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Review

Noninvasive stimulation of the temporoparietal junction: A systematic review

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ABSTRACT

Imaging and lesion studies have suggested numerous roles for the temporoparietal junction (TPJ), for example in attention and neglect, social cognition, and self/other processing. These studies cannot establish causal relationships, and the importance and relevance of (and interrelationships between) proposed roles remain controversial. This review examined studies that use noninvasive transcranial stimulation (NTS) to explore TPJ function. Of the 459 studies identified, 40 met selection criteria. The strengths and weaknesses of NTS-relevant parameters used are discussed, and methodological improvements suggested. These include the need for careful selection of stimulation sites and experimental tasks, and use of neuronavigation and concurrent functional activity measures. Without such improvements, overlapping and discrete functions of the TPJ will be difficult to disentangle. Nevertheless, the contributions of these studies to theoretical models of TPJ function are discussed, and the clinical relevance of TPJ stimulation explored. Some evidence exists for TPJ stimulation in the treatment of auditory hallucinations, tinnitus, and depersonalisation disorder. Further examination of the TPJ in conditions such as autism spectrum disorder is also warranted.

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1. Introduction

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The temporoparietal junction (TPJ) is a critical multimodal cortical region, the precise role and anatomy of which remains controversial. Not only are its functional roles and anatomical boundaries debated, but its very conception as a unified region with a common function is uncertain. Though definitions vary, the TPJ generally refers to an area of cortex at the junction of the inferior parietal lobule, lateral occipital cortex, and the posterior superior temporal sulcus (Mars et al., 2012; Fig. 1). The TPJ receives inputs from thalamic, limbic, somatosensory, visual and auditory areas, and has bidirectional connectivity with distal temporal and prefrontal regions (Decety and Lamm, 2007). Due to this location at the confluence of diverse information streams, the TPJ is hypothesised to be a critical hub for multisensory integration and processing.

Traditionally, evidence regarding TPJ function has emerged from functional imaging and lesion studies. Functional imaging studies implicate the TPJ in processes as varied as episodic memory retrieval (Vilberg and Rugg, 2008; Wagner et al., 2005), temporal processing (Davis et al., 2009), language and speech (Binder et al., 2009), resting state activity (Buckner et al., 2008; Greicius et al., 2003), vestibular function (Ventre-Dominey, 2014), attention (Corbetta and Shulman, 2002) and social cognition (Dunbar, 2012; Van Overwalle, 2009). The latter two constructs have attracted the bulk of the research interest, particularly regarding areas of overlapping activity in and near the right TPJ (rTPJ). Earlier studies examining the rTPJ in attention emphasise its involvement in bottom-up attentional reorienting based on stimulus salience (Corbetta and Shulman, 2002; Decety and Lamm, 2007). Some later papers suggest a further role of the rTPJ in top-down attentional processes (Geng and Vossel, 2013; Vossel et al., 2014). The rTPJ has also been implicated in left hemifield neglect, which refers to a deficit in attention to the left side of space (Ptak and Schnider, 2011). Similarly, many studies of social cognition have identified TPJ activity during processes involving mentalising (Gallagher and Frith, 2003; Saxe and Kanwisher, 2003) and related constructs such as belief attribution (Young and Saxe, 2008), imitation and control thereof (Santiesteban et al., 2012b; Sowden and Catmur, 2013), and moral processing (Greene et al., 2004; Young and Saxe, 2009). Important mentalising processes occur in the TPJ bilaterally (Perner et al., 2006). There is also a strong body of literature connecting TPJ activity to self-other and bodily-awareness processing, such as sense of agency (Farrer et al., 2003; Farrer and Frith, 2002; Ruby and Decety, 2001), self-other discrimination (van der Meer et al., 2011; Vogeley et al., 2001), and embodiment (Arzy et al., 2006). Indeed, out-of-body experiences (OBEs) may be related to multisensory integration failure at the TPJ (Blanke and Arzy, 2005; Blanke et al., 2002). OBEs involve the perception of being outside one's own body, and often observing oneself from this perspective.

