THE NEURAL BASIS OF MAP COMPREHENSION AND SPATIAL ABILTIES

by

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Chapter 1: Introduction

What spatial abilities are used during map tasks? Researching the question of how and when individuals use spatial abilities on map reading exercises is important in developing a cognitive model that explains how maps are processed by the human brain and ultimately interpreted and used by the map reader. This thesis investigates how spatial abilities are used during map tasks through a functional magnetic resonance imaging (fMRI) based analysis.

Functional MRI technology has the ability to uncover the neurological patterns of brain activation, and therefore the cognitive processing that underlies spatial abilities. Furthermore, functional MRI can be used to uncover the neural underpinnings of complex high-order cognitive tasks, like map tasks. This emerging technology may reveal what spatial abilities are used to solve map reading problems and what differences there are in how individuals cognitively process cartographic representations.

This paper identifies and defines two spatial cognitive abilities, spatial scanning and spatial relations, as outlined by cognitive psychologists. The first objective of this project is to identify if in fact spatial scanning and spatial orientation/relations are distinct and independent spatial abilities. The second goal of this project is to investigate the relationship between these two spatial abilities and map reading exercises. Two map tasks are presented that are hypothesized to require cognitive processes similar to the two outlined spatial abilities.

The research results include brain activation patterns of subjects who perform two map tasks under tightly controlled experimental conditions, as well as the brain activation patterns for two cognitive spatial abilities. I highlight the neurological similarities and differences between the two map tasks and the two spatial abilities tasks. By identifying the patterns of brain activation associated with all four spatial tasks, this research elucidates how people may draw upon spatial abilities to use maps.

The remainder of this thesis first reviews cognitive work done in cartography and the theoretical shifts that have taken place in this field. Research in cognitive spatial abilities is then reviewed, with an emphasis in how they have been studied in the geographic discipline, to reveal a growing need for further study of spatial abilities in regard to map reading. The methodological section of this thesis includes a discussion of the experimental design and how the functional magnetic resonance imaging technique works. The results section then systematically discusses the brain areas activated for each task and hypothesizes why that activation is significant.

Chapter 2: Cognitive Cartography: How did we get here?

Research in cartography has a rich history beginning in the 1950s, for example with Robinson's *The Look of Maps*, (1952). The practice of conducting experiments using psychological methodologies began to be routinely used by cartographers at this time. These early studies often focused on how map design influenced individuals' performance on map tasks (Medychyj-Scott and Board 1991). It was not until the 1970s that cartographic researchers began to focus on how and why maps were used. The focus of research became concentrated on the map reader, or the person involved in the map reading process (Hopkin and Taylor 1979; Olsen 1976; Board 1978). Wood (1972) stressed the idea that it may be the ability of the map reader that influenced performance on map tasks, not the map representation efficiency alone. Robinson and Petchenik (1978) developed this idea further and claimed that not enough attention was paid to the primary element in the map reading process namely, the cognitive characteristics of the map reader.

A series of papers in the 1970s led cartographers to realize the significance of human cognition in cartographic and subsequently geographic issues (Ratajski 1973; Morrison 1975; Robinson and Petchenik 1978). Since then many related papers have been written in cognitive cartography. A number of questions still remain in this sub-discipline of geography that are related to spatial abilities and map comprehension such as: Do individuals possess greater or lesser cognitive spatial abilities and/or map reading skills? How do we use spatial abilities on map reading exercises? Are there differences in cognitive patterns between individuals and groups (e.g. between genders)? These questions remain pertinent in today's cartography research arenas. Identifying the cognitive processes that control map reading provides the framework for a growing number of geographic research studies (Lobben 2004).

Geographers and other scholars continue to study how individuals interpret space and cartographic representations, why people make the spatial choices they do, and how we can better understand and model these processes. We may be able to better understand these processes by examining the organization of human cognitive spatial abilities. Golledge (2003:121) stresses that there is, "a major need to find out what are the essential spatial skills and to develop measurements and evaluation processes for them."

Chapter 3: Spatial Abilities

Cognitive studies of spatial abilities have been conducted by psychologists and geographers for over 35 years. Although there is a wealth of research present in the literature there is still an ongoing debate regarding spatial abilities. There is no definitive answer as to how many distinct spatial abilities human possess and when and how we use them in everyday life.

A large number of psychological studies have used well-established paper and pencil examinations to test for cognitive spatial abilities (Eliot and Smith 1983; Ekstrom et. al 1976). In this study, *The Kit of Factor-Referenced Cognitive Tests* (Ekstrom et. al 1976) has been chosen to: (1) define the two factor-referenced spatial abilities, spatial scanning and spatial relations, and (2) identify the basic tasks that are intended to test for these abilities. Based on extensive factor analytic research, *The Kit of Factor-Referenced Cognitive Tests* (Ekstrom et. al 1976) outlines twenty three cognitive factors. Six of the cognitive factors are spatial abilities. They include flexibility of closure, speed of closure, spatial relations, spatial scanning, visualization, and perceptual speed. Geographers and psychologists have at times had different definitions of the general term ‘spatial abilities’. For clarification, the term ‘spatial abilities’ is defined for this project as the ability to generate, retain, and manipulate visual (spatial) images (Lohman 1979). This project will investigate the existence of spatial scanning and spatial relations cognitive abilities.

These two spatial abilities have been chosen because they appear to have the closest parallels to map reading exercises.

Spatial Scanning

Spatial scanning is defined as visually exploring a wide or complicated spatial field in order to search an image for comprehension (Ekstrom et. al 1976). Visually exploring a spatial field or a 'maze-like' environment requires the ability to quickly scan the image, following the paths with one's eyes, and being able to identify and reject false leads.

Spatial Relations

Spatial relations is defined as the ability to perceive spatial patterns or to maintain orientation with respect to objects in space (Ekstrom et. al 1976). This factor tests figures that are hypothesized to be perceived as whole and it requires the mental rotation of configurations. Shepard (1971) offers a review of the processes involved in the mental rotation of shapes.

Factor Analysis

Factor-analytic research on cognitive abilities, including spatial abilities, has been present in the literature for over sixty-five years (Carroll 1993). *The Kit of Factor-Referenced Cognitive Tests* was issued in 1954, 1963, and 1976, and with each publication the definitions of cognitive abilities were further refined. The kits were designed to assist researchers in deciding what cognitive factors were considered sufficiently well confirmed to justify issuing a test for them (Carroll 1993). Therefore the abilities outlined in the 1976 *The Kit of Factor-Referenced Cognitive Tests* are based on a significant amount of previous research based on isolating cognitive abilities by means of factor analysis. The purpose of factor analysis is to discover simple patterns in the relationships among the variables. In particular, factor analysis seeks to mathematically reduce a set of observed variables to a smaller number of variables called factors, or categories. Unfortunately, this analytic process may overlook fine similarities and differences in cognitive abilities and is an indirect method of observation.

Gathering and analyzing neurological data collected by means of fMRI allows us to *directly* observe the portions of the brain involved in cognitive processing during specific spatial tasks. Thus, if two spatial abilities are in fact distinct, then there may be differences in the brain activation patterns that are present while performing these tasks. Furthermore, collecting neurological data associated with cognitive spatial ability exams gives baseline data to compare and contrast with map tasks.

Chapter 4: Spatial Abilities and Map Use: Making the Connection

The exact relationship between spatial abilities and map comprehension is still largely unknown. Most of the evidence linking spatial abilities and map use are anecdotal and intuitive (Stimutis and Barsam 1983). While it is hypothesized that spatial abilities are used during map reading, it is not known how or when. This idea is expressed by Montello et al. (1999: 516): “what is unclear is what role ‘spatial ability’ as it has been defined in psychometric research, plays in the performance of such real-world tasks as using a map.” Yet there are a few key studies that have looked at spatial abilities and their role in interacting with the environment and map reading.

Gilmartin and Patton (1984) administered five map-use experiments that were analyzed for sex group differences. It was found that no differences existed between females and males. They concluded that geographers cannot accept at face value all psychosocial research and attempt to apply their results to the geographic discipline. Furthermore, they stated that “the specific spatial behaviors and abilities that interest geographers may not be tapped by other investigators (psychologists)…and many questions regarding the importance of spatial abilities in geography and cartography still face us” (Gilmartin and Patton 1984: 616).

Montello et al. (1999) gave a battery of tests including psychometric tests and a variety of map, spatial knowledge acquisition, and spatial memory tasks to investigate sex-group differences. They concluded that on average males and females have different performance levels in regards to abstract psychometric spatial tasks and spatial tasks set in realistic environmental and map settings. This research did not address what spatial abilities, as defined by the psychometric tasks, are used in the geographic or environmental tasks.

Alber and Golledge (1999) studied spatial cognitive abilities in the use of Geographic Information Systems (GIS). They discussed what spatial abilities would be involved in a map overlay operation in GIS based on definitions of spatial abilities produced by both psychologists and geographers and previous studies examining spatial abilities. Alber and Golledge suggested that the map overlay tasks required the spatial cognitive abilities of mentally visualizing and manipulating spatial objects. But again there was no direct cognitive data included in their study to prove that specific spatial abilities they had suggested were being used during the overlay task.

Functional MRI Research Addressing Spatial Abilities

Functional MRI studies of spatial cognition have investigated mental rotation and visual search abilities. Many of the fMRI studies that examine mental rotation have focused on sex differences. The neuroimaging literature addressing sex differences in mental rotation tasks are inconsistent, and there have been no imaging studies to date that have addressed the spatial ability of mental rotation and its role during map use. There are also no known studies that have used fMRI to study the spatial scanning cognitive ability or its possible involvement in visual search tasks in both abstract and map environments. There is room in both the cartographic and neuroimaging literature to address which spatial abilities are used during map tasks and which cognitive brain functions accompany these abilities.

Chapter 5: Tasks

Psychometric Cognitive Spatial Abilities Tasks

The first half of this experiment tests for the existence of spatial scanning and spatial relations cognitive spatial abilities. The testing instrument chosen to test for the spatial scanning ability is the “Map Planning Test” (Figure 1). It was developed from one of the Army Air Force (AAF) Printed Classification Tests that is used in *The Kit of Factor-Referenced Cognitive Tests* (Ekstrom et. al 1976). The instructions are to find the shortest line between two indicated letters. The correct line cannot include a circle.

The task known as the “Card Rotation Test” is used as the testing instrument for spatial relations (Figure 2). It comes from the Thurstone’s Cards tests used in *The Kit of Factor-Referenced Cognitive Tests* (Ekstrom et. al 1976). The instructions require the subject to identify if the figure in the card on the right has been flipped compared to the figure in the card on the left.

Map Tasks

The second half of this experiment pairs one of the cognitive tasks outlined above with a map task that is hypothesized to require a similar spatial judgment. The map tasks themselves are original to this project and were developed to simulate real world map use. The intent is to create map tasks that emulate actual map use rather than simply replicating the abstract cognitive task that is tested in the psychometric exams.

Right/Left Turn Choice

The first map task asks the subject to decide if they must make a left or right turn at a designated point in order to reach a destination (Figure 3). The pattern of travel is not always in an upright direction. The task is balanced so that each subject had to make an equal number of turn choices from upright, 90 degree, 180 degree, and 270 degree.

This task is paired with the mental rotation task because mentally rotating two-dimensional images seems to be an integral process associated with reading most two-dimensional maps (Lobben 2004). When a person navigates in the real world with the help of a map, there will be times when the person is not traveling in a northward direction (the direction in which most maps are oriented). Therefore, it can be hypothesized that people will rotate the map in their "mind's eye" to update the direction and orientation of the map before making a decision of whether to turn left or right at an intersection to reach a desired destination. Shepard and Hurwitz (1984) tested this theory and concluded that the more a map was rotated away from an upright position the longer it took the subject to answer the task. Therefore, they suggested that when a map is rotated in two-dimensional space, the subject will first rotate the map to an upright position before making the choice of turning to the left or to the right to reach the final destination. This study will further test Shepard and Hurwitz's theory by examining similarities in brain activation patterns for the cognitive rotation tasks and the right/left turn choice map task.

Find the Shortest Path

The second map task in this study asks the subject to find the shortest path between two locations (Figure 4) without traveling down roads blocked by an accident as denoted by a star symbol. This symbol was chosen because of its use in real-time web-based traffic maps posted on the internet to show areas of congested traffic due to car accidents. The direction of travel was balanced in this task with an equal number of paths running along the horizontal and vertical axis, as well as a balanced number of short and long correct paths.

