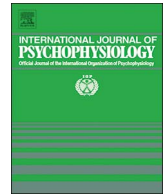




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Different levels of visual perceptual skills are associated with specific modifications in functional connectivity and global efficiency

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ABSTRACT

The disembedding ability (i.e., the ability to identify a simple masked figure within a complex one) depends on attentional mechanisms, executive functions and working memory. Recent cognitive models ascribed different levels of disembedding task performance to the efficiency of the subtended mental processes engaged during visuo-spatial perception.

Here we aimed at assessing whether different levels of the disembedding ability were associated to the functional signatures of neural efficiency, defined as a specific modulation in response magnitude and functional connectivity strength in task-related areas. Consequently, brain activity evoked by a visual task involving the disembedding ability was acquired using functional magnetic resonance imaging (fMRI) in a sample of 23 right-handed healthy individuals. Brain activity was analyzed at different levels of information processing, from local responses to connectivity interactions between brain nodes, as far as to network topological properties.

All different levels of information processing were significantly modulated by individual behavioral performance. Specifically, single voxel response magnitude, connectivity strength of the right intrahemispheric and interhemispheric edges, and graph measures (i.e., local and global efficiency) were negatively associated to behavioral performance. Altogether, these results indicate that efficiency during a disembedding task cannot be merely attributed to a reduced neural recruitment of task-specific regions, but can be better characterized as an enhanced functional hemispherical asymmetry.

1. Introduction

Since the early 50s, Witkin and colleagues performed a series of experiments to highlight the individual differences in simple cognitive tasks involving visual perception (Witkin et al., 1954) and tracked down subject's performance variability to stable psychological dimensions, namely cognitive styles (Riding and Cheema, 1991). Among many neuropsychological tasks, the Embedded Figures Test was one of the most used to evaluate the disembedding ability, i.e. the ability to identify a simple masked figure within a complex one (Witkin, 1971). The Embedded Figures Test scores were continuously distributed along a dimension called 'field dependency' (Witkin et al., 1954). The two extremes of such dimension identified two groups of subjects: field independent and field dependent individuals. The difference between the two extremes can be illustrated with a simple analogy: field independent people are able to "see within the forest" (i.e., pick up the different trees), whereas the field dependent individuals "see the forest"

(i.e., the forest as a whole entity) (Witkin and Goodenough, 1981).

Despite a large amount of research, in the late 70s, cognitive styles were still detached from other neuropsychological constructs and from modern cognitive science theories (for a historical perspective, please refer to Kozhevnikov, 2007). In addition, several authors argued against the field dependent/independent cognitive style, suggesting that the disembedding ability could simply represent individual variations in perceptual spatial abilities rather than a psychological dimension (Riding and Cheema, 1991; Sternberg, 1999; Zhang, 2004). Moreover, Pascual-Leone reviewed the disembedding ability as an interplay between attentional and inhibitory processes, executive functions and working memory (Pascual-Leone, 1989). Finally, novel experimental models of working memory (Baddeley and Della Sala, 1996; Miyake et al., 2001) and attentional processes (Goode et al., 2002; Pascual-Leone, 2000) suggested that the disembedding ability was significantly modulated by top-down and bottom-up mechanisms (Guisande et al., 2007; Hao et al., 2013; Walter and Dassonville, 2011), reframing the

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individual variability on these tasks into a more general cognitive efficiency model of the subtended mental processes engaged during visuo-spatial processing (Evans et al., 2013; Motes et al., 2008; Rittschhof, 2010).

In general, when cognitive operations can be performed efficiently, i.e. quickly or effortlessly, resource allocation is minimized and performance maximized (Rypma et al., 2006). Previous functional studies investigated the neural correlates of varying performance across different tasks in terms of efficiency in both healthy (Rypma and Prabhakaran, 2009) and skilled populations (e.g., professional musicians or elite athletes), mainly focusing on sensorimotor and associative areas (Bernardi et al., 2013; Del Percio et al., 2008; Di Russo et al., 2005; Krings et al., 2000). Efficiency-related functional changes in task-specific areas are consistently associated with a reduction in responses magnitude and changes in functional connectivity irrespectively of the tasks used (Bernardi et al., 2014; Bernardi et al., 2013; Brancucci, 2012; Train the Brain Consortium, 2017; Coynel et al., 2010; Sun et al., 2007).

Up to now, no functional study assessed the neural modifications associated to different levels of disembedding abilities, as a possible functional signature of cognitive efficiency. Therefore, here we aimed at characterizing the neural correlates of different disembedding performances in healthy adults during the completion of the Mangina-Test through functional magnetic resonance imaging (fMRI). Among many tasks, the Mangina-Test (Mangina, 1981; Mangina, 1998) proved to be sensible in detecting subtle differences in disembedding performances, even with learning disabilities (Mangina et al., 2000) or during early stages of pathological aging (Beuzeron-Mangina and Mangina, 2009; Beuzeron-Mangina and Mangina, 2000).

