超扫描视角下的社会互动脑机制

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摘 要 超扫描技术可同时记录多名被试在同一认知活动中的脑活动，并通过分析脑间活动同步及其与行为指标间的关系描述社会互动的脑机制。本文总结了近十多年超扫描研究对社会互动脑机制的研究成果，在其基础上指出脑间活动同步可作为社会互动的神经标记，刻画社会互动中感知运动、信息传递与加工、思维决策等三大层面上的互动情形，并阐述了超扫描技术研究的局限性及其研究展望与应用潜能。

关键词 社会互动 超扫描技术 脑间活动同步 神经标记

1 引言

社会互动是人类生活不可或缺的组成部分，对其背后神经基础的研究则成为了近年来脑科学研究者倍加关注的焦点。近几十年来，社会认知神经科学的研究已获得一系列成果，如研究表明颞顶联合区 (temporo-parietal junction, TPJ) 与内侧前额叶皮质 (medial prefrontal cortex, MPFC) 的活动水平与心理理论、他人信念推理等社会认知活动息息相关 (van Overwalle, 2009)，镜像神经元系统 (mirror neuron system, MNS) 则被认为负责他人肢体动作的解读 (Hari & Kujala, 2009)，并与模仿、语言理解、意图揣测与共情等认知功能紧密相连 (胡晓晴，傅根跃，施臻彦，2009)。然而，由于社会互动由多人参与形成的本质，研究中只关注单个大脑的活动的方法无法对多人互动中的脑机制做出全面深入的解读 (Hasson, Ghazanfar, Galantucci, Garrod, & Keysers, 2012; Koike, Tanabe, & Sadato, 2015)。为解决这一问题，超扫描技术应运而生。

2 超扫描技术及其发展现状

2.1 超扫描技术简介

超扫描 (Hyperscanning) 指同时记录参与同一认知活动的两人或多人的脑活动，通过分析脑间活动同步及其与行为指标间的关系，揭示社会互动相关的脑机制。Montague 等 (2002) 首次提出了超扫描概念，通过使用两台 fMRI 设备同时记录两名被试在共同完成欺骗游戏时的脑活动，以探索欺骗行为的脑机制。此后，一系列基于脑电 (EEG) (Babiloni et al., 2006)、功能性近红外成像 (fNIRS) (Funane et al., 2011) 以及脑磁图 (MEG) 等技术设备的超扫描技术纷纷涌现（图 1）。超扫描视角下的社会互动脑机制研究包含以下特征：（1）数据采集层面，采用联结多台相同设备或将同一设备分配给多人的手段同时采集多人的脑与行为数据；（2）数据分析层面，不关注认知活动伴随的单一个体脑活动，而重点分析认知过程中多名个体的脑间活动同步 (interpersonal neural synchronization, INS)。脑间活动同步指标代表个体间脑信号的相关性或相干性，可衡量个体间互动关系。因此，超扫描技术得以记录多人实时互动中的脑数据，并利用脑间活动同步指标量化不同主体间的互动关系，提高研究生态效度。

2.2 超扫描研究概况

2002 年以来，超扫描技术呈现迅猛的发展趋势。以 hyperscanning 等为关键词，在 Web of Science 等数据库中可得到近 150 篇学术论文（图 2A）。在技术手段上，EEG、fNIRS、fMRI 与 MEG 设备均已

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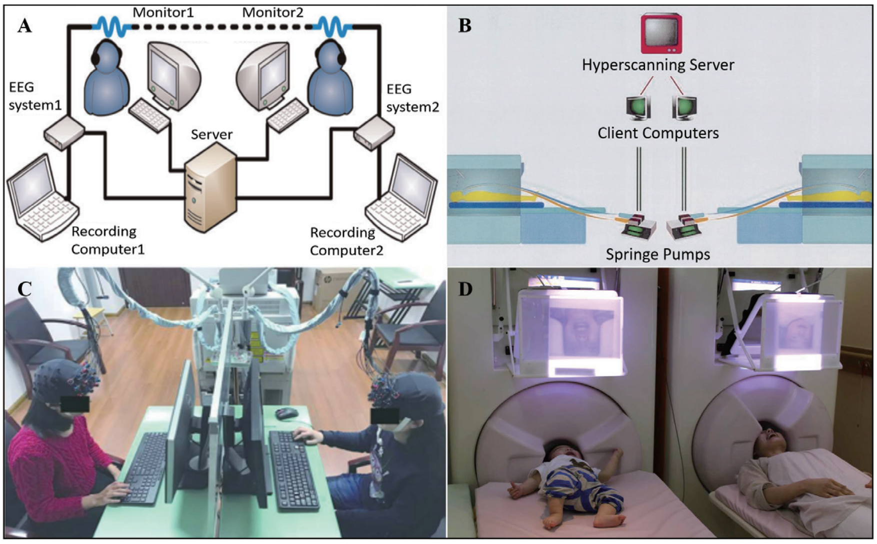