Finding a particular kind of object, or path, in a field of objects is known as a visual search process. Visual search is a fundamental activity that takes place during map reading (Lloyd 1997; Nelson et al. 1997; Shortridge 1982). The shortest path map task requires a difficult visual search; there is no ‘pop-out’ effect for the shortest path. It is hypothesized that the subject must scan the map image to correctly identify the shortest path out of many possible paths. This scanning action is hypothesized to require extensive eye movement and attentional involvement to detect the target path. Therefore, it may require the same cognitive processing as the spatial scanning cognitive ability, which involves visual search of an abstract non-map environment for the shortest line connecting two points. Lloyd (1997) provides a full review of relevant theories regarding visual search processes in map environments.

Chapter Six: Methods

Experimental Design

Each subject took part in four experimental conditions: (1) finding the shortest line between two letters (spatial scanning cognitive task), (2) mental rotation of abstract geometric shapes (spatial relations cognitive task), (3) finding the shortest path between two locations (spatial scanning map task) and, (4) making a right/left direction choice on a map image (spatial relations map task). Each of the four tasks has an associated, matched control task. The control task was used to eliminate brain activity resulting from perceiving the stimuli, pushing the answer box, and moving the eyes. Furthermore, the control condition and the experimental condition in each task used the exact same images, required the subject to press the answer box in the same manner, and to move their eyes in a similar way, but the control condition did not include any spatial reasoning. The brain activation that is the same for the experimental condition and its control condition is subtracted out of the final results. What is left in the final analysis is the isolated cognitive brain function associated with performing the spatial reasoning aspects of the experimental condition. This approach is called the subtractive method (Posner 2005). The subtractive method was done for each subject across each of the four task conditions.

The spatial scanning cognitive experimental task instructions were, “what numbered box falls on the shortest line connecting the two indicated letters. The shortest line may not include a circle." The control instructions were, "scan along the highlighted path. What numbered box do you pass?" (Figure 5).

The spatial relations cognitive experimental task instructions were, "is the object on the right flipped?" The contrasting control instructions were, "is the image on the right the same object?" (Figure 6).

The find the shortest path map experimental task (spatial scanning map task) instructions were, "what numbered box do you pass on the shortest path between the indicated letters? You may not pass an accident symbol." The control instructions were, "travel along the highlighted path. What numbered box do you pass?" (Figure 7).

The final task was the right/left turn choice map task (spatial relations map task). The experimental task instructions were, "if traveling from Point A to Point C, do you turn left or right at Point B?" The control instructions were, "is Point A to the left or right of Point B?" (Figure 8).

Each stimulus run, also known as a scan, tested one of the four experimental conditions. The scan runs included both the experimental task and the control task presented in a controlled sequence (Figure 9). Each scan run lasted six minutes and thirty-six seconds. The four experimental conditions were repeated twice using the same images in a different order for data integrity. Thus, each subject participated in eight functional scan runs. The subject keyed in their answer to the task via a button box programmed for the right hand only.

<u>Functional MRI</u>

The development of fMRI technique, using the blood oxygen level-dependant (BOLD) method, has provided researchers with the ability to localize brain activity and link it to specific known cognitive processes. It is possible for researchers to understand the neural location of map reading in addition to measuring the success of map use. The ability to characterize patterns of brain activation during map reading allows the experimenter to link patterns of activation in one task, a spatial cognitive task, to the patterns in another task, a map reading task, in order to understand the cognitive similarities and differences of these varying spatial tasks.

The goal of functional neuroimaging is to map the activity of the living brain. Functional MRI measures vascular parameters such as the cerebral blood oxygenation. The physiological basis of this method is the fact that brain cell activity is associated with changes in glucose and oxygen consumption through what is known as neurovascular coupling in cerebral blood flow (CBF) (Kim and Ugurbil 1997**)** When a subject is given a task there is an increase in neural activity within a particular area of the brain which corresponds with an increase in the cells' metabolic rate and an increase in the amount of CBF. If blood flow increases more than oxygen metabolism, less oxygen is removed from the blood and blood oxygenation increases. The MR signal is sensitive to this change due to the paramagnetic properties of deoxyhemoglobin. The BOLD method identifies areas of the brain that show changes in deoxyhemoglobin levels. Regions with greater oxygenated verses deoxygenated blood appear brighter in an MR image. For a more extensive review of how functional MRI works see *Introduction to Functional Magnetic Resonance Imaging: Principles and Techniques* (Buxton 2002).

The MRI and fMRI scanning for this project was performed on a 3T (three Tesla) scanner with a head only, fast switching gradient coil. The unit is located in the MR Facility of Straub Hall at the University of Oregon. First, an initial high resolution anatomical MRI scan was taken to determine the structural configuration of each subject's brain; followed by a set of functional scans. The functional scans consisted of a series of thirty-two four millimeter thick, horizontal functional brain scans, also known as slices, which were taken every 2.1 seconds while the subject performed experimental tasks or controls. Each slice consisted of 3.125 x 3.125mm volume elements known as voxels (there are 64 x 64 voxels in each slice). Each voxel contains data in the form of a series of intensity values (sampled once every 2.1 seconds) which reflect the brain's activation over time. This series of activations for a single voxel, or region of voxels, is known as a time course.

The fMRI data analysis was performed using Brain Voyager software. The data went through a number of preprocessing steps. First, the data were corrected for three-dimensional head motion. Next, the data were subjected to temporal filtering to eliminate non-brain-activity-related slow changes or drifts. Finally, spatial data smoothing was done at 3mm isotropic Gaussian kernel for statistical purposes of making the noise distribution Gaussian.

The functional images were then aligned to the anatomical images for each scan. All images were normalized into Talairach space (Czanner et al. 1997). This is done by registering each subject's brain images to eight known anatomical anchor points and fitting a grid to the anatomy. Registering each brain into Talairach space minimizes the difficulty in identifying and defining brain regions across subjects. It also increases the accuracy of multi-subject averaging.

The project used a hypothesis driven analysis known as the General Linear Model to identify activated voxels (Fristion et al. 1995). A statistical neural model was built for each subject and condition based on the events. The reaction time for each event (i.e., each trial) is first modeled with a square wave whose width is equal to the reaction time. During this period of time, the subject is engaged in cognitive processing specific to the task at hand and one should therefore observe task-specific neural processing during this period. However, since the BOLD response is delayed by an average of six seconds relative to the neural events giving rise to it, the initial reaction-time-defined neural response is convolved with a model of the hemodynamic response (defined as the response to a briefly presented external stimulus). This operation results in a slightly delayed neural model for each event.

The testing hypothesis represented the contrast of the experimental condition verses the control condition for each of the four scan types. For each voxel, if the activation for the experimental condition is greater than that of the control condition for a given statistical threshold it appears as a colored voxel. The collection of all colored voxels in all brain slices is known as a statistical brain map.

The statistical brain maps illustrate which voxels have the highest likelihood of being activated by the tasks, based on the observations of this experiment. The statistical brain maps shown in this paper are averaged across all subjects for each task. The p value for this experiment is <0.0003, which is more stringent than is generally used in other published fMRI studies. The positively marked task conditions show up as red, orange or yellow. The yellow indicates the highest likelihood of activation.

Subjects

My study included twelve subjects between the ages of 21-27. The subjects consisted of six women and six men, to have equal representation. All subjects were recruited from the University of Oregon and were right handed. Subjects were paid $10.00 an hour for their participation in the experiment and each scan took approximately one and a half hours. There was in addition a pre-scan practice session that took place in an MRI simulator unit where subjects were exposed to cognitive tasks similar to the ones they would be performing in the magnet, so it was clear how to perform each task

Chapter 7: Results

There were common regions of activation for all four experimental conditions that include bilateral activation in the frontal eye fields (FEF), the Inferior Parietal Lobe (IPL), Superior Partial Lobe (SPL), and the Cingulate Cortex. Other significant areas of activation for each task are outlined below. Additional areas of significant activation for the spatial scanning cognitive task include: Dorsolateral prefrontal cortex, Orbiotfrontal gyrus, and parahippocampal gyrus. Activations for the spatial scanning map task include: Dorsolateral prefrontal cortex, the Orbiotfrontal gyrus, thalamus, and the PPA. The spatial relations cognitive task elicits lateral occipital complex (LO). The spatial relations map task has activity in the MT, the parahippocampal gyrus and the cerebellum vermis.

Chapter 8: Discussion

The project is set up for a four-way comparison (Figure 10) of the brain activation patterns across the different tasks. First, if there is significant difference in brain activation between the two psychometric cognitive tasks, then it suggests that the tasks test for distinct spatial abilities.

The second comparison is between the spatial scanning cognitive and map tasks. In a route planning exercise people need to be able to: (1) find available routes; and (2) reject ones that do not fit their needs. I have hypothesized that that the cognitive task and the map task will elicit similar brain activation patterns because the tasks are very similar. Both tasks ask the subject to find the shortest path, although the cognitive task is abstract and the map task is a real world map exercise.

The third comparison is between the spatial relations cognitive and map tasks. It has been suggested that people may use a map like an object and rotate it to an upright position to determine if they should turn left or right at an intersection when the individual's orientation does not match the map orientation. If this is true, then there may be similar brain activation patterns with the mental rotation of a geometric object.

Lastly, I compare the two map tasks. Although the map tasks *appear* to be different tasks, the fMRI images can answer if they trigger similar areas of brain activation and cognitive processing as when a subject is engaged in map comprehension.

<u>All Tasks</u>

To begin the discussion it is appropriate to look at similarities in brain activation for all four spatial tasks combined (Figure 11). The diversity of visuospatial tasks used in this study allows for evaluation of areas of activation that may be involved in spatial attention. Mesulam (1990) proposed a neural network approach to spatial attention. This model cites three interconnected cortical areas, the premotor cortex (including the frontal eye fields), the posterior parietal cortex, and the cingulate cortex. In my study, significant activations are seen in all three of these areas for the four spatial tasks at a p value of <0.005. These results are consistent with previous spatial attention studies (Posner et al. 1984; Corbetta et al. 1993; Nobre et al. 1998; Gitelman et al. 2002). Due to the variety of spatial tasks included in this experiment, the results corroborate evidence that the frontal, parietal and cingulate grouping of cortical activations provides a flexible large-scale neural network for all types of spatial attentional behavior (Gitelman et al. 1999).

The frontal eye fields (FEF) are known to partly control exploratory behavior (Mesulam 1981), such as eye movement. The role of the FEF in the attentional network has had varying explanations. The involvement of the FEF in the spatial tasks included in this study may be due to the subjects fixating on the images (Law et al. 1997), smooth pursuit and/or saccadic eye movements (Corbetta 1998; Nobre et al. 1998; Berman et al. 1999), and working memory (Sweeney et al. 1996; Courtney et al. 1998).

The parietal complex includes both the inferior parietal lobule (IPL) and the superior parietal lobule (SPL). They are integral to the sensorimotor representation of external body space. The posterior parietal complex is part of the attentional system. It may be critical in selecting one stimulus location among many, and in shifts of visual attention to new targets in space (Faillenot et al. 1997; Clark and Bourtos 1999). My findings show clear overlap in activation for all the tasks, extending from the IPL to the SPL in both hemispheres. Given that the spatial layouts of the stimuli and the cognitive tasks differed greatly in each of our four experimental conditions, the activation in the SPL and IPL suggests that this region performs general attentional functions, such as simply focusing spatial attention (see Wojciulik and Kanwishers 1999).

The anterior cingulate cortex (ACC) in conjunction with the basal ganglia represents part of the anterior attention system. This system plays an executive role in selecting and controlling various brain areas in order to perform complex cognitive tasks. The ACC can scan available visual objects and scenes and select an object or stimuli with particular properties as defined by a set of instructions. The ACC works by recruiting and controlling the posterior attention system (Posner and Dehaene 1994). The cingulate cortex has been implemented in a number of spatial attention studies (Masulam et al. 2000), as well as in eye movement studies. It may be more significantly involved in pursuit eye movements rather than saccades (Berman et al. 1999). The involvement of the ACC in this study provides furthers the evidence that there is an interconnected spatial attention system that involves a number of brain areas.

The next section compares and contrasts the tasks pairs described above, highlighting findings other than those previously mentioned. All the tasks share the triad of cortical areas known for spatial attention. The p value for the remaining results is <0.0003.