We hypothesize that different levels of Mangina-Test performance may be associated with modifications in neural responses and connectivity in task-related brain areas of healthy subjects (Mangina et al., 2009a; Mangina et al., 2009b). In accordance with this, subjects with higher visuo-spatial skills would perform this disembedding task more efficiently, ultimately recruiting brain resources in a more parsimonious manner. Consequently, we explored brain activity at different levels of information processing, from local responses (i.e., voxel level) to connectivity strength between brain nodes (i.e., edge level). In addition, to further characterize the underlying phenomenon of improved efficiency in a more comprehensive and sensible manner, we took into account the topological properties of the task-related network (i.e., network structure level). Notably, graph theory approaches have recently quantified efficiency in terms of the cost of transmitting information within large-scale brain networks (Bullmore and Sporns, 2009), rather than on the activity of single brain voxels. Specifically, here we measured the local and global efficiency indices to quantify the ability of the brain to integrate information during the Mangina-Test at the local (i.e., node neighborhoods) and global level (i.e., between more distant nodes in the whole network), respectively (Latora and Marchiori, 2001, 2003). In this framework, the concept of efficiency during a visual spatial task extends beyond the small-scale level (i.e. single node) to the large-scale brain network structure (i.e., from nodes to edges, to motifs and hubs).

2. Material and methods

2.1. Subjects

Twenty-three young right-handed healthy subjects (13 M/10F; mean age \pm s.d. = 26 \pm 3 yrs) were enrolled in the study. All subjects received a clinical examination to exclude any medical, neurological or psychiatric disorder that could affect brain function or metabolism. They also underwent a brain structural MRI exam to rule out any brain morphological abnormality or pathology. No subject had taken any drug at least four weeks prior to the clinical evaluation and the fMRI study. All subjects signed a written informed consent prior to the enrolment into the study, under a protocol approved by the Ethics

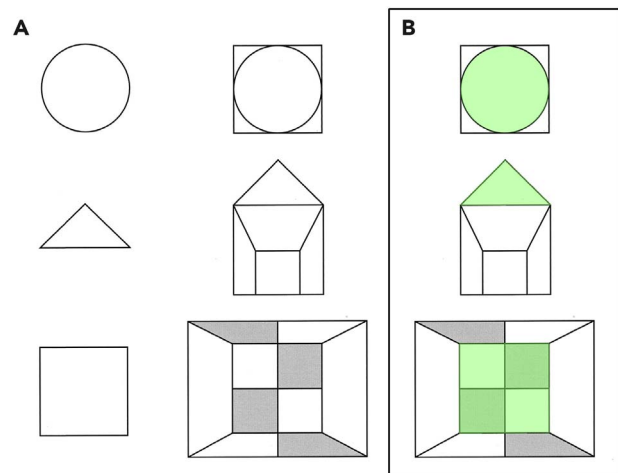


Fig. 1. Panel A depicts three simple stimuli used as demonstration in the Mangina-Test. The task consists of identifying the simple visual stimulus on the left column into a simultaneously presented complex configuration on the right, according to their exact geometrical properties. Panel B reports the correct responses (in green) as obtained from the paper-and-pencil version of the test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Committee of the University of Pisa, Italy (Protocol 1616/2003). All subjects retained the right to withdraw from the study at any time.

2.2. Stimuli and task

The task of the Mangina-Test consists of identifying a simple visual stimulus that is masked (inserted) into a simultaneously presented complex configuration, according to their exact geometrical properties: size, dimension, direction, spatial orientation and shape (Fig. 1). A feasible computer-adapted administration of 44 pairs of stimuli of the Mangina-Test was used during the fMRI session. The first four pairs of stimuli of the Mangina-Test were used for training, while the 5th-to-44th stimuli were presented in a pseudo-randomized order, during the fMRI session, as described elsewhere (Mangina et al., 2009a; Mangina et al., 2009b). Subjects were instructed to carefully look at the stimuli, to mentally identify the simple stimulus within the complex configuration, and to press a button with their right hand when being confident of successful identification. Stimuli pairs were presented every 30 s and were replaced by a fixation cross following button press. Therefore, stimulus duration was self-paced and corresponded exactly to the time spent for the identification of the simple stimulus within the complex one, i.e. response time (RT). Each fMRI run contained eight stimuli pairs with two 15 s (or more, depending on response time) of rest at its onset and ending, to obtain a baseline measure of activity (270 s of total duration). Five runs were obtained in each fMRI session. Stimulus presentation and subjects' responses were handled by using the software package Presentation (<http://www.neurobehavioralsystems.com>). A paper-and-pencil version of the Mangina-Test was administered immediately after scanning, in order to counter-check the correct responses given during the fMRI session and to verify visual perceptual skills.

2.3. Image acquisition

Responses to different stimuli were measured using blood oxygen level dependent (BOLD) contrast with the acquisition of T2*-weighted gradient echo planar images (GRE-EPI) in a 1.5 T GE scanner (General Electric, Milwaukee, WI). In each time series, the whole brain volume was acquired 108 times, each volume consisting of 33 contiguous 4 mm thick axial slices (TR = 2.5 s, TE = 40 ms, FA = 90°, FOV = 24 cm, IPR = 64 \times 64 voxels and 3.75 \times 3.75 mm). High-resolution T1-weighted spoiled gradient recall images (SPGR) (TR = 19.58 ms,

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