图 1 常见的超扫描技术平台

注：（A）EEG 超扫描技术 (Mu, Guo & Han, 2016)；（B）fMRI 超扫描技术 (Montague, et al., 2002)；（C）fNIRS 超扫描技术 (Hu, et al., 2017)；（D）MEG 超扫描技术 (Hirata et al., 2014)。

用于超扫描研究（图 2B）。EEG 具备时间分辨率高、易操作、低成本等优势，在多种超扫描技术中使用最广，但较低的空间分辨率 (Hari, Henriksson, Malinen, & Parkkonen, 2015) 使其无法精确定位脑电信号发出的位置，难以描述脑间活动同步发生的解剖学位置。fMRI 为最早被使用的超扫描技术，空间分辨率高，但较高的成本及被试需以躺卧状态接受扫描的方式限制了该技术在更多情境下的使用 (Liu & Pelowski, 2014b)。fNIRS 允许被试进行一定范围内的自由活动，可在更具高生态效度情境下记录大脑皮层活动，但难以应用于以皮层下活动为重点的研究 (Scholkmann, Holper, Wolf, & Wolf, 2013)。MEG 技术同时具备较高的空间分辨率与时间分辨率 (Hari & Salmelin, 2012)，于近年出现与 EEG 同时应用于超扫描研究的进展 (Ahn et al., 2018)。此外，近两年出现了经颅交流电刺激 (tACS) 超扫描研究 (Novembre, Knoblich, Dunne, & Keller, 2017; Szymanski, Müller, Brick, Von Oertzen, & Lindenberger, 2017; Varlet, Wade, Novembre, & Keller, 2017)，拓展了现有框架下社会互动脑机制的研究范畴。

近年来，超扫描研究进展迅速，其研究主题、技术手段、分析方法与范式的多样，提供了互动个体完成的社会认知活动的内在机制证据。本文从脑间活动同步指标入手，对现有超扫描研究视角下的社会互动脑机制进行了整合与总结，并对其局限性和展望进行了梳理。

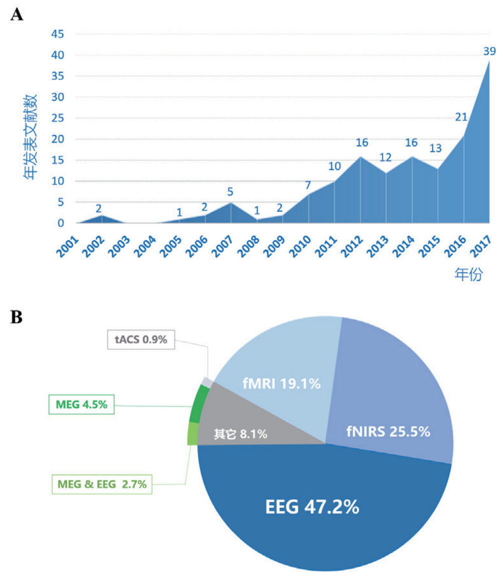

图 2 2001-2017 年超扫描研究发展现状

（A）发表论文数量概况；（B）所用技术设备分布情况

数据来自以下数据库：Web of Science，BIOSIS Citation Index，MEDLINE，Inspec，KCI，Russian Science Citation Index，Pubmed，SciELO Citation Index，PsycINFO，PsycARTICLES，Psychology and Behavioral Sciences Collection；文献搜索所用关键词：hyperscanning, inter-brain coherence, inter-brain connectivity, inter-brain correlation, inter-brain synchronization, interpersonal brain synchronization