Comparison of Cognitive Tasks

The results display neurological differences that suggest spatial scanning and spatial relations may be two distinct spatial abilities. First, the spatial scanning cognitive task has extensive bilateral activation in the dorsolateral prefrontal cortex (DLPFC) (Figure 12). DLPFC activation occurs when increased numbers of items in the image are searched and with tasks that require increased search effort (Donner et al 2002; Nobre et al. 2003). The DLPFC activation in the spatial scanning task may show the need for more attentional resources to reject and ignore distracting information, or goal-relevant verses goal-irrelevant stimuli, such as paths that do not lead to the correct location, letters that surround the task image, and circles that block paths (Lavie 2000; De Focker et al. 2001; Olivers et al. 2004). The DLPFC in essence acts like a filter.

Previous studies show that activation in the left occipital gyrus occurs in the left of the lateral occipital (LO) complex (Epstein et al. 2003). In this study, LO activation is present for the spatial relations cognitive task, but not the spatial scanning cognitive task (Figure 13). The LO complex tends to respond to object changes more than visuospatial changes. This is consistent with its role in processing the shapes of objects (Kourtzi and Kanwisher 2001). It has been hypothesized that when people mentally rotate an object they update their mental picture of that object as they rotate it in their “mind’s eye” to an upright position. The LO complex may be activated in the spatial relations task because the task may require the subject to constantly compare the stationary object to the mentally rotating object.

Lastly, there is significantly more anterior cingulate cortex (ACC) activation in the spatial scanning task than in the spatial relations task (Figure 14). When the threshold is increased to a value of $p<0.0003$, the ACC drops almost completely out for the spatial relations task. This suggests that it takes more spatial attention to perform the scanning task than it does to mentally rotate a two-dimensional object. It also suggests that the spatial scanning cognitive task is more difficult and perhaps is a better measure of overall spatial ability.

Comparison of Spatial Scanning Cognitive and Map Tasks

The spatial scanning cognitive task and the find the shortest path map task (i.e., the spatial scanning map tasks) have a number of similarities. They both have extensive bilateral DLPFC (Figure 15). As noted above, the DLPFC in known to be activated in complex visual search tasks, acting as a filter of task-relevant verses task-irrelevant stimuli (Lavie 2000; De Focker et al. 2001; Olivers et al. 2004). The DLPFC is also heavily involved in manipulating representations and monitoring information within working memory (Owen 2000; Petrides 2000). Working memory allows people to search a representation, like a map, remember what they have seen, and incorporate it with incoming information to help answer the question “which is the shortest path or line?”

The next area of similarity between the spatial scanning map and cognitive tasks is in the orbitofrontal cortex (Figure 16). The map task has bilateral activation and the cognitive task has right hemisphere activation. The orbitofrontal cortex is known for its role in the inhibition and anticipation of a response (Fuster 1996; Walton et al. 2004).

Lesions in this area can lead to disinhibition and obsessive compulsive behaviors (Baxter et al. 1990). Activation in the orbitofrontal cortex may suppress internal signals to respond until a subject is done performing the tasks. Orbitofrontal activation is only seen in this experiment for the tasks with four potential answers. The role of this region may be to override premature response. A subject may think they know the correct answer to the task, but wait until they have check all possibilities before answering.

The final area of similarities to be highlighted is bilaterally in the parahippocampal place area (PPA) (Figure 17). Epstein et al. (1999) equates activation in the parahippocampal cortex with processing information about spatial structures of a viewed environment. Other neuropsychological studies also implement the PPA in scene perception (Aguirre et al. 1998; Epstein et al. 2001). PPA activity is not affected by the subject's familiarity with a place and it does not increase when the subject experiences a sense of motion through a scene (Epstein et al. 1999). The PPA responds to photographs of landscapes, cityscapes, parks, and houses, but not to faces, objects or scrambled scenes (Epstein et al. 2003).

The map task elicits extensive PPA activation. The viewer interprets the map as a real place, which is perhaps not surprising, especially to geographers. But the viewer also sees the abstract cognitive representation as a place. The cognitive task image may share enough map-like properties in its design or spatial layout to constitute the representation of a real place and, in turn, is perceived that way by the subjects. It may look like the road networks of an urban area or a subway map.

Comparison of Spatial Relations Cognitive and Map Tasks

The only significant activation similarity the mental rotation cognitive task (spatial relations cognitive task) and the right/left turn choice task (spatial relations map task) share is those for spatial attention. Although, when the threshold is increased to a p value of <0.0003 the anterior cingulate cortex (ACC) drops out for the spatial relations cognitive task, while significant activation is still seen in the ACC for the spatial relations map tasks. Again this suggests that the map task is a more difficult task and may be a better test for overall spatial ability.

Activation in the medial temporal complex (MT+), which includes areas MT and MST, is seen bilaterally for the spatial relations map task compared with no significant activation in this area for the cognitive task (Figure 18). Activation in this task is most likely in the MT, and possibly the MST (Dukelow et al. 2001). The area known as MT encodes basic motion elements and MST has higher-order motion-processing abilities (Barton et al. 1996; Petit and Haxby 1999). MST has been implicated in the perception of both object and self-rotation (Britten and van Wezel 1998; Tanaka et al. 1993). MST may be a synaptic bridge between the dorsal and ventral streams of visual processing and could be important for switching attention among stimuli located in extrapersonal space (Gitelman et al. 1999). MT+ activation has been noted in other experiments using a two-dimensional rotation task (Jorden et al. 2002; Podzebenko et al. 2002), but at the p value of <0.0003 used in this experiment MT+ activation does not show up for the cognitive task. Perhaps the right/left turn choice task (spatial relations map task) engaged the subject in a rotational exercise in which the viewer senses motion. It may be due to the subject sensing themselves rotating their imagined body or their imagined extra-personal space in the map environment to answer the task.

The idea of imaged or sensed movement is further demonstrated with activation in the cerebellum vermis for the map task, but not the cognitive task (Figure 19). The cerebellum vermis is known to be activated during imagined movement, or when a person imagines themselves doing complex motor activities, like walking or swinging a golf club (Ross et al. 2003). This suggests that the subjects imagined themselves moving down the path and/or imagined themselves turning to solve the right/left choice task.

The spatial relations map task also elicits bilateral activation in the dorsomedial thalamus (Figure 20). This thalamic structure is implemented in mental imagery when a viewer-centered perspective is taken or for example when a person imagines themselves inside the environment instead of looking down on it. If a person has a lesion in this brain area, spatial neglect is experienced in which a person is unable to recognize or respond to a particular part of space when a viewer-centered perspective is taken verses an alocentric one (Ortigue et al. 2001). Their topographic knowledge is preserved and they do not do have memory impairment, but rather a disorder in mental imagery processes that operated in a body-centered system. Activation in the dorsomedial thalamus for the map task suggests that the subjects took a viewer-centered vantage point, or put themselves inside the map to solve the left/right choice task.

The last area of significant difference between the spatial relations map and cognitive task is in the parahippocampal place area (PPA) (Figure 21). The map task has bilateral PPA activation and suggests that the subjects perceived the map to be a real place with spatial configurations that are consistent with other types of viewed environments.

Comparison of Map Tasks

Subject responses to the map tasks display a number of differences suggesting that the tasks require different cognitive processes. But there are also striking similarities between the tasks. Both tasks have bilateral PPA activation and cerebellum vermis activation (Figure 22). The PPA activation provides evidence that cartographic representations are perceived as real places, or scenes. The cerebellum vermis activation suggests that the subjects imagined themselves moving or performing complex motor activities. It is interesting to note that while the spatial scanning cognitive task may be perceived as a scene, it can be suggested that the subjects do not imagine themselves moving within the scene or environment because of the lack of activation in the cerebellum vermis. Activation in the PPA coupled with cerebellum vermis activation may be caused by the spatial language used in the instructions of both the map tasks, which indicate that these stimuli represent real places that can be navigated.

Chapter 9: Conclusions

This research project has explored some basic questions within cartographic, geographic and psychological research. Examining the use of spatial abilities in map reading exercises is a not a new inquiry, but this project investigates this old question with a new methodological approach, leading to some new conclusions.

First, there are enough differences in neurological activations between the spatial scanning and spatial relations tasks to suggest that they are two distinct spatial abilities that exist independently of one another. Furthermore, the study provides baseline data to compare neurological activation for spatial abilities and map tasks.

Second, this project helps to identify the neurological cognitive processes for some map tasks, which helps define how the human brain functions. The spatial scanning cognitive ability has areas of brain activation similar to the find the shortest path map task, suggesting that the spatial scanning ability is used in a visual search process conducted in map environments.

Lastly, the spatial relations cognitive task does not share enough common areas of brain activation with the right/left turn choice map task to suggest that it is used in the map task. They appear to be differing tasks. They both may be mental rotation tasks, but they are apparently not the same type of mental rotation.

There are a few other conclusions that do not address the research questions directly but are interesting to note. First, the data presented here and in many other research papers suggest that a network of areas underlies most spatial behavior and spatial tasks. This study demonstrates that a wide variety of visual spatial tasks engage the same spatial attention network.

Second, there may not be a ‘map lobe’, but the human brain does recognize maps as places. This study also suggests that map design can be relatively abstract and still convey a representation of place. This insight and may lead to future work with fMRI and map design.

The findings of this project may eventually lead to a comprehensive understanding of precisely which spatial abilities are required for a range of map-use tasks. Understanding which spatial abilities are used during map tasks can potentially guide us to new ways of teaching map reading, with educational exercises that specifically target key cognitive spatial abilities.

Finally, one can examine neurological data collected by means of fMRI in new ways, such as looking at sex and age differences, as well as differences in high verses low performers. Geographers, using this methodology in the future will not have to rely solely on behavioral data, such as performance, reaction times, and general correlation statistics for answers about human behavior, but can use this data in conjunction with fMRI to more definitively answer questions about the cognitive systems underlying spatial abilities and real-world map use.

Spatial Scanning Cognitive Task

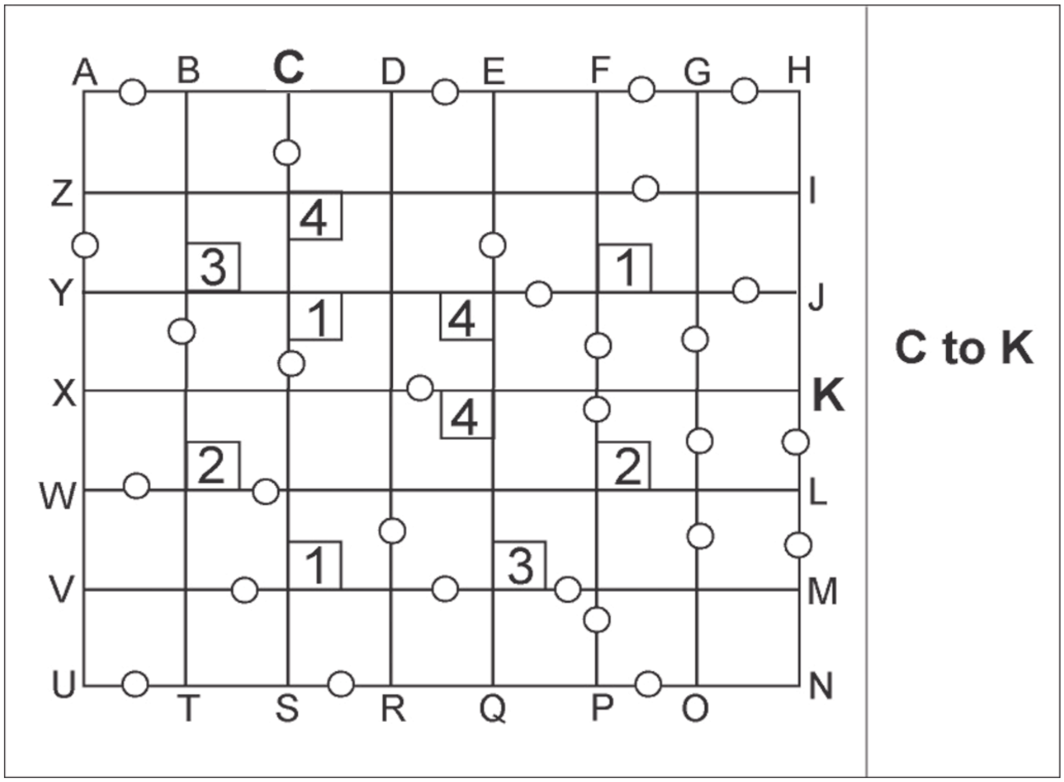


Figure 1. The spatial scanning cognitive task instructions ask the subject to report the numbered box on the shortest line between the indicated letters. The shortest path cannot include a circle.

