

Common Neural Activations Associated with Spatial Processing Across Multiple Domains: A Meta-Analysis

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Abstract

Spatial cognition is a branch of cognitive psychology that studies how people acquire and use knowledge about their environment in order to determine where they are, how to obtain resources, and how to find their way to home. Given that researchers from a wide range of disciplines, such as neuroscience, cognition, and sociology, have already discovered how humans and other animals sense, interpret, behave in, and communicate in space, the present meta-analysis study focuses on the fact that spatial processing is involved in many domains and that each domain is supported by several brain structures. However, a meta-analysis of neuroimaging studies help to answer the question if it's possible to find a common core network of regions intrinsically devoted to spatial processes. Greater activation was found in dorsal fronto-parietal network that according to literature is responsible for a range of high diverse functions; from spatial attention to control and working memory. All these functions are important to process and manipulate spatial representations.

Keywords: *Spatial Processing; Cognition; Neural Networks; Frontal; Parietal; fMRI; PET*

Introduction

Where is my right hand now? Where is the fork in relation to the knife? How far away from me is the glass? Where is the nearest post office? All these questions present some appreciation of where things are located in space. However, each of these examples has computational demands that are quite different. For instance, having in the mind where objects are in immediate space and where body parts are located may show more confidence on sensory maps of space. Through the position of the body (egocentric space) or eye gaze (retinocentric space) the sensory maps of space can be coded. On the contrary, knowing the way of the neighboring post office may depend on more abstract memory maps of space. In order to find the location of an object in relation to another (allocentric space) may there is the need of a different computation from this that is used to find the location of one object relative to one self (egocentric space).

Aim of the Study

The explosion of interest in cognitive neuroscience comes from that fact that recent advances in neuroscience try to shed new light on the mechanisms that support cognition. Within this endeavor, the field of spatial cognition is particularly well placed due to the ease with which similar (spatial) experimental paradigms can be applied to both humans and animals.

To recap, spatial ability is the capacity to understand and remember the spatial relations among objects. The spatial ability can be considered as a unique type of intelligence that is different from other forms of intelligence, such as verbal ability, reasoning ability, and memory skills. In this thesis we have seen that spatial processing is involved in many domains which are interrelated among each other and develop throughout the life. For example, there are five types of spatial abilities which include visuospatial images, spatial attention, visuospatial WM, navigation and auditory spatial attention. Each of these abilities has unique properties and importance to many types of tasks and they are supported by several brain structures. Such structures we mean dorsolateral prefrontal cortex (PFC) and posterior parietal cortex (PPC) for visuospatial attention, the dorsal and ventral stream for visuospatial WM, parahippocampal gyrus, hippocampus and retrosplenial cortex (RSC) for spatial navigation and prefrontal cortex (PFC) for auditory spatial attention.

The question is if it's possible to find a common core network of regions intrinsically devoted to spatial processing. So, the present study is aimed to investigate the brain regions that are commonly activated and recruited across different types of spatial processing using a meta-analytic approach.

Method

Study selection: To identify appropriate articles for the Space processing, several online electronic databases (e.g. Psycinfo, Medline, PubMed) were searched using various combinations of relevant search terms: "space", "spatial", "navigation", "space processing", "spatial attention", "spatial working memory", "route", "mental rotation", "neuroimaging", "fMRI", "PET", "functional magnetic resonance imaging", "positron emission tomography". Moreover, further studies were found by means of the "related articles" function of the PubMed database and by tracing the references from review articles and the identified papers. Additional studies were included searching within the references of a previous meta-analysis [1]. The following inclusion criteria were used to select articles for the present meta-analysis:

