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Objective analysis of the topological organization of the human cortical visual connectome suggests three visual pathways

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ABSTRACT

The cortical visual system is composed of many areas serving various visual functions. In non-human primates, these are broadly organised into two distinct processing pathways: a ventral pathway for object recognition, and a dorsal pathway for action. In humans, recent theoretical proposals suggest the possible existence of additional pathways, but direct empirical evidence has yet to be presented. Here, we estimated the connectivity patterns between 22 human visual areas using resting-state functional MRI data of 470 individuals, leveraging the unprecedented data quantity and quality of the Human Connectome Project and a novel probabilistic atlas. An objective, data-driven analysis into the topological organisation of connectivity and subsequent quantitative confirmation revealed a highly significant triple dissociation between the retinotopic areas on the dorsal, ventral and lateral surfaces of the human occipital lobe. This suggests that the functional organisation of the human visual system involves not two but three cortical pathways.

1. Introduction

Human visual cortex is composed of many visual areas, each of which is known to contain a map of the visual field and can be linked to various visual functions (Wandell, Dumoulin, & Brewer, 2007). The overall organisation of information processing defined by the connections between these visual field maps is less well understood. The prevailing view, first introduced in the early eighties based on disconnection studies in the macaque (Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Mishkin, 1982), is that the visual cortical areas are arranged into two visual processing pathways: a ventral pathway for perception and a dorsal pathway for action (Goodale & Milner, 1992; Milner & Goodale, 2006). However, recent work has started to question the validity of this

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influential model, stating that it might be too strong and inconsistent with recent data (De haan & Cowey, 2011; Schenk & Mcintosh, 2010). In particular, it is increasingly unclear if the human visual cortical system is comprised of just two or more visual pathways, or none at all. Indeed, the primary support of the dual pathway model in humans has been deduced from dissociable consequences of naturally occurring lesions and functional localisation studies (Goodale & Milner, 1992; Haxby et al., 1991; Milner & Goodale, 2006; Ungerleider & Haxby, 1994). Yet, although these studies inform about the distribution of dissociable functions across visual cortex, they do not demonstrate the existence of interconnected pathways nor can they rule out the possibility of additional cortical visual pathways.

There are several reasons why additional processing pathways might be expected in humans. First, the human brain, both in terms of its overall volume and the size of visual cortex, is much bigger than the primate brain, suggesting additional functions that might require additional or more specialised visual processing capabilities. Second, previous work suggests the existence of a large white matter fibre bundle, the inferior fronto-occipital fasciculus connecting human ventral occipital and inferior frontal cortex, that appears absent in non-human primates (Catani & Thiebaut de schotten, 2008; Forkel et al., 2014). Third, recent theoretical work proposed the existence of three major visual processing pathways in humans. For instance, based on observations of multiple clusters of face- and limb-selective regions on the lateral and ventral occipitotemporal surfaces of the brain, it has been proposed that the human cortical visual system comprises a dorsal occipitoparietal stream, a lateral occipitotemporal stream and a ventral occipitotemporal stream (Weiner & Grill-Spector, 2013). In this model, the additional lateral stream, consisting of areas that are classically assigned to the dorsal stream, incorporates different aspects of vision, action and language. This view expands on earlier proposals that the difference between humans and non-human primates in the anatomical location of area MT/V5 relative to other dorsal and ventral visual areas might be related to a cortical expansion to accommodate language function in humans (Orban, Van essen, & Vanduffel, 2004; Ungerleider, Courtney, & Haxby, 1998). The proposal of separable visual processing streams in human lateral and ventral occipitotemporal cortex also fits well with data suggesting a duplication of various other types of object response-selectivity across these two pieces of cortex (Hasson, Levy, Behrmann, Hendler, & Malach, 2002, Konkle & Caramazza, 2013; Taylor & Downing, 2011).

Despite an increasing appreciation of the similarity of the retinotopic organisation of occipital cortex in humans and non-human primates, there further are salient differences in the relative position of several high-level visual areas (Arcaro & Kastner, 2015; Orban, 2016; Orban, Zhu, & Vanduffel, 2014; Vanduffel, Zhu, & Orban, 2014). For instance, recent measurements suggest that areas LO-1 and LO-2, located on the lateral occipitotemporal surface of the human brain, have undergone a large-scale relative location-shift with respect to their putative homologues, V2A and OTd, in the macaque. V4A and OTd are located directly adjacent to V4v and inferior to the MT/V5 cluster and are part of a cluster of posterior inferior temporal (PIT) areas. Human areas LO-1 and LO-2 are located more superiorly, directly adjacent to V3d and they appear to be disconnected from the putative human PIT (phPIT) cluster. In addition, the human hemifield representation hV4 can be found on the ventral occipitotemporal surface, whereas its putative homologue in the macaque is comprised of a ventral upper quadrant representation and a lateral lower quadrant representation of the visual field. In humans there further exist visual field maps on the ventromedial occipitotemporal surface, VO-1 and VO-2 (Brewer, Liu, Wade, & Wandell, 2005; Wandell et al., 2007). These areas might correspond to cytoarchitectonic area TFO in the macaque, for which recent preliminary evidence suggests that it consists of two central visual field maps that have been tentatively labelled TFO-1 and TFO-2 (Orban et al., 2014). In the macaque, TFO-1 directly abuts area V4A, while their putative human homologues, VO-1 and LO-1, are separated by area hV4 (several centimetres of cortex). These differences in the topological arrangement of some of the high-level retinotopic areas suggest a large-scale reorganisation that appears consistent with the notion of an additional lateral pathway in humans (Weiner & Grill-Spector, 2013), though it would suggest that the pathway originated from the classical ventral stream.

In addition to these considerations, still other theoretical accounts propose that the classical ventral and dorsal visual pathways should not be understood as unified systems. For instance, Kravitz et al. (Kravitz, Saleem, Baker, & Mishkin, 2011; Kravitz, Saleem, Baker, Ungerleider, & Mishkin, 2013) proposed the existence of three dorsal pathways for visuospatial processing related to spatial working memory, visually guided attention and navigation, and six ventral sub-systems that each serve specialised behavioural, cognitive and affective functions. Importantly, this work relates to the macaque and thus argues that the classical dual-systems hypothesis has been over-simplified from its outset. This would suggest that the human visual system should also not be understood in terms of two (and only two) unified visual processing pathways. However, it is also possible that the apparently distinct functional properties within pathways do not reflect strictly separate sub-pathways, but a gradient-like organisation (Freud, Plaut, & Behrmann, 2016).

All these theories notwithstanding, the notion of two visual processing pathways ultimately concerns an empirical hypothesis about the wiring of the cortical visual system. Thus, it must be tested against the connections between the cortical visual areas. Indeed, the work that led to the postulation of the dual-pathways hypothesis involved a series of cross-lesion disconnection studies (Mishkin, 1966; Ungerleider & Mishkin, 1982). These studies cannot be performed in humans, because they involve removing cortical areas as well as interhemispheric connections. Additional connectivity-based evidence for two visual pathways in non-human primates was presented in the early nineties, which was based on anatomical tract tracer injection data. In their seminal work, Felleman and van Essen presented a matrix of the connections between the visual areas of the macaque (Felleman & Van Essen, 1991). The availability of this matrix enabled Young to derive the topological organisation of the cortical visual connectome in a data-driven manner and confirm that the structural connectivity markers can be

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