Spatial Relations Cognitive Task

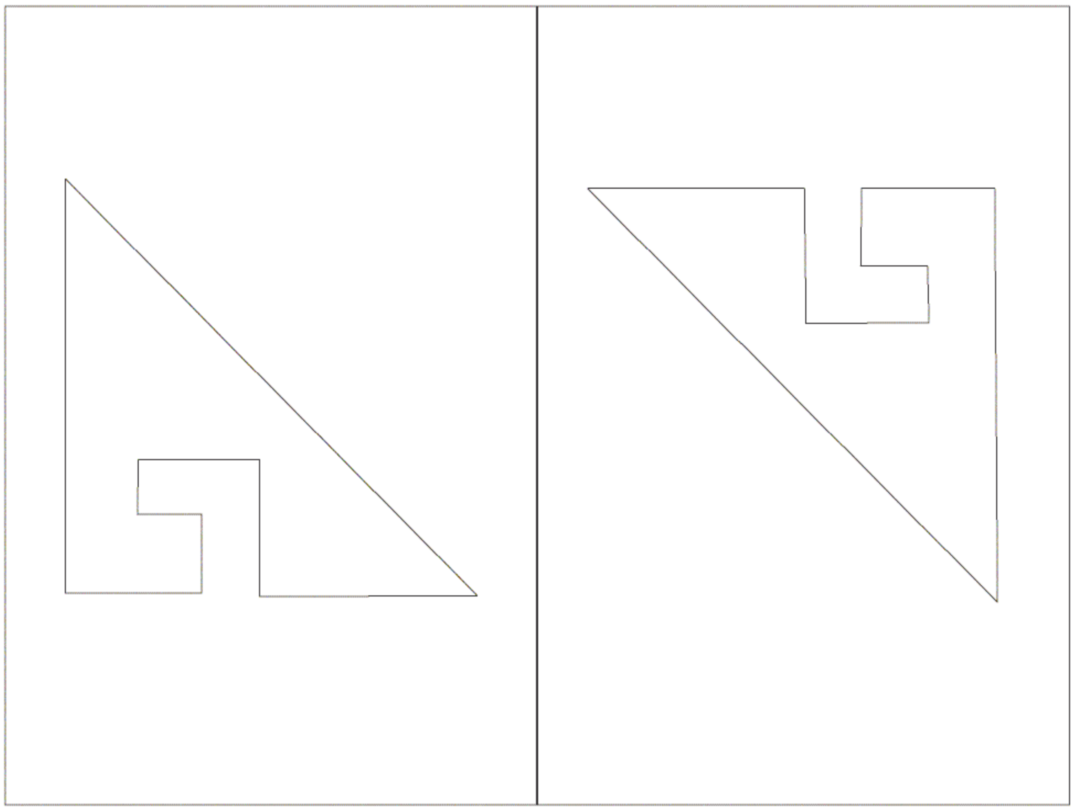


Figure 2. The spatial relations cognitive task instructions ask the subject to identify if the figure on the right has been flipped compared to the figure on the left.

Right/Left Turn Choice Map Task

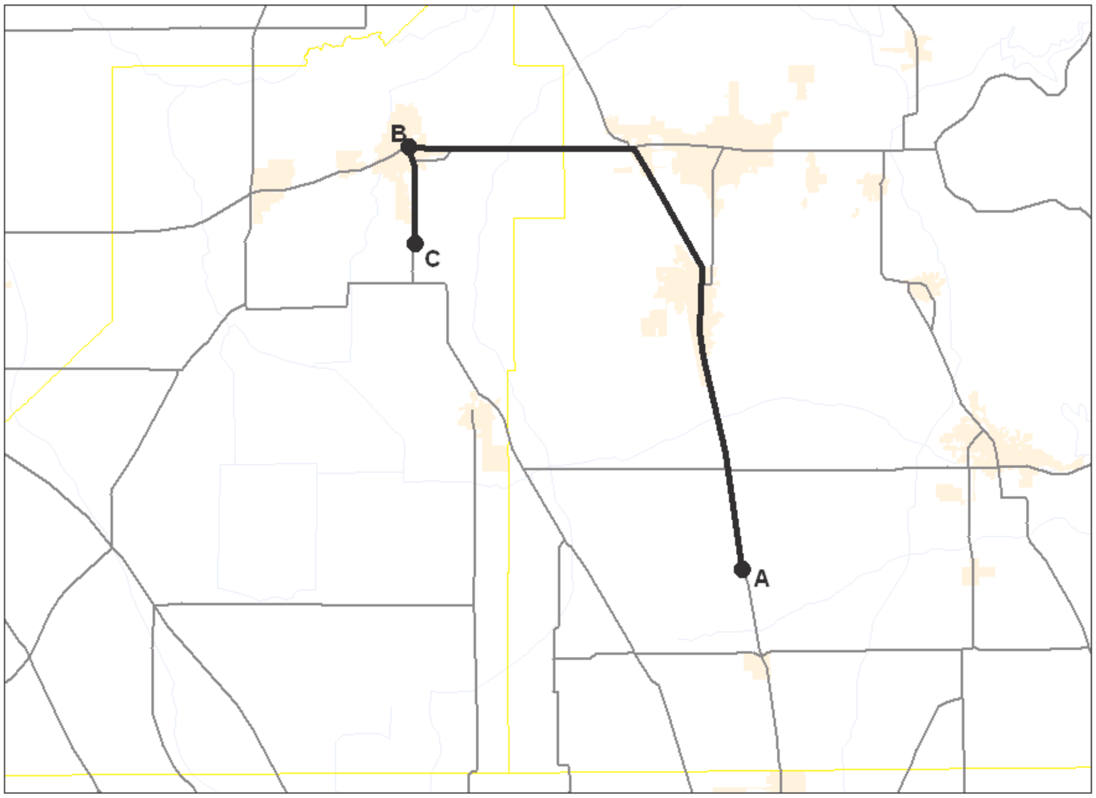


Figure 3: The right/left turn choice map task instructions ask the subject: "If traveling from Point A to Point C, do you turn left or right at Point B?"

Find the Shortest Path Map Task

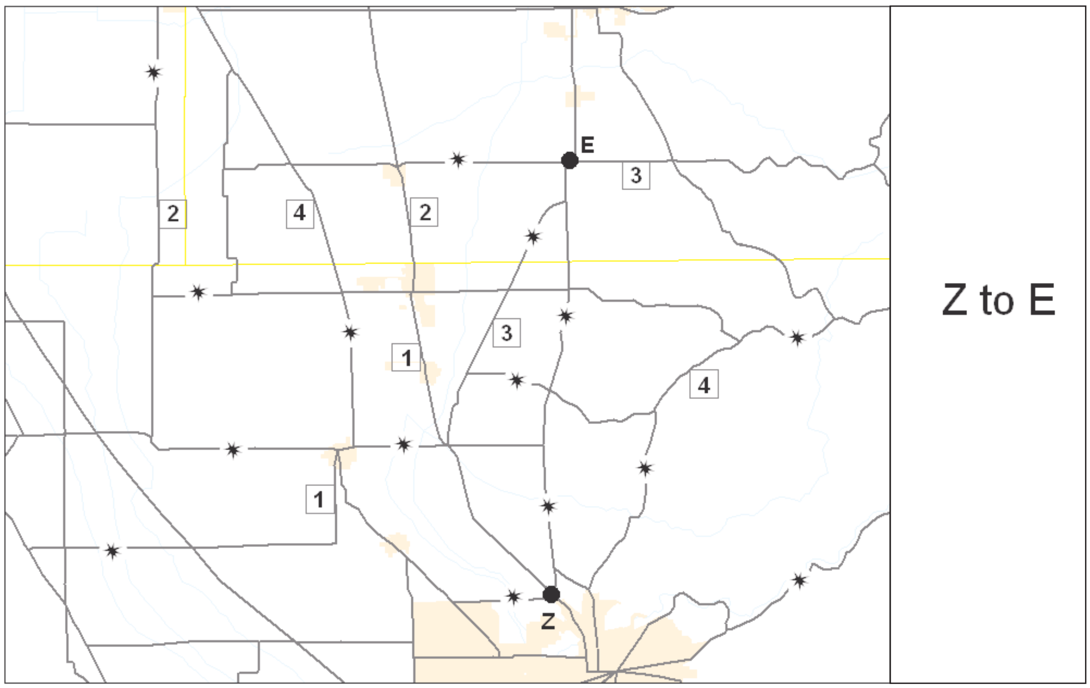


Figure 4. The shortest path map task instructions ask the subject to report the numbered box they pass on the shortest path between the indicated letters. Subjects may not pass an accident symbol.

Spatial Scanning, Cognitive: Task vs. Control

Task

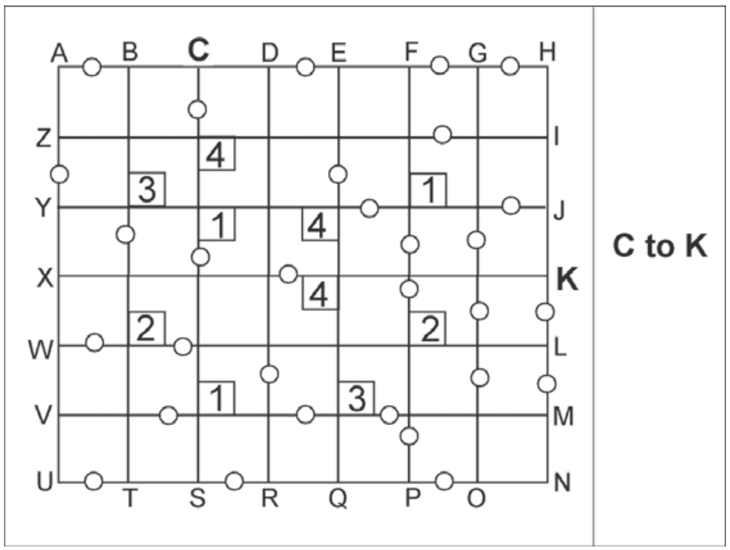
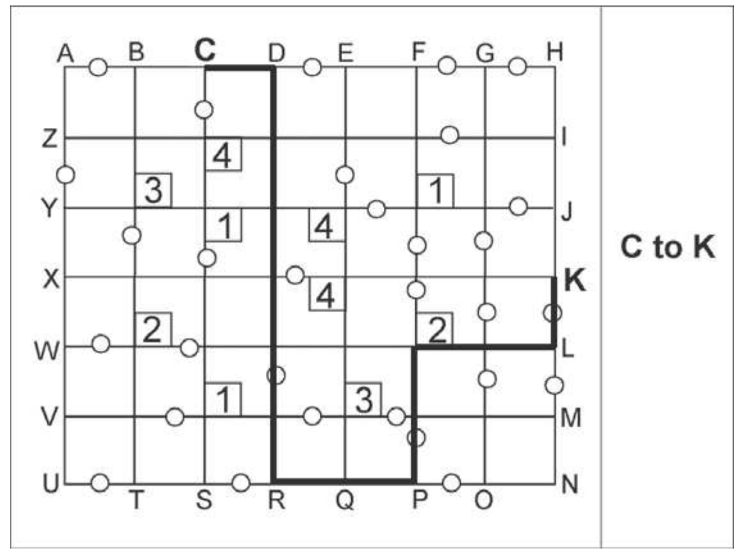


Figure 5.The spatial scanning cognitive task instructions ask the subject to report the numbered box on the shortest line between the indicated letters. The shortest line cannot include a circle.

Control



The control instructions ask the subject to scan their eyes along the highlighted path and report what numbered box they pass.