3 超扫描视角下的社会互动脑机制研究

超扫描研究的共同点在于探索社会互动中多名个体的脑活动及其联系，而其差异多体现为具体社会互动任务中所涉及心理与认知功能的不同。本文据此将已有超扫描研究分为以下三种类型（表 1）：

a. 探索感知与运动层面的社会互动：该类研究通常探索个体在执行相同任务时的脑活动情形，任务内容多为动作（如敲击节拍）(Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010) 或音乐任务（演奏 (Lindenberger, Li, Gruber, & Muller, 2009)、演唱 (Osaka et al., 2015)），不涉及语义信息传递与思维和决策等高级心理功能，被试间也不存在任务目标与动机的分歧。

b. 探索信息传递与加工层面的社会互动：该类研究旨在探索个体沟通与交流中的脑活动，被试以言语 (Spiegelhalder et al., 2014)、符号 (Stolk et al., 2014)、表情 (Anders, Heinzle, Weiskopf, Ethofer, & Haynes, 2011)、眼神 (Cavallo et al., 2015) 等方式沟通是其主要任务形式。

c. 探索思维与决策层面的社会互动：此类研究探索社会互动中的个体目标、动机与决策等高级认知功能的脑机制。如考察个体在“合作”与“竞争”不同任务目标下的脑活动差异 (Cui, Bryant, & Reiss, 2012; Funane et al., 2011)，或经济决策任务中“合作”或“背叛”、“信任”或“欺骗”决策的脑机制 (Chiu et al., 2008; De Vico Fallani et al., 2010)。

3.1 感知与动作层面的社会互动脑机制

Dumas 等 (2010) 首次利用 EEG 超扫描技术探索个体动作同步的脑机制，发现当两被试模仿彼此手势时，其动作一致性与右侧顶叶中部 mu、beta 与 gamma 频段脑电信号的同步正相关。Yun, Watanabe 和 Shimojo 等 (2012) 则通过 fNIRS 超扫描发现，两名被试利用手势完成一系列互动任务后，其动作同步水平与额下回、前扣带回、海马旁回的脑间活动同步均得到提高。另外，脑间活动同步可反映双人杂技任务的技能熟练度 (Filho et al., 2016) 与个体言语节律的同步程度 (Kawasaki, Yamada, Ushiku, Miyauchi, & Yamaguchi, 2013)。MEG 超扫描研究则发现感觉运动皮层等区域的脑间活动同步与手势同步程度正相关 (Zhdanov et al., 2015; Zhou, Bourguignon, Parkkonen, & Hari, 2016)。以上研究均表明脑间活动同步与动作一致性间的关联，为进一步探讨两者间的因果关系，Szymanski 等 (2017) 开展了 tACS 超扫描研究：两名被试同时接受两台 tACS 设备于右侧前额和右侧顶叶的信号刺激，并被要求在实验中与对方或机器按相同节奏击鼓。不同实验条件下，被试接收的信号刺激包括——一致信号（均为 5Hz 且同相位）、非一致信号（分别为 5Hz 与 7Hz，相位不同）及控制条件下的虚假信号。结果发现，一致与非一致信号条件下，被试动作同步程度相较控制条件均有所减退，该现象在人机同步中则未出现。个体在接收 tACS 刺激上的差异被认为是导致一致信号未增进动作同步的原因。Varlet 等 (2017) 的研究中，两名被试同时接受初级运动皮层同频率的 tACS 刺激，发现同时接受 10Hz 与 20Hz 的信号并未影响被试的动作同步程度。而 Novembre 等 (2017) 则发现对左侧初级运动皮层 20Hz 下的 tACS 同相位刺激提升了被试间动作节拍的同步程度，并认为对同相刺激的感应增进了动作同步。由于目前 tACS 超扫描研究数目有限，行为同步与脑间活动同步的因果性关联尚未得出一致结论，而探索刺激信号的具体频率与脑区分布对动作同步的影响或将成为该领域未来研究的重点。