1. Only articles that utilized PET or fMRI methodology were considered. We did not restrict the study selection to a certain imaging technique to maximize statistical power. Electrophysiological (e.g. electroencephalography, magnetoencephalography, skin conductance response [SCR]), transcranial magnetic stimulation (TMS) and behavioral-only studies were excluded. Both blocked and event-related studies were allowed.
2. Only articles with experiments that performed a whole brain analysis were included: i.e. articles performing only region of interest (ROI) analysis were excluded.
3. Only articles with experiments that yielded a clear contrast representing locations of greater activation the spatial conditions as compared with control conditions were included. Control conditions typically consist in a task devoid of the spatial component.
4. Only articles that reported areas of peak activation in a standardized coordinate space (e.g. Talairach and Tournoux, 1988, or MNI [2]) were considered. Other articles (e.g., only reported Brodmann areas [BAs] or only showed contrast maps) were excluded. A few exceptions: some original articles did not report the coordinates of the results. The coordinates could however be found in Zacks 2008 [1]. These studies have been included in the current research. Tailarach coordinates had been reported into MNI space before performing the meta-analysis using a linear transformation [3,4].
5. Only peer-reviewed articles reporting novel data involving a sample size of at least 5 participants were included.

Based on these criteria, 85 studies were found to be eligible for inclusion into the space meta-analysis. Together, these studies reported 985 activation foci obtained from 1114 subjects.

ALE consistency analysis: The peaks of activation were used to generate an Activation Likelihood Estimation (ALE) map, using the revised ALE algorithm for coordinate-based meta-analysis of neuroimaging results [5].

Results

Spatial processing: all activations

The activation meta-analysis of all spatial processing studies includes 85 studies. Together, these studies reported 985 activations foci obtained from 1114 subjects. A large number of brain regions were identified as consistently activated across all studies and be grouped in six main lobes:

1. Parietal lobe (right cerebrum) including, superior parietal lobule (BA 7), precuneus (BA 7, 19), inferior parietal lobule (BA 40), gray matter (BA 7, 19, 40). Parietal lobe (left cerebrum) including, precuneus (BA 7, 19), inferior parietal lobule (BA 40), gray matter (BA 7, 19, 40).
2. Frontal lobe (right cerebrum) including, sub-gyral (BA 6), superior frontal gyrus (BA 6), inferior frontal gyrus (BA 9), middle frontal gyrus (BA 9), grey matter (BA 6, 9). Frontal lobe (left cerebrum) including, sub-gyral (BA 6), precentral gyrus (BA 4, 6), inferior frontal gyrus (BA 9), middle frontal gyrus (BA 46), gray matter (BA 6, 4, 9, 46).

3. Occipital lobe (right cerebrum) including, superior occipital gyrus (BA 19), precuneus (BA 31), cuneus (BA 19), middle occipital gyrus (BA 19), inferior occipital gyrus (BA 18), lingual gyrus (BA 17), gray matter (BA 19, 31, 18, 17). Occipital lobe (left cerebrum) including, cuneus (BA 19), middle occipital gyrus (BA 37), gray matter (BA 19, 37).
4. Temporal lobe (right cerebrum) including, middle temporal gyrus (BA 37), gray matter (BA 37).
5. Sub-lobar (right cerebrum) including, insula (BA 13), gray matter (BA 13), thalamus, medial dorsal nucleus. Sub-lobar (left cerebrum) including, insula and gray matter.
6. Limbic lobe (right cerebrum) including, posterior cingulate (BA 30), gray matter (BA 30). Limbic lobe (left cerebrum) including, posterior cingulate (BA 31), gray matter (BA 31).

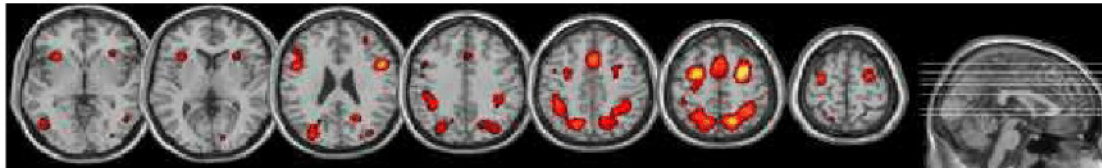


Figure 1: Axial presentation of common activations related to spatial processing across different domains. The figure shows activations mainly in dorsal Fronto- Parietal and in the Supplementary motor area (SMA).