Spatial Relations, Cognitive: Task vs. Control

Task

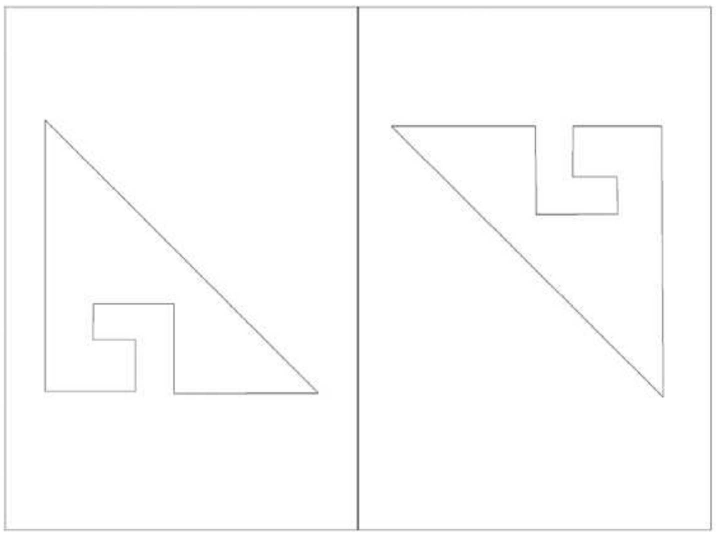
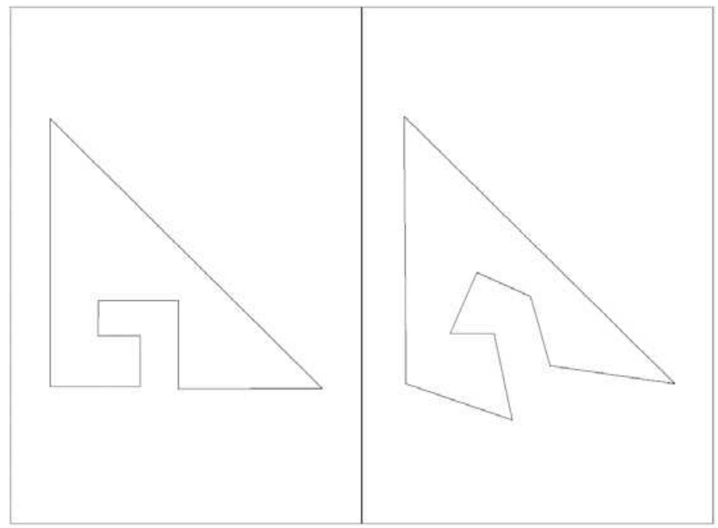


Figure 6. The spatial relations cognitive task instructions ask the subject to identify if the figure on the right has been flipped compared to the figure on the left.

Control



The control instructions ask the subject if the object on the right is the same object.

Find the Shortest Path: Task vs. Control

Task

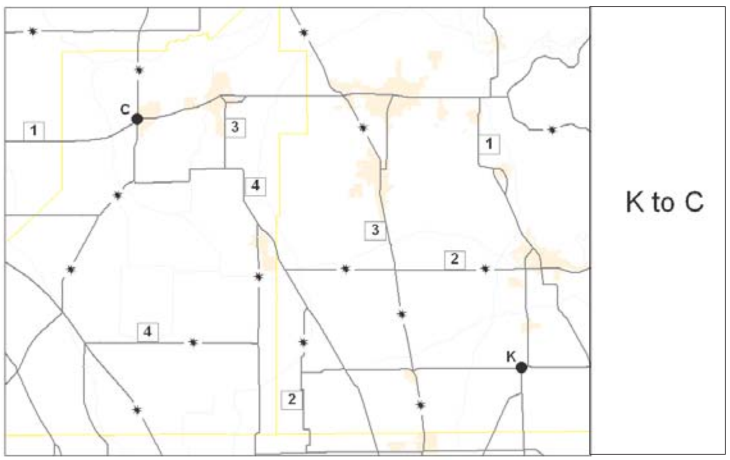
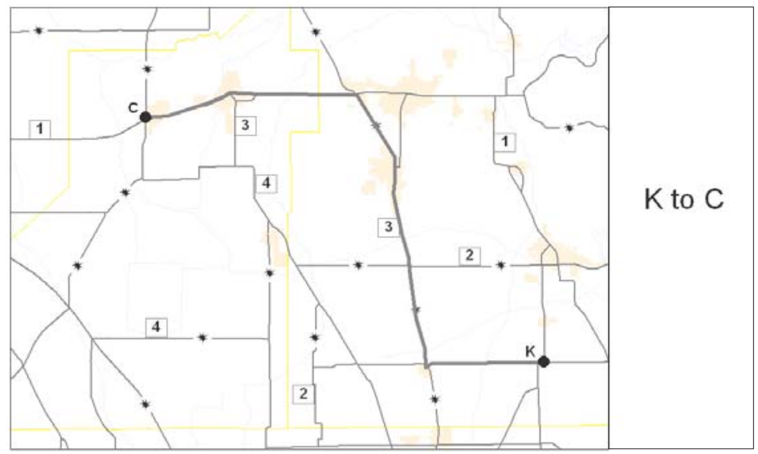


Figure 7. The shortest path map task instructions ask the subject to report the numbered box they pass on the shortest path between the indicated letters. Subjects may not pass an accident symbol.

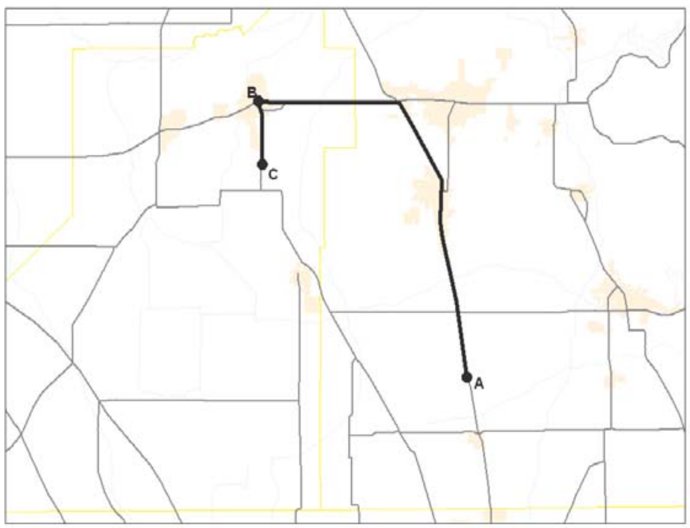
Control



The control instructions ask the subject to scan their eyes along the highlighted path and report what numbered box they pass.

Right/Left Turn Choice: Task vs. Control

Task



Control

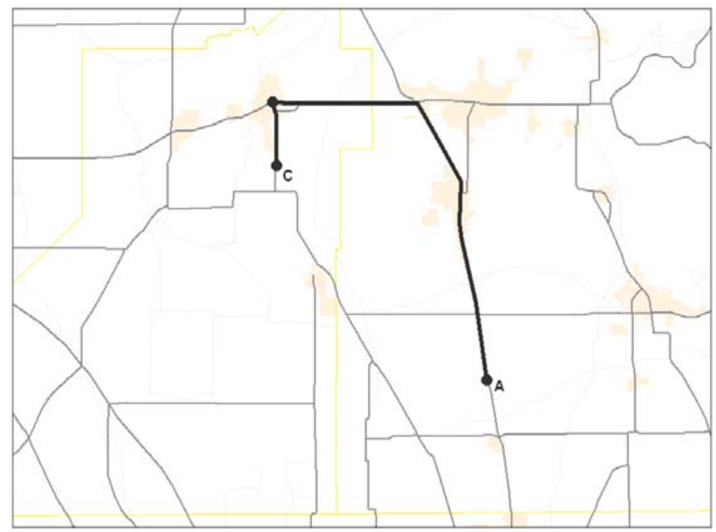


Figure 8. The right/left turn choice map task instructions ask the subject: "If traveling from Point A to Point C, do you turn left or right at Point B?"

The control instructions ask the subject to report if Point A is to the left or right of Point C on the page.

Stimulus Run

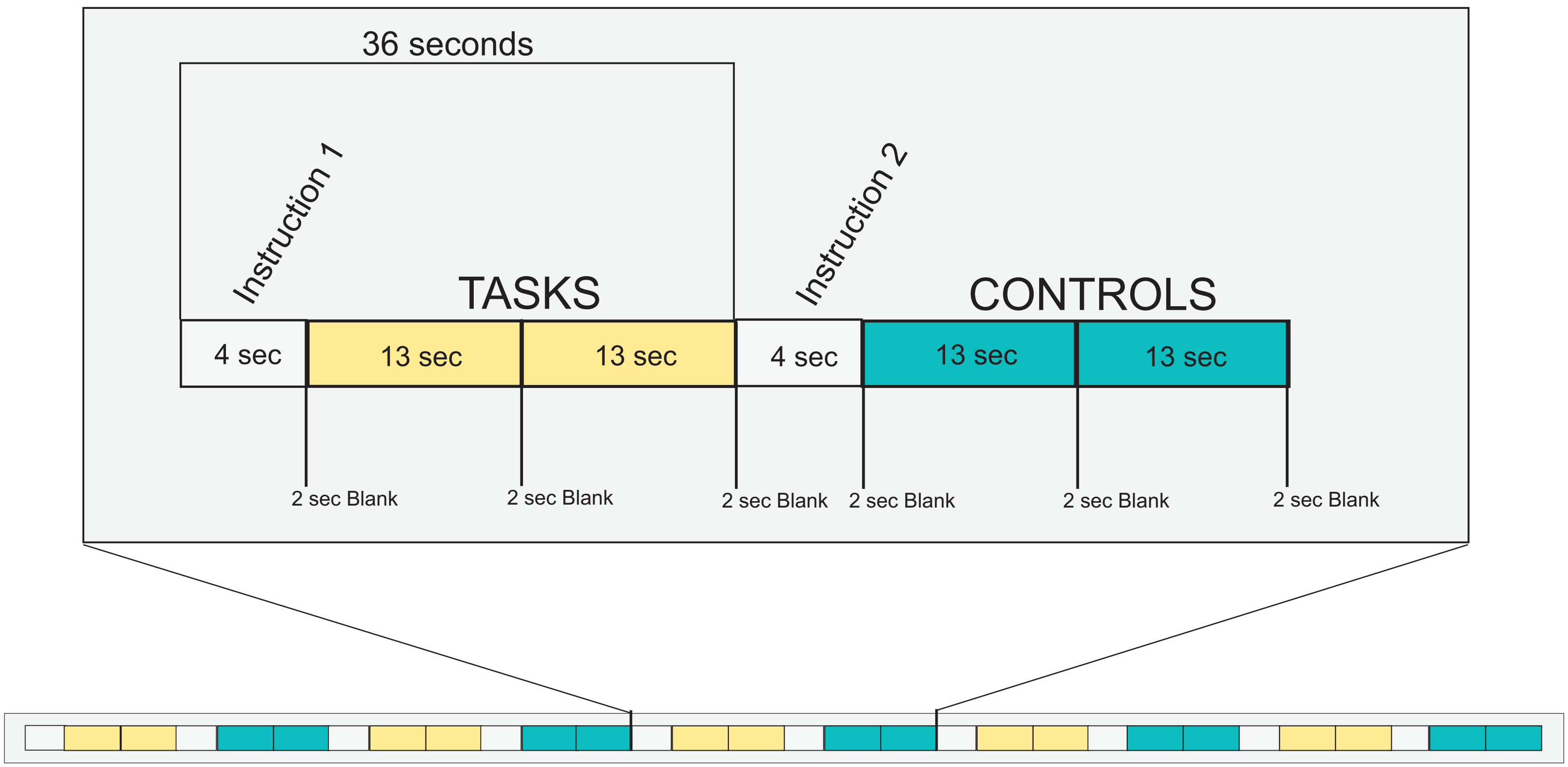


Fig. 9. The stimulus run shows the order of the stimulus images (tasks and controls) in the experiment.