表 1 超扫描研究所考察的社会互动层面、研究主题与任务范式

社会互动层面	研究主题	任务范式
感知与运动层面	1 动作同步的脑机制	1 手势模仿任务
	2 合奏与合唱行为的脑机制	2 节奏同步任务
	3 动作同步与脑间活动同步的因果关系	3 合奏与合唱任务
信息传递与加工层面	1 言语沟通的脑机制	1 讲述与倾听任务
	2 非言语沟通的脑机制	2 眼神、手势、符号交流任务
思维与决策层面	1 合作与竞争情形下的脑机制	1 合作与竞争按键任务
	2 合作与背叛决策的脑机制	2 回合制合作与竞争任务
	3 欺骗与信任的脑机制	3 经济决策任务

除此以外，音乐的演奏与发声为另一种常见的同步任务形式。采用 EEG 超扫描技术，Lindenberger 等 (2009) 发现吉他手的合奏使其前额叶 theta 波段出现脑间活动同步，且同步程度与合奏中行为一致性显著相关。其它 EEG 超扫描研究显示，合奏行为可诱导脑电信号 theta 和 delta 频段脑间活动同步的出现 (Sanger, Müller, & Lindenberger, 2012)，而 alpha 频段的脑间活动同步则反映了合奏中的情感共鸣 (Babiloni et al., 2012) 和知识共享程度 (Novembre, Sammler, & Keller, 2016)。fNIRS 超扫描研究则表明前额叶脑间活动同步的提升也出现在小提琴合奏

(Balardin et al., 2017)、合唱 (Osaka et al., 2015) 与击鼓 (Duan et al., 2015) 中。

综上所述，镜像神经元 (Schippers, Roebroeck, Renken, Nanetti, & Keysers, 2010)、感觉运动区 (Zhdanov et al., 2015)、前额叶与右侧额顶叶 (Balardin et al., 2017) 存在的明显的脑间活动同步在社会互动的感知运动层面发挥了活跃作用。尽管一些动作任务被认为涉及预测他人行为等高级心理功能 (Liu & Pelowski, 2014a)，相关研究发现无意识情形下达成的动作同步同样伴随着显著的脑间活动同步 (Yun et al., 2012)，表明动作一致性与脑间活动同步存在密切关联。

3.2 信息传递与加工层面的社会互动脑机制

采用 fMRI 超扫描技术，Spiegelhalder 等 (2014) 让一位被试倾听另一位被试的发言，以探索言语交流的脑机制，发现讲述者言语相关脑区与倾听者的听觉功能相关脑区存在脑间活动同步。此后的 EEG 超扫描研究同样发现言语交流中出现颞叶、顶叶等区域的显著脑间活动同步 (Pérez, Carreiras, & Duñabeitia, 2017; Tadić, Andjelković, Boshkoska, & Levnajić, 2016)，此外，非言语性线索 (Jiang et al., 2012) 及沟通者间的亲密关系 (Kinreich, Djalovski, Kraus, Louzoun, & Feldman, 2017) 也会影响言语交流中的脑间活动同步。而以非言语信息进行的交流过程，如目光接触 (Saito et al., 2010)、眼神交流 (Cavallo et al., 2015; Hirsch, Zhang, Noah, & Ono, 2017; Leong et al., 2017)、面部表情交流 (Anders et al., 2011)、符号交流 (Stolk et al., 2014)、手势交流 (Schippers et al., 2010) 均能诱导额叶、颞叶、运动皮层等脑区脑间活动同步的产生。

除两被试间的互动，一些超扫描研究考察了三人及三人以上的互动场景，如三人无领导小组讨论 (Jiang et al., 2015)、演讲者与多名听众间互动 (Tadić et al., 2016)、课堂教学中的师生互动 (Dikker et al., 2017)、多人音乐任务 (Babiloni et al., 2012; Duan et al., 2015) 与游戏 (Astolfi et al., 2010b) 等，表明脑间活动同步也可描述更复杂的多人互动情形，如其同步程度可区分无领导小组讨论中的领导者与非领导者 (Jiang et al., 2015)，反映教学情境中教学风格、学生参与度等 (Dikker et al., 2017)。

以上研究表明脑间活动同步可反映社会互动中的信息交流与沟通情形，如沟通成功与否 (Stephens, Silbert, & Hasson, 2010) 与非言语因素 (Jiang et al., 2012) 的影响。单人条件或人机互动中的脑间活动同步普遍低于真人互动条件 (Cui et al., 2012; Funane et al., 2011; Kawasaki et al., 2013; Piva, Zhang, Noah, Chang, & Hirsch, 2017; Tomlin et al., 2006)，表明脑间活动同步或可反映交流中各社会主体间联结程度 (Schoot, Hagoort, & Segaert, 2016)，而真实互动对象间的信息交互或为其产生前提。

