Functional hierarchy of the visual system as revealed by resting-state connectivity

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Introduction

The brain is a highly hierarchical system, a fact which has been supported by a number of anatomical and functional studies in humans and primates [1, 2]. Recently, low-frequency fluctuations in the BOLD-signal have been used to study the functional hierarchy of the brain while in a putative resting state [3]. More specifically, a partial correlation analysis was used to study whether pairs of regions were uniquely correlated, when all other influences were partialed out. The original approach used an anatomical template to perform the analysis which was relatively coarse. In this study, we address the question whether resting-state BOLD fluctuations reveal a hierarchical pattern when studying the human visual system on a much finer scale.

Methods

After informed consent was given, 6 subjects participated in a battery of standard visual stimuli:

1. a retinotopic mapper, to identify classical visual areas V1 and V2 ventral and dorsal. V3, V3A, V4 and VP
2. an eccentricity mapper, which was used to define a central part (foveal, first degree of the visual field) and a peripheral part
3. a moving star field to identify hMT.

Experiments were performed using a Siemens Trio scanner at 3T, equipped with a 8-channel 'occipital' phased-array coil, which was specifically designed to fit around the visual cortex. Furthermore, resting-state data was collected while the participants were lying with their eyes closed for 5 minutes. The imaging parameters were as follows: gradient echo EPI with a matrix size of 128x128. FOV= 196x196 mm^2 resulting in an in-plane resolution of 1.53x1.53 mm^2, 30 slices of 1.5 mm were obtained with a distance factor 15%. TR/TE = 3000/33 ms, flip angle = 84º, partial Fourier 6/8, BW = 1628 Hz/Pixel. The data from the visual stimuli were analyzed using standard retinotopic techniques, the resting state data was analyzed using the partial correlation framework as described by Salvador et al. The variance of the partial correlations over subjects was used to assess their significance.

Results and Discussion

left	V4	VP	V2v	V1v	V1d	V2d	V3	V3A	hMT+
V4		0.33						0.16	
VP	0.33		0.33						
V2v		0.33		0.38					
V1v			0.38		0.31				
V1d				0.31		0.28			
V2d					0.28		0.35		
V3						0.35		0.58	
V3A	0.16						0.58		
hMT+									

right	V4	VP	V2v	V1v	V1d	V2d	V3	V3A	hMT+
V4									
VP			0.36						
V2v		0.36							
V1v					0.53				
V1d				0.53		0.4			
V2d					0.4		0.51		
V3						0.51			
V3A									
hMT+									

Figure 1. Significant partial correlations for the left and right hemisphere when central and peripheral parts are merged before the analysis

left	V4	VP	V2v	V1v	V1d	V2d	V3	V3A	hMT+
V4		1							
VP	1		2						
V2v		2		2					
V1v			2		1				
V1d				1					
V2d							1	1	
V3						1		2	
V3A						1	2		
hMT+									

right	V4	VP	V2v	V1v	V1d	V2d	V3	V3A	hMT+
V4		2							
VP	2		2						
V2v		2		2					
V1v			2		2				
V1d				2		1			
V2d					1		2		
V3						2		2	
V3A							2		
hMT+									

Figure 2. Number of significant correlations over the subjects when the central and peripheral parts are treated as separate areas. 1 means either center-center or peripheral-peripheral parts are connected. 2.means both

The first analysis shows a remarkable degree of hierarchy. Especially in the left hemisphere, almost all significant partial correlations are concerned with areas one step up/down in the hierarchy, for instance from V2v to VP/V1v. Also of interest is the fact that only in V1 there is cross-talk between dorsal and ventral streams within an area (V1v<->V1d) and that the only other connection between the dorsal and the ventral stream is to be found from V3A to V4. In the second analysis, especially in the right hemisphere, more significant partial correlations are shown, all of which follow a hierarchical pattern. It seems that for instance the connection from right VP to V4 is not significant when the complete areas are taken into account, as in figure 1, but that it is significantly connected for both central-central and peripheral-peripheral sub-regions, when these are treated separately. This indicates that these central and peripheral regions are uniquely connected, connections which are lost when they are treated as a single region.

Potentially, these results could be confounded by imperfect definition of the visual areas, as the fact that neighbouring areas are connected is then trivial, because they share a common activation source. We have, however, eliminated voxels at the boundaries between regions, or where the assignment to a particular region was ambiguous. .The partial correlation method indicates unique connections with all other contributions partialed out. In general the standard correlation coefficients between regions in visual cortex were very high, so the absence of a significant correlation in figure 1 does not imply low correlation between regions.

For the first time it is shown here that the specificity of the method is improved by considering smaller sub-units within a region. Furthermore it is remarkable, that the connections which show up as being unique closely follow the known pathway of information flow within the visual system.

References: 1. Felleman and van Essen et al. Cere Cor 1991 2. Salvador et al. Cere. Cor. 2005