Task Comparison Matrix

Spatial Scanning | Spatial Relations

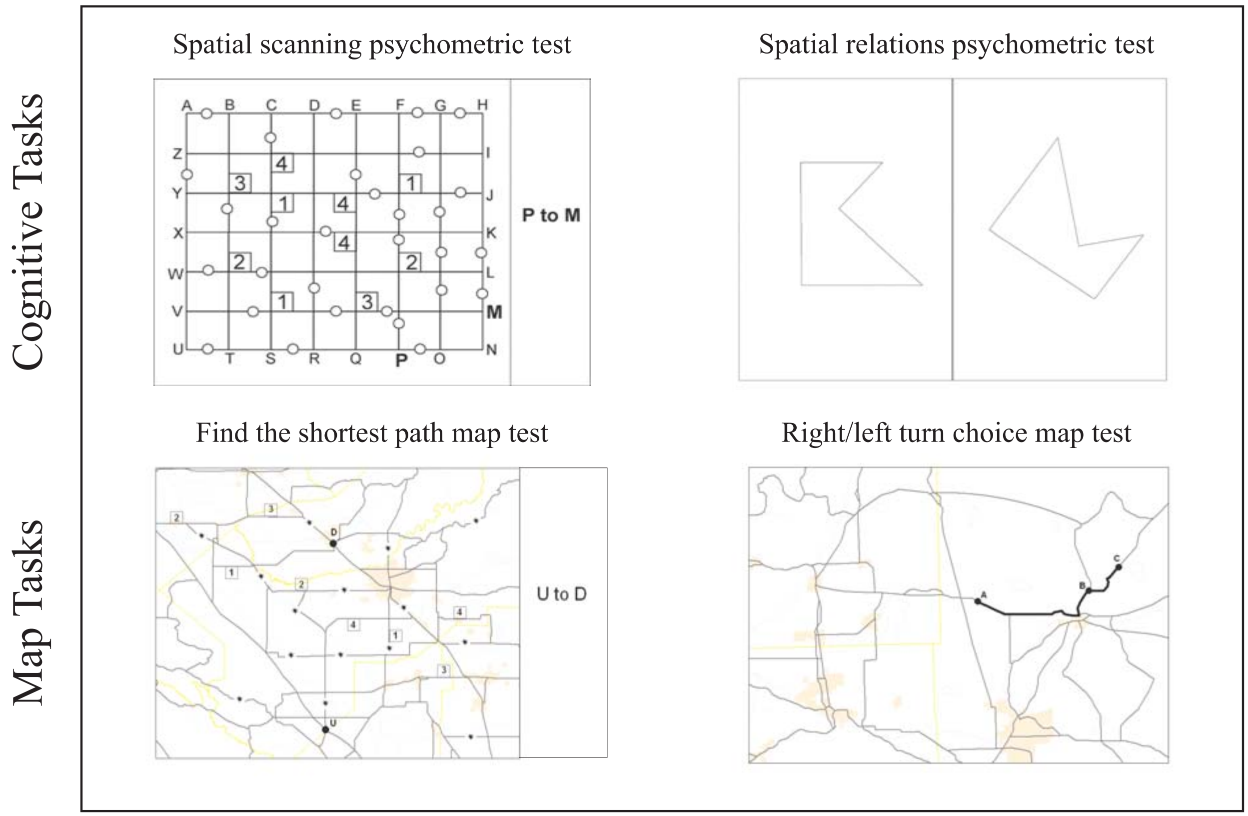


Figure 10. The tasks are set up for a four-way comparison: 1) Comparison of the two cognitive tasks, 2) Comparison of the spatial scanning cognitive and map tasks, 3) Comparison of the spatial relations cognitive and map tasks, and 4) Comparison of the two map tasks.

Activation for all tasks

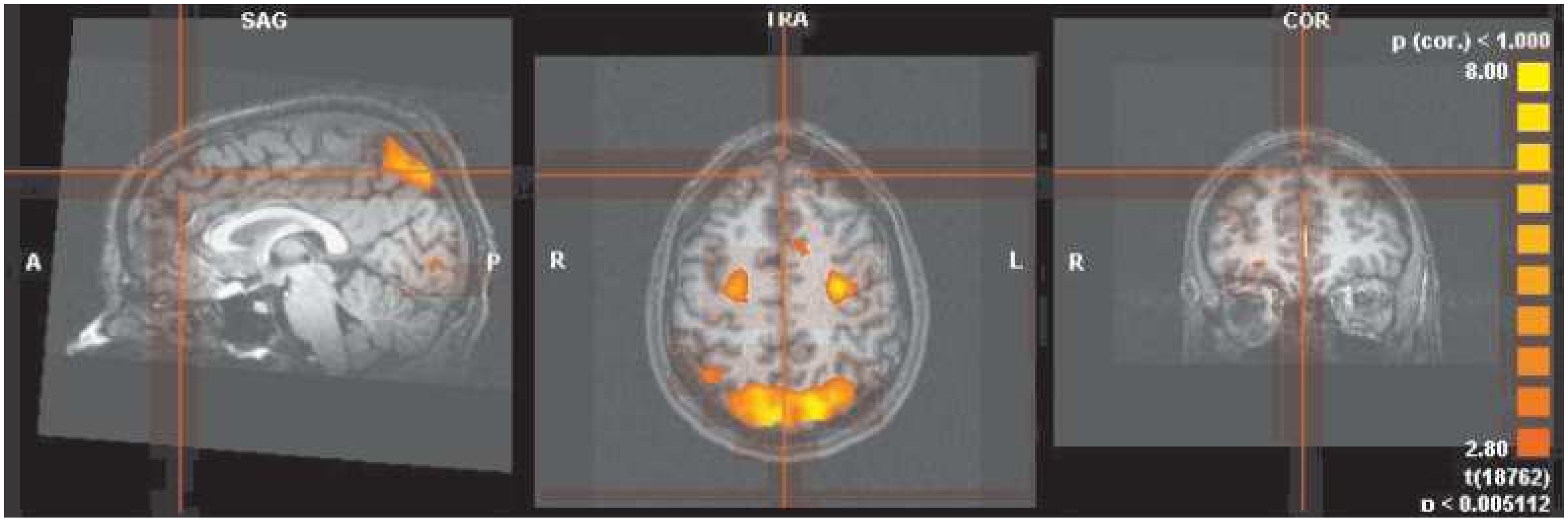


Figure 11. All four experimental tasks share activation in the frontal eye fields (FEF), the parietal complex (including both the superior parietal lobule (SPL) and the inferior parietal lobule (IPL)), and the anterior cingulate cortex (ACC) at the threshold $p<0.005$.

Differences in activation for the Cognitive Tasks

Spatial Relations

Spatial Scanning

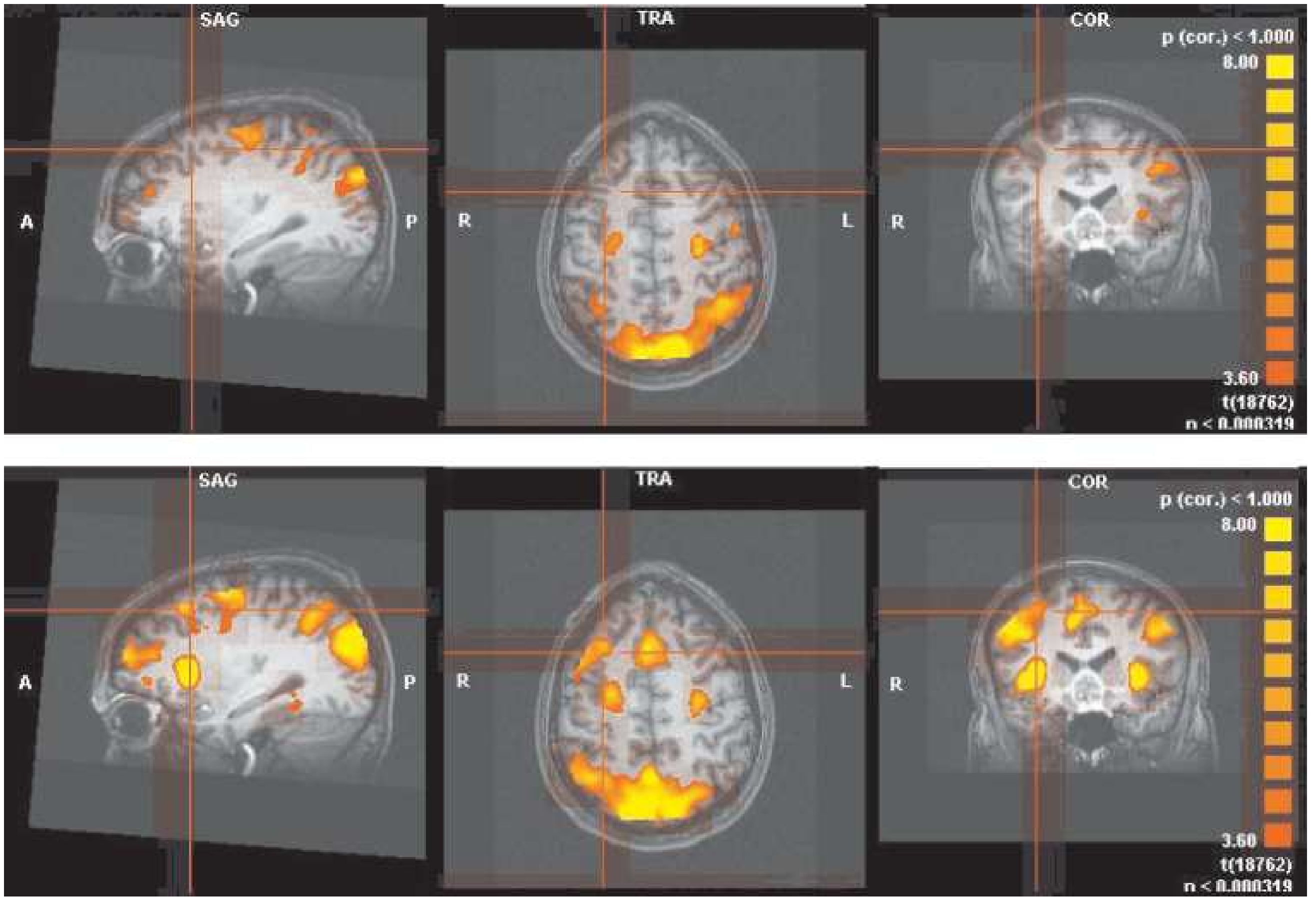


Figure 12. The red cross hairs point to activation in the dorsolateral prefrontal cortex (DLPFC) in the spatial scanning task ($p<0.0003$), but not in the spatial relations task.

Differences in activation for the Cognitive Tasks: 2

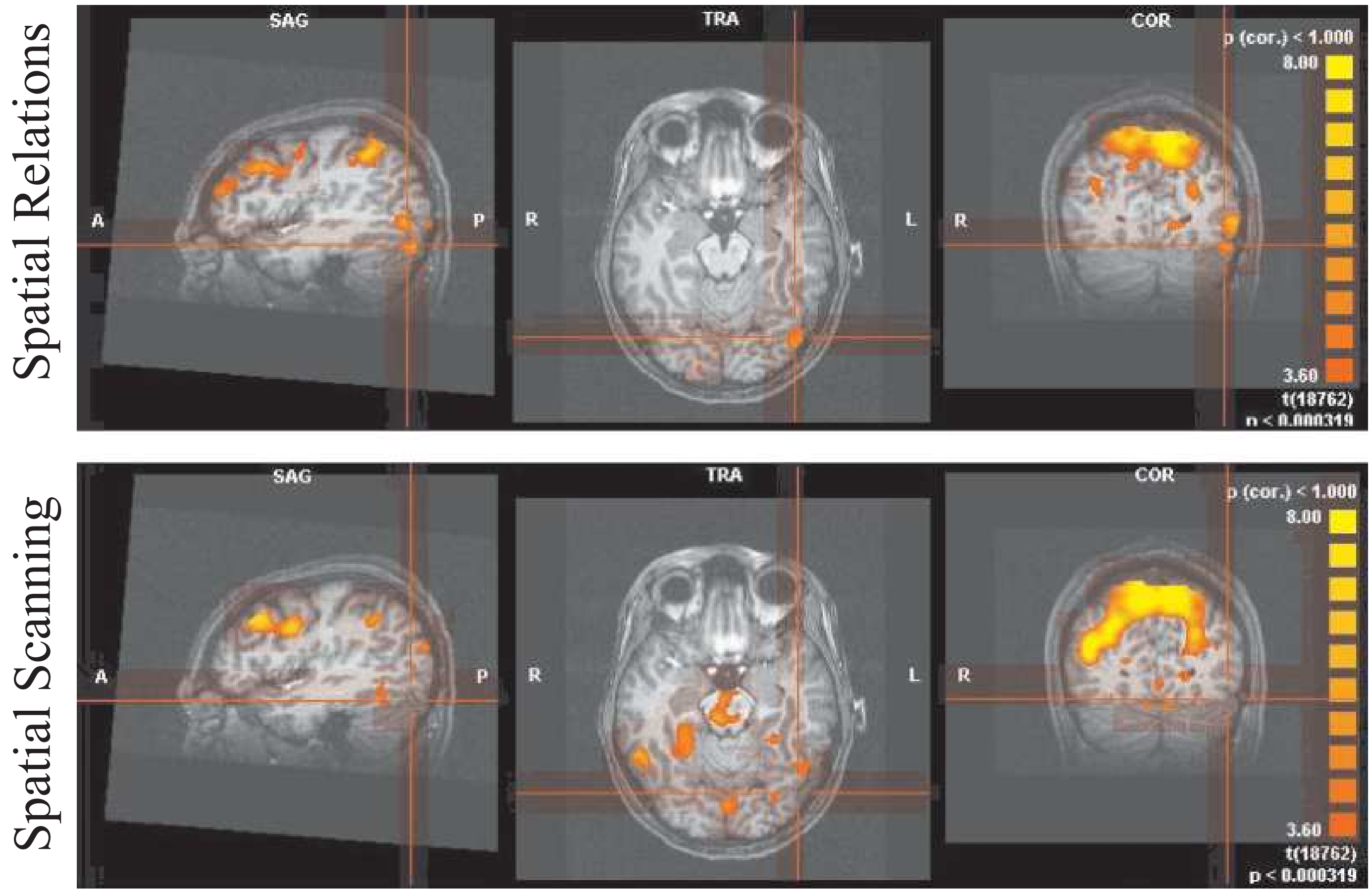


Figure 13. The red cross hairs point to activation in the lateral occipital cortex (LO) in the spatial relations task (p<0.0003), but not in the spatial scanning task.