3.3 思维与决策层面的社会互动脑机制

Funane 等 (2011) 最早利用按键任务考察合作行为的脑机制：任务中，两名被试在听到提示音后倒数十秒并按键。利用按键后得到的反馈，被试可以调整节奏，尽可能同时按键，按键时间越接近代表行为同步程度越高、合作成绩越好。此类任务中合作行为体现为双方同时进行按键等动作，被称为同时性互动 (concurrent interactions) (Liu & Pelowski, 2014a)。研究发现合作中被试前额叶出现脑间活动同步，且任务成绩好的被试组脑间活动同步显著高于较差组，体现了合作任务成绩与脑间活动同步的相关。Cui 等 (2012) 利用以上范式发现竞争任务下被试前额叶脑间活动同步显著低于合作任务，表明任务目标与意图的差异会影响脑间活动同步的高低。利用同一范式，研究发现脑间活动同步可反映合作任务中个体性别差异 (Baker et al., 2016; Cheng, Li, & Hu, 2015)、异性个体间的亲密关系 (Pan, Cheng, Zhang, Li, & Hu, 2017)、催产素 (Mu et al., 2016) 与社会性威胁 (Mu, Han, & Gelfand, 2017) 对合作行为的影响。

而回合制的合作与竞争任务中，合作与竞争条件下均出现了脑间活动同步 (Liu et al., 2016; Liu, Saito, & Oi, 2015)：该类任务中个体的合作通过轮流行动的形式实现，即回合制互动 (turn-based interactions) (Liu & Pelowski, 2014a)。Liu 等 (2015) 的棋盘游戏任务中，两名被试轮流在棋盘上放置圆盘，一名被试需要在将圆盘摆放为规定图案，另一名被试则需在合作与竞争条件下帮助或阻碍前者摆出规定图形。实验发现合作和竞争条件下右侧后颞上沟均出现脑间活动同步；但仅在竞争条件下，阻碍者和建筑者的额下回 (Liu et al., 2015)、顶下小叶 (Liu, Saito, Lin, & Saito, 2017) 部位出现明显脑间活动同步，表明个体对他人意图的表征——“合作”与“竞争”均可通过脑间活动同步指标体现。

此外，一些研究借助经济决策任务发现脑间活动同步可反映合作与背叛 (Astolfi et al., 2009; De Vico Fallani et al., 2010)、信任与欺骗 (King-Casas, 2005;

Tang et al., 2016; Zhang, Liu, Pelowski, & Yu, 2017) 及共情 (Astolfi et al., 2015) 等高级认知功能。如囚徒博弈 (De Vico Fallani et al., 2010)、斗鸡博弈 (Astolfi et al., 2010a) 超扫描研究中，相对于至少一方选择“背叛”，双方均选“合作”时前额叶等区域出现更高脑间活动同步。

以上研究表明，在社会互动的思维、决策等高级认知功能层面，脑间活动同步可反映个体所持目标、意图与决策的差异，扣带回 (King-Casas, 2005; Tomlin et al., 2006)、颞顶联合区 (Jiang et al., 2015; Piva et al., 2017; Tang et al., 2016)、前额叶 (Babiloni et al., 2006; De Vico Fallani et al., 2010; Jahng, Kralik, Hwang, & Jeong, 2017) 等脑区在以上认知过程中发挥了作用。鉴于以上脑区在计划与控制、他人意图揣测等领域的功能 (van Overwalle, 2009)，可认为其脑间信号同步反映了个体在社会互动情形中的一系列高级认知功能，如目标执行、心理理论及决策等。

4 总结与展望

4.1 研究总结

综上所述，本文认为脑间活动同步可作为描述互动个体参与的社会认知活动的客观神经标记，在社会认知科学领域中体现出强大的研究与应用潜力。同时，研究表明不同形式的社会互动现象背后可能存在普遍的心理与脑机制，其详细机制仍有待进一步探索。然而，当下社会互动的超扫描研究存在明显的局限，体现在（1）现有设备与数据采集技术尚无法实现对自然情境下社会互动的研究。（2）社会互动过程常伴随情绪、生理活动以及眼神交流等变化，需整合行为 - 生理 - 眼动 - 脑数据的多模态超扫描平台。（3）需借助数学建模等手段，为脑间活动同步与社会互动间关系提供更坚实的解释与科学依据。