Lesion studies tend to paint a similar portrait in terms of deficits associated with TPJ damage. One challenge regarding synthesis and making inferences, however, is that damage is infrequently focal to the TPJ specifically, so functional contributions can be more difficult to pinpoint with confidence. Having noted this caveat, the lesion literature is particularly rich regarding TPJ involvement in attention and visual neglect (Committeri et al., 2007; Ticini, 2013). Damage to the rTPJ has long been associated with neglect symptoms (Di Pellegrino, 1995; Friedrich et al., 1998; Karnath et al., 2003; Vallar and Perani, 1986), although it is increasingly acknowledged that neglect is heterogeneous both behaviourally and anatomically (Karnath et al., 2004). Two recent activation likelihood estimation meta-analyses examining lesion-symptom mapping studies relevant to visual and spatial neglect affirm this diversity (Chechlacz et al., 2012; Molenberghs et al., 2012). Separate lesion sites were found to be divergently influential in different tasks, and damage to different regions within the TPJ itself had different implications. For example, more posterior lesions (including the angular gyrus) impacted allocentric function more greatly than in egocentric frames of reference, which were more heavily influenced by lesions to supramarginal and superior temporal gyri (Chechlacz et al., 2012). Regarding attention more generally, lesion evidence supports TPJ involvement in both top-down (Geng and Vossel, 2013) and bottom-up attention processes (Castiello and Paine, 2002; Corbetta et al., 2005; Posner et al., 1984). The lesion literature also supports the notion that the TPJ is critical to a range of other processes, including language and speech (Buchsbaum et al., 2011) and motor-sensory abilities such as perception-action coupling (Ro et al., 1998). Left TPJ damage has been associated with ideational apraxia (De Renzi and Lucchelli, 1988), and TPJ damage in general impacts a range of bodily-awareness and self-other processing abilities, such as vestibular function, internal body models and postural stability (Pérennou et al., 2000; Ventre-Dominey et al., 2003). It can also result in deficits such as anosognosia and personal neglect (Committeri et al., 2007; Starkstein et al., 1992) and contribute to the likelihood of OBEs (Blanke and Arzy, 2005). The self-other processing that occurs at the TPJ may also be critical in terms of higher order social cognitive processes. For example, one study examining 13 patients with TPJ lesions found imitative control and perspective-taking performance to be relatively impaired in a manner that was significantly correlated (Spengler et al., 2010). TPJ lesions have also been found to effect facial emotion recognition and emotional empathy (Shamay-Tsoory, 2011; Starkstein et al., 1992), as well as mentalising processes such as belief attribution (Samson et al., 2004).

There is significant debate as to whether the rTPJ primarily subserves attention, social cognition, or a co-dependent combination of both. Earlier papers tend to advocate the primacy of either attention (Mitchell, 2008) or social cognition (Saxe and Wexler, 2005), or attempt to explain overlapping function in terms of unified, co-dependent processes (Decety and Lamm, 2007). In the latter case, the TPJ is viewed as a critical hub in predicting external events and reorienting attention based on stimulus salience. According to Decety and Lamm (2007) these lower-level processes are important in a domain general way, but are also essential to higher order processes such as mentalising, which requires complex processes of 'attending-to' and 'theorising-about' social stimuli. More recently, a number of papers have applied more 'fine-grained' analyses and suggest that distinct neural regions may exist for different processes within the TPJ, which may or may not overlap in terms of functional integration (Carter and Huettel, 2013; Kubit and Jack, 2013; Mars et al., 2012; Scholz et al., 2009). On average, attention tasks elicit activity in more dorsal/anterior TPJ areas (Fig. 2), whereas social cognition tasks tend to activate more ventral/posterior TPJ sites (Carter and Huettel, 2013; Kubit and Jack, 2013). Furthermore, an examination of the rTPJ conducted by Mars et al. (2012) identified three subregions (using tractography-based parcellation), and then explored their resting state functional connectivity. They reported a dorsal cluster in the inferior parietal lobule (IPL) with functional connectivity to the lateral anterior prefrontal cortex (laPFC), a ventral anterior TPJ cluster connected to

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