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THE DIRECT, NOT V1-MEDIATED, FUNCTIONAL INFLUENCE BETWEEN THE THALAMUS AND MIDDLE TEMPORAL COMPLEX IN THE HUMAN BRAIN IS MODULATED BY THE SPEED OF VISUAL MOTION

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Abstract—The main visual pathway that conveys motion information to the middle temporal complex (hMT+) originates from the primary visual cortex (V1), which, in turn, receives spatial and temporal features of the perceived stimuli from the lateral geniculate nucleus (LGN). In addition, visual motion information reaches hMT+ directly from the thalamus, bypassing the V1, through a direct pathway. We aimed at elucidating whether this direct route between LGN and hMT+ represents a 'fast lane' reserved to high-speed motion, as proposed previously, or it is merely involved in processing motion information irrespective of speeds. We evaluated functional magnetic resonance imaging (fMRI) responses elicited by moving visual stimuli and applied connectivity analyses to investigate the effect of motion speed on the causal influence between LGN and hMT+, independent of V1, using the Conditional Granger Causality (CGC) in the presence of slow and fast visual stimuli. Our results showed that at least part of the visual motion information from LGN reaches hMT+, bypassing V1, in response to both slow and fast motion speeds of the perceived stimuli. We also investigated whether motion speeds have different effects on the connections between LGN and functional subdivisions within hMT+: direct connections between LGN and MT-proper carry mainly slow motion information, while connections between LGN and MST carry mainly fast motion information. The existence of a parallel pathway that connects the LGN directly to hMT+ in response to both slow and fast speeds may explain why MT and MST can still respond in the presence of V1 lesions.

Key words: Conditional Granger Causality, fMRI, hMT+, speeds, thalamus, visual motion.

INTRODUCTION

The perception of speed of a moving object is fundamental to fully reconstruct the ever-changing characteristics of the environment we live in. Detecting and processing the information related to moving visual stimuli have a crucial biological relevance because of its role in spatial navigation and in determining the ability to promptly react to the sudden appearance of potential obstacles or dangers. Although several areas of the cortex are involved in these tasks (Allman and Kaas, 1971; Ungerleider and Desimone, 1986; Lamme and Roelfsema, 2000; Huk and Heeger, 2001; Sincich and Horton, 2003; Wandell et al., 2007; Bradley and Goyal, 2008), there is a general agreement that the core region for visual motion processing in primates, including humans, is the middle temporal complex (hMT+), as demonstrated by many studies that investigated its anatomical and functional roles (Dubner and Zeki, 1971; Zeki, 1974, 1980, 2004; Maunsell and van Essen, 1983a,b; Albright et al., 1984; Rodman and Albright, 1987; Tanaka and Saito, 1989; Tootell et al., 1995; Dumoulin et al., 2000; Ptito et al., 2001, 2003; Huk et al., 2002; Zeki, 2004; Born and Bradley, 2005; Bradley and Goyal, 2008; Amano et al., 2009).

It is well known from studies in macaques that the main visual pathway that conveys motion information to MT (homologous to hMT+) originates from the primary visual cortex (V1) (Lamme and Roelfsema, 2000) which, in turn, receives spatial and temporal features of the perceived stimuli from the lateral geniculate nucleus (LGN) (Born and Bradley, 2005). In addition to this main pathway, several anatomical studies have revealed the existence of a direct connection that conveys visual motion information from the thalamus to hMT+ directly, bypassing the V1 (Ptito et al., 1991; Bittar et al., 1999; Sincich et al., 2004; Bridge et al., 2008; Lanyon et al., 2009; Warner et al., 2010; Jayakumar et al., 2012; Krug, 2012).

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Abbreviations: BOLD, blood oxygenation level-dependent; CGC, Conditional Granger Causality; EPI, echo-planar imaging; FM, fast motion; hMT+, middle temporal complex; HRFs, hemodynamic response functions; LGN, lateral geniculate nucleus; ROI, region of interest; SM, slow motion; V1, primary visual cortex.

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Consistent with these anatomical findings, we have recently provided evidence demonstrating the direct functional influence of LGN on hMT+, which is not mediated by the activity of V1. This new observation strongly supports the existence of a bilateral pathway that connects LGN directly to hMT+ (Gaglianese et al., 2012). This connection is believed to be involved in visual motion processing (Zeki, 1974; Rodman et al., 1989; Girard et al., 1992; Schoenfeld et al., 2002; Schmid et al., 2010; Gaglianese et al., 2012; Jayakumar et al., 2012; Qin and Yu, 2013), however it is not clear, yet, whether the motion information it conveys is relatively unspecific or relevant only in specific stimulus attributes, such as in a particular range of motion speeds.