4.2 研究展望

超扫描已被证实在社会互动脑机制研究中具备独特的研究价值与应用潜能，将在以下方面有所体现：（1）教学质量评估：师生脑间活动同步与学习效果 (Holper et al., 2013)、教学风格 (Dikker et al., 2017)、学生参与度 (Dikker et al., 2017) 等多种教学因素相关。该指标的应用可为教学状况评估提供科学、动态的评价标准。（2）异常人群社会功能缺陷评估：脑间活动同步指标可区分健康人群与边缘性人格障碍者 (Bilek et al., 2017) 及高功能自闭症患者 (Chiu et al., 2008)，对社会功能缺陷脑机制的研究或将成为未来研究重点。（3）其它应用前景：如医患互动 (Kawano, Majima, Maekawa, Katagiri, & Ishigame, 2016)、领导力评估 (Jiang et al., 2015; Venturella, Gatti, Vanutelli, & Balconi, 2017) 及心理咨询与治疗的机制探索与效果评估。

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The Brain-to-Brain Correlates of Social Interaction in the Perspective of Hyperscanning Approach

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Abstract Hyperscanning approach is a type of neuroimaging technique. It refers to the measuring of neural activities simultaneously from two or more agents involved in the same social interactions. Then inter-brain coupling (or interpersonal neural synchronization, INS) is analyzed and used to explain brain-to-brain neural correlates of social interactions in the perspective of group level. During the past decade, hyperscanning approach has become more and more popular, and has been a powerful approach to elucidate intrinsic property of higher cognition with social interactions in condition of higher ecological validity, such as cooperation/competition, behavioral synchrony/imitation, interpersonal communication and economic decision-makings, etc. In this paper, we first review and summarize the previous hyperscanning studies over the past decade, which are followed by limitations and future studies on other research fields with social interaction.

First, stronger interpersonal neural synchronization (INS) emerges in prefrontal cortex (PFC) and/or right temporal-parietal junction (TPJ) with better coordination performances during singing, instrument playing and game of charades. More interestingly, several pieces of evidence show INS is correlated with the empathy and shared knowledge. Second, enhanced prefrontal INS is also observed in the interpersonal communication task (face-to-face verbal communication task, emotional transmission and so on). Further, INS can predict verbal and/or non-verbal communication quality, such as teacher-student interactions during teaching, leader emergence during a non-leader group discussion task. Third, enhanced INS is consistently obtained in PFC and/or TPJ during two participants performing both the concurrent cooperation task (such as joint key-press task) and the turn-taking cooperation/competition task (such as disk-game task), while no or much lower INS is found in control conditions. Such evidence indicates that INS can serve as a neuromarker to depict the cooperation and competition behaviors in social context. Moreover, prefrontal INS is also found in economic games (such as trust game, prisoner's dilemma, et al.) and spontaneous deception, etc. To summarize, interpersonal neural synchronization in widely-distributed network in the brain, especially in fronto-parietal network, could explain social interaction in the group level, which gives us a deep understanding of the nature of social interaction from the level of sensation/motion, decision-making and information transmission.

However, the limitations on hyperscanning studies should also be mentioned. First, portable equipment and much higher-resolution fNIRS equipment are required to be used in many types of natural social interactions. Second, eye movement and physiological activities are important in social interactions, a multimodal hyperscanning platform with combination of behavioral, physiological, eye movement and brain data needs to be developed. Third and most importantly, an optimal mathematical model should be built up based on multiple levels of data, which can help us to understand the nature of interpersonal neural synchronization and intrinsic property of social interaction.

Finally, the hyperscanning approach has huge potentials in both scientific research and clinic applications, such as dynamic evaluation of teaching quality, dynamic evaluation of psychological counseling, measurement of social function deficiency and optimizing inference resolution in patients with autism, and schizophrenia and so on.

Key words social interaction, hyperscanning, interpersonal neural synchronization, neuromarker