Activation differences for the Cognitive Tasks: 3

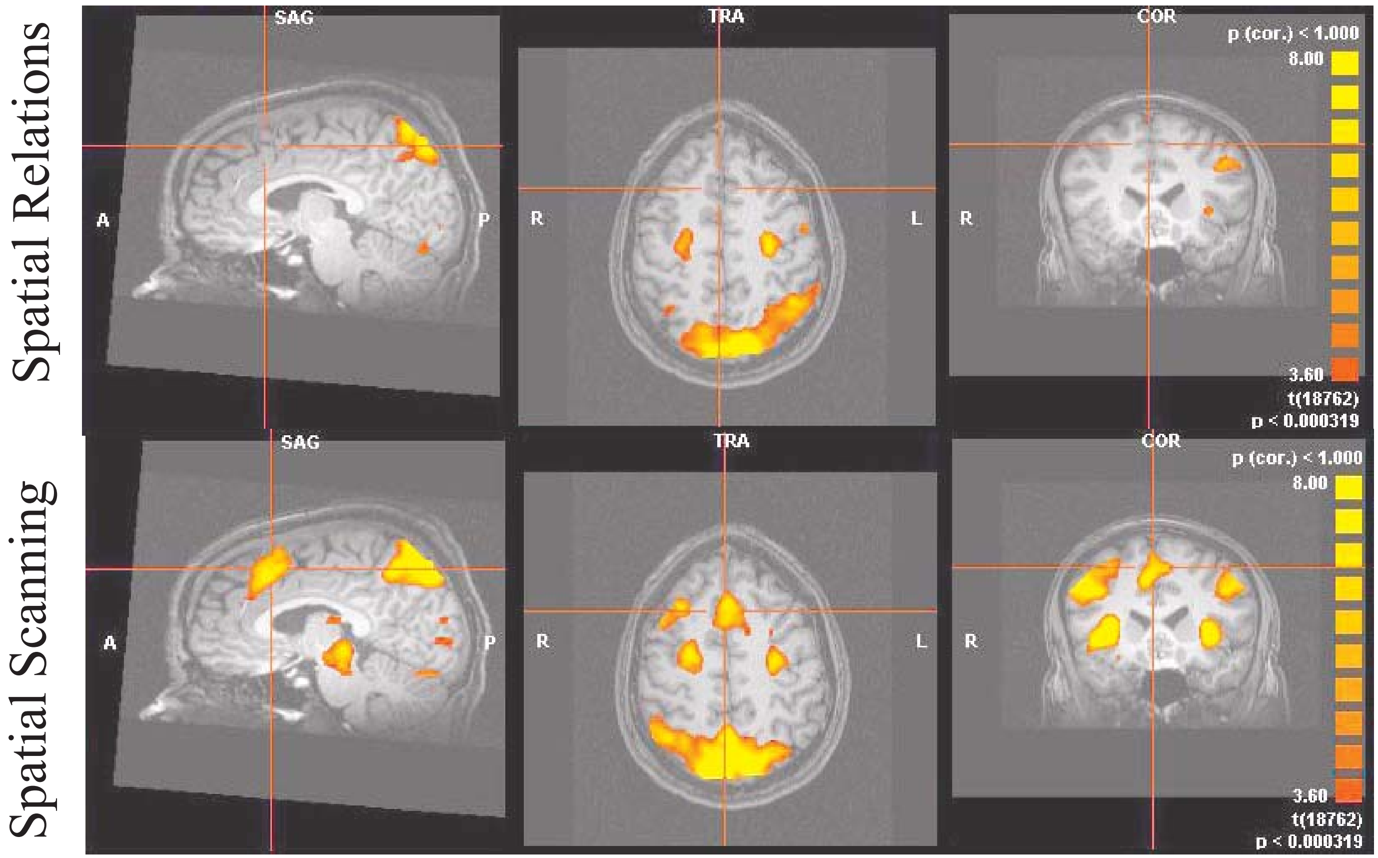


Figure 14. The red cross hairs point to activation in the anterior cingulate cortex (ACC) in the spatial scanning task, while the spatial relations task shows no activation in this area at the treshold p<0.0003.

Similarities in activation for the Spatial Scanning Tasks: 1

Cognitive task

Map task

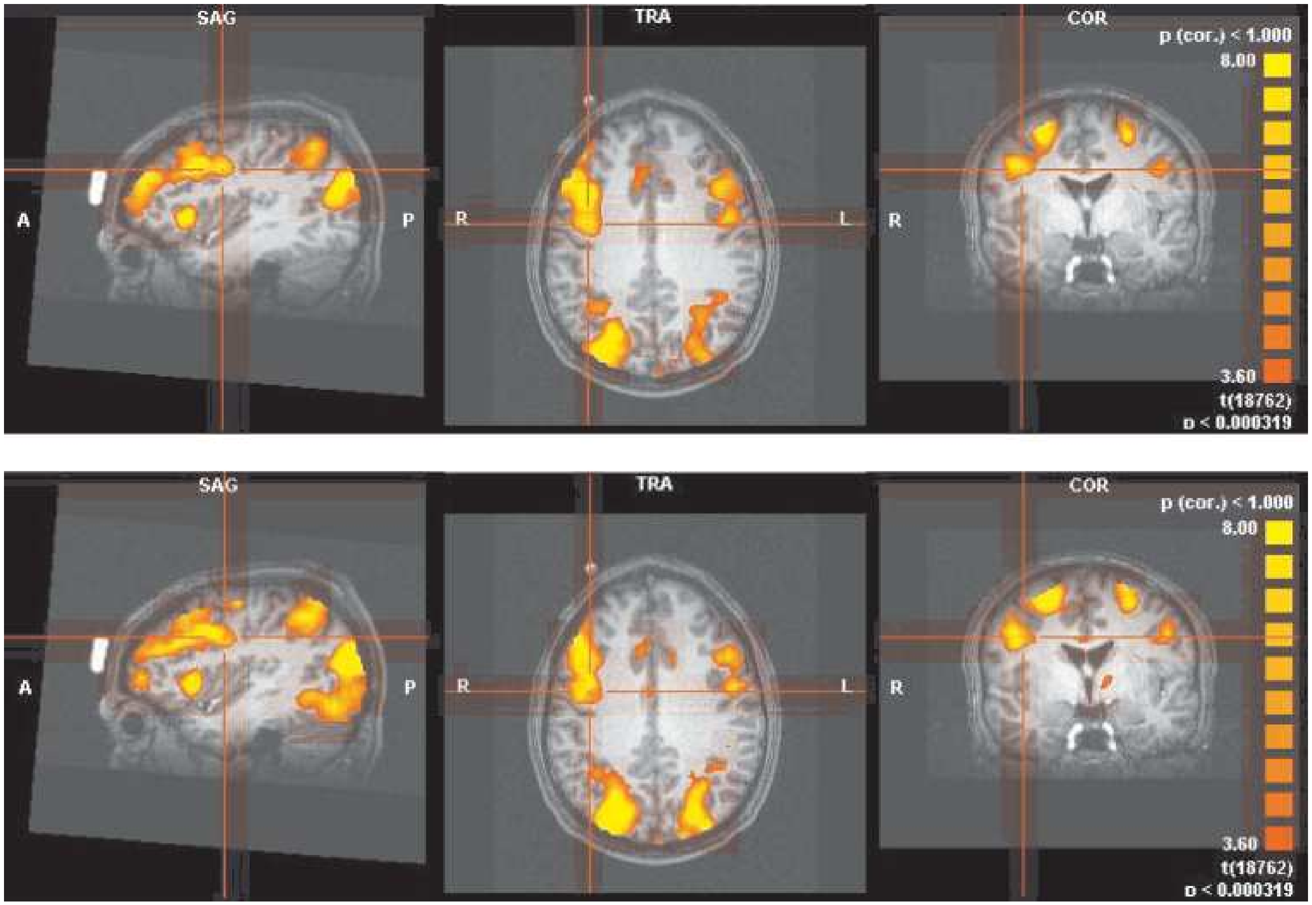


Figure 15. The red cross hairs point to activation in the dorsolateral prefrontal cortex (DLPFC) in both the spatial scanning map and cognitive tasks ($p<0.0003$).

Similarities in activation for the Spatial Scanning Tasks: 2

Cognitive task

Map task

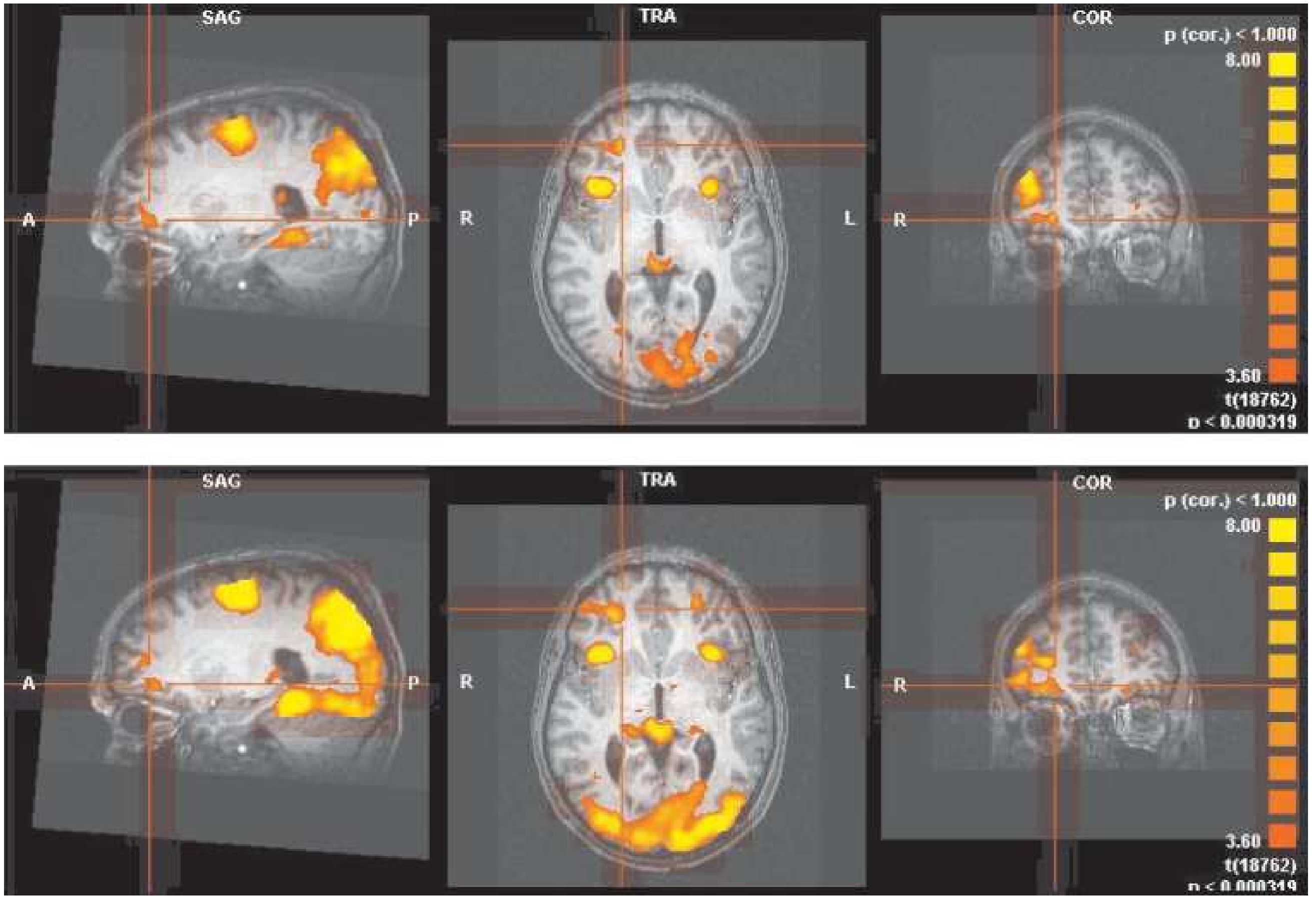


Figure 16. The red cross hairs point to activation in the orbitofrontal cortex in both the spatial scanning map and cognitive tasks (p<0.0003).