It has been documented previously (Zeki, 1974; Maunsell and van Essen, 1983; Rodman and Albright, 1987; Tanaka and Saito, 1989; Lagae et al., 1993; Cheng et al., 1994; Perrone and Thiele, 2001) that macaque MT neurons as a whole are truly sensitive to the object speed. Similarly, Lingnau and colleagues have provided evidence for the speed tuning of blood oxygenation level-dependent (BOLD) responses in hMT+ over different temporal frequencies (Lingnau et al., 2009). Furthermore, both electroencephalography and magnetoencephalography studies have demonstrated that, in hMT+, fast visual stimuli moving at approximately 20–30 deg/s elicit stronger neural responses and have shorter response latencies than slow stimuli moving at <6 deg/s (Ffytche et al., 1995; Kawakami et al., 2002; Wang et al., 2003). In particular, Ffytche et al. (1995) have shown that the activity in hMT+ emerges earlier than that in V1 for fast (22 deg/s) but not for slow (<6 deg/s) motion stimuli, suggesting that the direct connection between the thalamus and hMT+ is recruited only during the perception of fast speeds. Supporting this view, Chawla et al. (1998, 1999) have speculated that the differential speed responses in hMT+ measured by functional magnetic resonance imaging (fMRI) may be explained by the existence of such a direct connection. However, this interpretation has been questioned by a later experiment, showing that lesion of V1 does not abolish responses to either fast or slow motion in MT of macaque monkeys (Azzopardi et al., 2003). Therefore, if and how certain visual properties, such as motion speeds, can actually modulate the recruitment of the direct pathway conveying motion-related information from LGN to hMT+ is still an open question.

Given these premises, here we have aimed at elucidating whether visual motion stimuli characterized by different speeds are processed by the brain through different pathways, namely, an indirect pathway passing through V1 or a direct pathway between LGN and hMT+, and further, whether this latter direct connection represents a 'fast lane' reserved only for high-speed motion, as proposed previously, or it is merely involved in processing motion information irrespective of speeds. To attain this aim, we have evaluated fMRI responses elicited by moving visual stimuli and applied connectivity analyses to investigating the effect of motion speed on the strength of the LGN → hMT+ functional interaction. Specifically, the causal influence between LGN and hMT+, independent of V1, was explored using the Conditional Granger Causality (CGC) (Chen et al., 2006; Ding et al., 2006) in the presence of slow and fast visual stimuli, respectively. Moreover, because hMT+ contains a subset of functional divisions exhibiting distinct response properties to visual motion (Huk et al., 2002; Amano et al., 2009; Kolster et al., 2010), we also investigated whether motion speeds have different effects on the connections between LGN and these specific divisions within hMT+. For this purpose, we performed the same CGC analysis at a finer scale by computing the causal influence between LGN and single voxels within different divisions of hMT+.

EXPERIMENTAL PROCEDURES

Subjects

BOLD fMRI responses of three healthy human volunteers (24 ± 4 years of age, one female) were collected while observing a visual motion stimulus. All subjects had normal or corrected-to-normal vision. Anatomical and functional MRI data were acquired with the understanding and written consent from each subject in accordance with the protocol approved by the RIKEN fMRI Safety and Ethics Committee, and in compliance with national legislation and the Code of Ethical Principles for Medical Research Involving Human Subjects of the World Medical Association (Declaration of Helsinki).

Data acquisition

Data were acquired using an Agilent 4-T whole-body MRI scanner (Agilent Technologies, Santa Clara, CA, USA). At the beginning of each experimental session, whole-brain high-resolution ($1 \times 1 \times 1$ mm^3) T1-weighted spoiled gradient recalled images were acquired for each subject. Functional images were acquired with a 4-channel array surface coil (Nova Medical Inc., Wilmington, MA, USA), covering the most posterior part of the subject's head, including hMT+. Functional echo-planar imaging (EPI) images were reconstructed using a T-SENSE approach with an acceleration factor $R = 2$ (Kellman et al., 2001). For each subject, we collected 15 oblique axial slices every 731 ms. Each slice, 3 mm in thickness, was scanned with a field of view of 192×192 mm^2 and a matrix size of 64×64, resulting in an in-plane resolution of 3×3 mm^2. Throughout a scan, we used a pressure sensor placed on the abdomen and a finger pulse oximeter to monitor and acquire respiration and heart-beat signals, which were used for offline removal of physiological artifacts contained in functional images (Hu et al., 1995).

Visual stimulation

Subjects underwent two different runs in an event-related fashion. Visual stimuli were generated in MATLAB R2009a (The Mathworks Inc., Natick, MA, USA) and were projected onto a frosted glass screen placed inside the magnet bore behind the subject's head, using an LCD projector (Silent Vision 6011, Avotec, Inc., Stuart, FL, USA). The projected visual stimulus, subtending