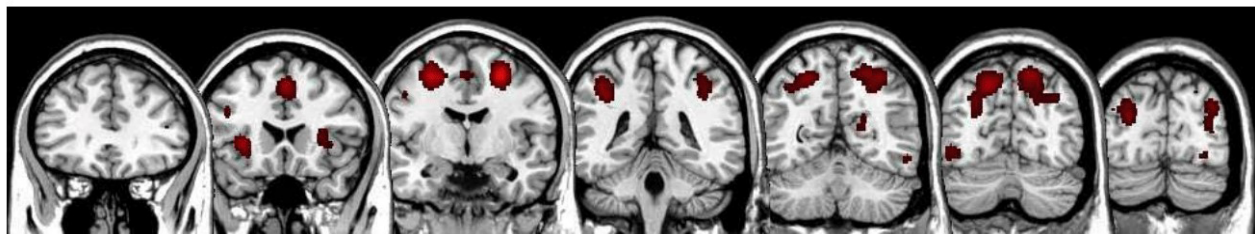


Figure 2: Coronal presentation of common activations related to spatial processing across different domains. The figure shows activations mainly in dorsal Fronto- Parietal and in the Supplementary motor area (SMA).



Figure 3: Sagittal presentation of common activations related to spatial processing across different domains. The figure shows activations mainly in dorsal Fronto- Parietal and in the Supplementary motor area (SMA).

Discussion and Conclusion

Theories about the neural systems for spatial cognition support the existence of two parallel chains, or streams, of areas: the ventral stream, leading downward into the temporal lobe, and the dorsal stream, leading forward into the parietal lobe [6]. Areas of the ventral stream play a critical role in the recognition of visual patterns, including faces, whereas areas within the dorsal stream contribute to conscious spatial awareness and to the spatial guidance of actions, such as reaching and grasping. However, numerous other association areas in the cerebral hemisphere mediate cognitive functions that depend in some way on the use of spatial information. These areas occupy a continuous region of the cerebral hemisphere, encompassing large parts of the frontal, cingulate, temporal, parahippocampal, and insular cortices. These areas are connected to each other anatomically and to the parietal cortex by a parallel distributed pathway [7].

In the present meta-analytic study, we found greater activation to some regions of parietal and frontal cortex bilateral (see Figure 1, 2, 3). More than a decade ago, Corbetta and Shulman published their influential review article in which they introduced the concept of two anatomically and functionally distinct attention systems in the human brain [8]. Broadly speaking, a dorsal fronto-parietal system was proposed to mediate the top-down guided voluntary allocation of attention to locations or features, whereas a ventral fronto-parietal system was assumed to be involved in detecting unattended or unexpected stimuli and triggering shifts of attention. Focusing on visual scenes usually contain many different objects, which cannot all be processed simultaneously because of the limited capacity of the visual system. Previous studies have demonstrated activations over large portions of dorsal fronto-parietal cortex during a variety of selective attention tasks [8,9]. In humans, these regions include intraparietal sulcus and superior parietal lobule area in posterior parietal cortex, defined by spatial topographic mapping, as well as the frontal eye field and the putative human supplementary eye field in frontal cortex. In sum, the execution of various spatial imagery paradigms consistently activates core areas of the dorsal fronto-parietal visual pathway, including bilateral parietal, prefrontal and premotor areas [10-23].

To conclude, as it is referred above no one area is uniquely responsible for the ability to carry out spatial tasks and that spatial cognition is a function of many brain areas. Beneath the unity of our spatial perception lies a diversity of specific representations. The distributed nature of spatial cognition and the many purposes it serves means that we construct internal representations of space not once but many times in parallel. The question is how these many representations function together so seamlessly? This question would be an interesting challenge for future research.

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