、情绪的右半球假说和效价假说的实验结果。例如,Ross(2021)提出的“情绪类型假说”就非常值得我们借鉴,该假说认为,右半球负责加工与生存密切相关的基本情绪(尤其是愤怒、恐惧等),而左半球主要处理社交性情绪(愉悦、爱等)以及同样与社交高相关的语言。这种分化源于进化需求——右半球的快速反应机制利于应对即时威胁,左半球的精细调控则适应复杂社交。我们建议未来在同一项研究中通过同时考察婴儿语言和情绪加工,证实或修订该理论观点。

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Hemispheric Lateralization in Infant Language and Emotion Processing

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Abstract The developing human brain exhibits remarkable functional specialization, with hemispheric lateralization emerging as a fundamental organizational principle that begins during fetal development. This review synthesizes current knowledge about the neural underpinnings of language and emotion processing in infants (ages 0~12 months) and toddlers (ages 1~3 years), focusing on the establishment of hemispheric asymmetry and its implications for both typical and atypical neurodevelopment.

Structural and functional hemispheric asymmetries manifest early in ontogeny, preceding the contralateral organization of sensorimotor systems. Unlike the strict contralaterality observed in primary sensory and motor pathways, cognitive lateralization represents a relative dominance where one hemisphere assumes primary responsibility while maintaining bilateral involvement. This specialized organization enhances neural efficiency by reducing redundant processing and enabling the parallel computation of complex cognitive functions. Crucially, the developmental trajectory of lateralization serves as a sensitive biomarker of neurodevelopmental integrity, with atypical patterns predicting subsequent emergence of conditions including autism spectrum disorder (ASD), schizophrenia, and obsessive-compulsive disorder.

Our comprehensive analysis reveals robust evidence of left-hemisphere dominance in infant language processing at multiple neurobiological levels. Structural MRI studies demonstrate early leftward asymmetries in perisylvian regions and white matter tracts, particularly the arcuate fasciculus connecting Broca's and Wernicke's areas. Functional neuroimaging confirms this specialization, with left temporal regions showing preferential activation for speech stimuli as early as the neonatal period. Notably, this typical pattern appears disrupted in infants at high risk for ASD, who exhibit either reduced leftward lateralization or paradoxical right-hemisphere dominance - a finding with significant implications for early identification.

The neural substrates of emotion processing present a more complex picture. While the right-hemisphere hypothesis receives substantial support from studies on emotional prosody and facial expression processing, competing evidence for valence-specific lateralization (the left hemisphere for positive affect, right for negative) complicates theoretical accounts. Developmental studies suggest this dichotomy may reflect different processing stages, with initial right-hemisphere bias for rapid emotion detection followed by valence-dependent lateralization during conscious evaluation. Methodological variations in stimulus selection and experimental paradigms likely contribute to these discrepant findings.

Three critical directions emerge for advancing this field:

First, refined experimental paradigms must address the inherent confounds of current emotion research. The prevalent use of emotional speech stimuli inadvertently engages both language and emotion networks, potentially obscuring emotion-specific lateralization. We recommend developmentally appropriate alternatives: non-linguistic auditory stimuli (e.g., emotional music) for younger infants and dynamic visual stimuli (e.g., facial/bodily expressions) for older infants. These approaches would provide a clearer characterization of emotion processing networks.

Second, the field urgently requires longitudinal investigations to map the dynamic development of functional asymmetry. Existing cross-sectional designs cannot adequately capture the potentially non-linear trajectories of lateralization establishment. Prospective studies with dense sampling intervals could identify critical periods and developmental milestones in hemispheric specialization, while clarifying the relationship between early atypical patterns and subsequent neurodevelopmental outcomes.

Third, integrative research designs simultaneously assessing language and emotion processing could yield transformative insights. The known behavioral coupling of these domains suggests their neural substrates may develop interactively. Combined assessment protocols would not only reveal potential synergies in typical development but also enhance early identification of neurodevelopmental risk through multi-modal neural signatures.

The exceptional plasticity of the infant brain underscores the clinical importance of this research. By elucidating both normative and atypical patterns of functional lateralization, we move closer to developing sensitive, objective markers for early intervention. Future work should prioritize: (1) Standardized protocols for assessing lateralization across development, (2) Mechanistic studies examining genetic and environmental influences on asymmetry development, and (3) Translational applications linking neural markers to behavioral outcomes.

This synthesis highlights how the study of early hemispheric specialization bridges fundamental neuroscience with clinical applications. As neuroimaging technologies advance, refined characterization of lateralization patterns promises to transform our understanding of both typical brain development and the origins of neurodevelopmental disorders.

Key words infants, hemispheric lateralization, language processing, emotion processing