Similarities in activation for the Spatial Scanning Tasks: 3

Cognitive task

Map task

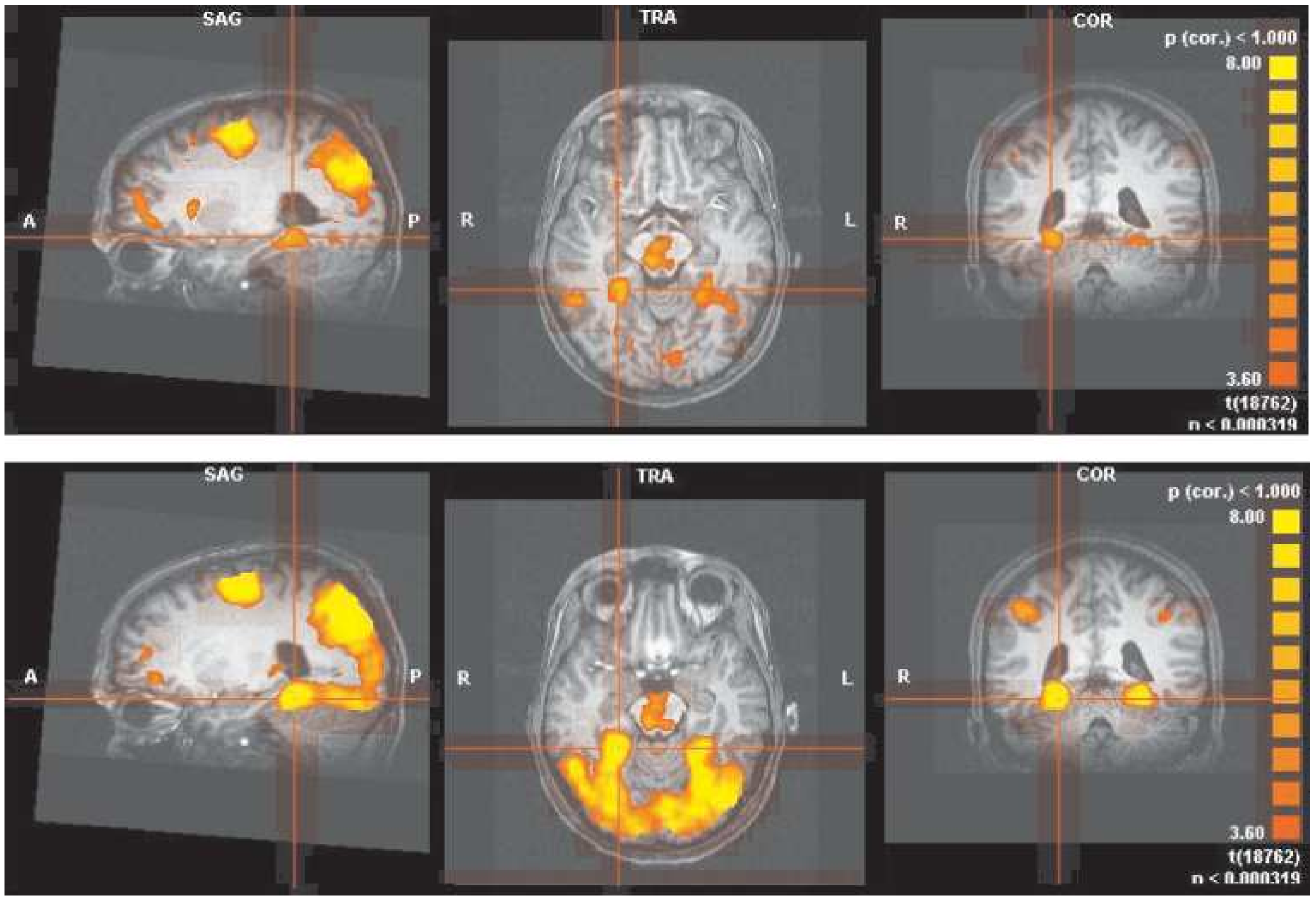


Figure 17. The red cross hairs point to activation in the parahippocampal place area (PPA) in both the spatial scanning map and cognitive tasks (p<0.0003).

Differences in activation for the Spatial Relations Tasks: 1

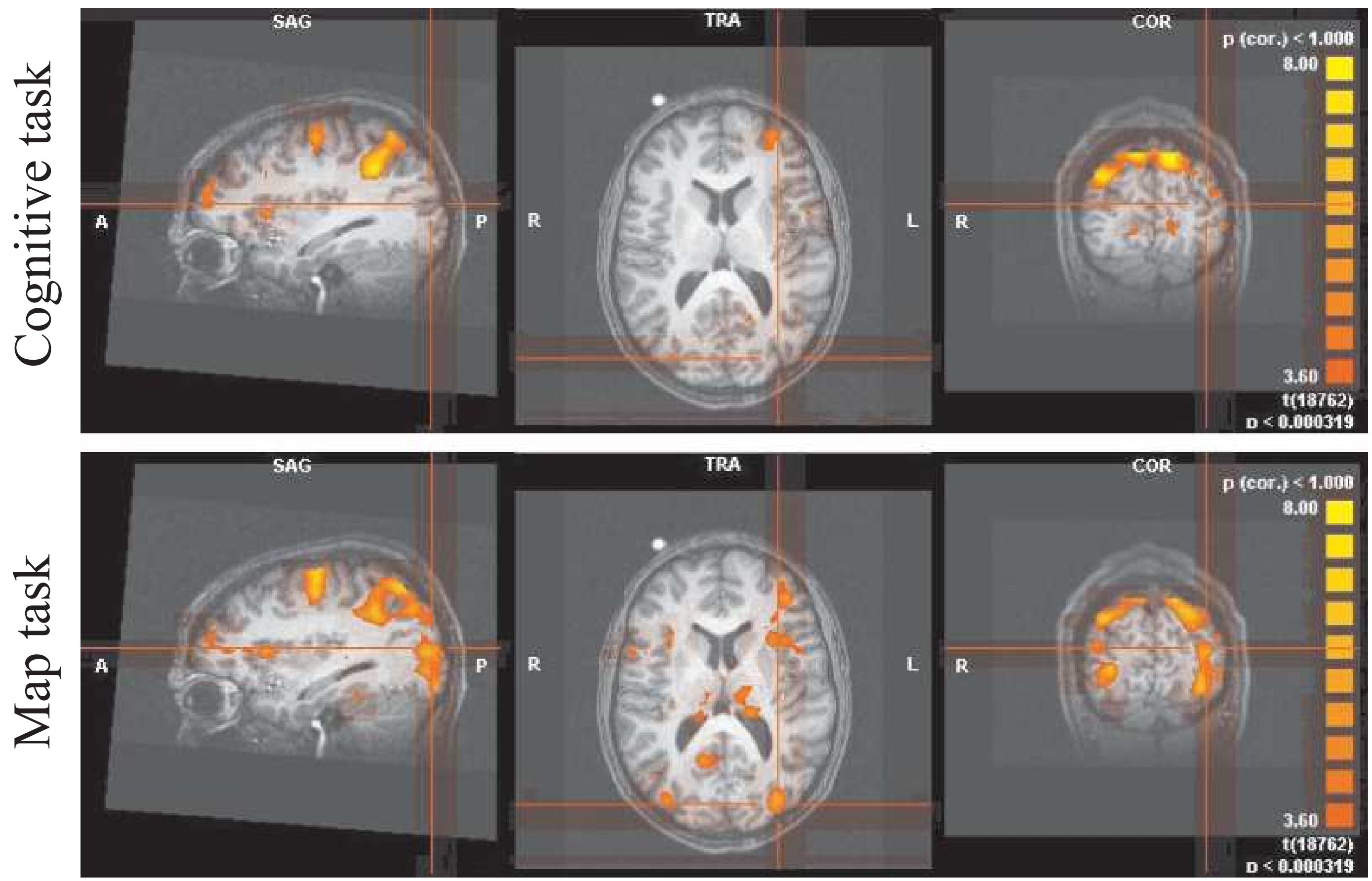


Figure 18. The red cross hairs point to activation in the medial temporal lobe (MT) in the spatial relations map task (p<0.0003), but not in the spatial relations cognitive task.

Differences in activation for the Spatial Relations Tasks: 2

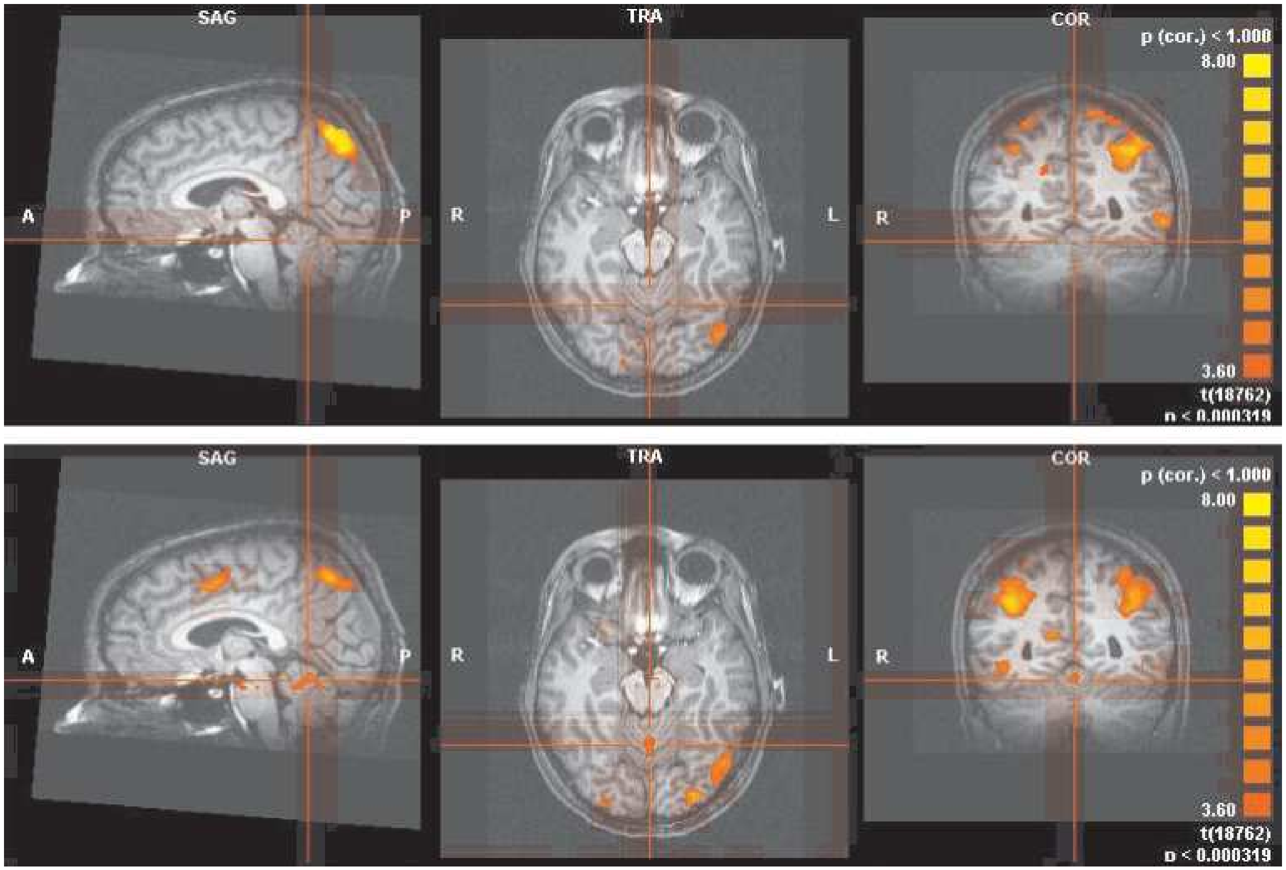


Figure 19. The red cross hairs point to activation in the cerebellum vermis in the spatial relations map task (p<0.0003), but not in the spatial relations cognitive task.

Differences in activation for the Spatial Relations Tasks: 3

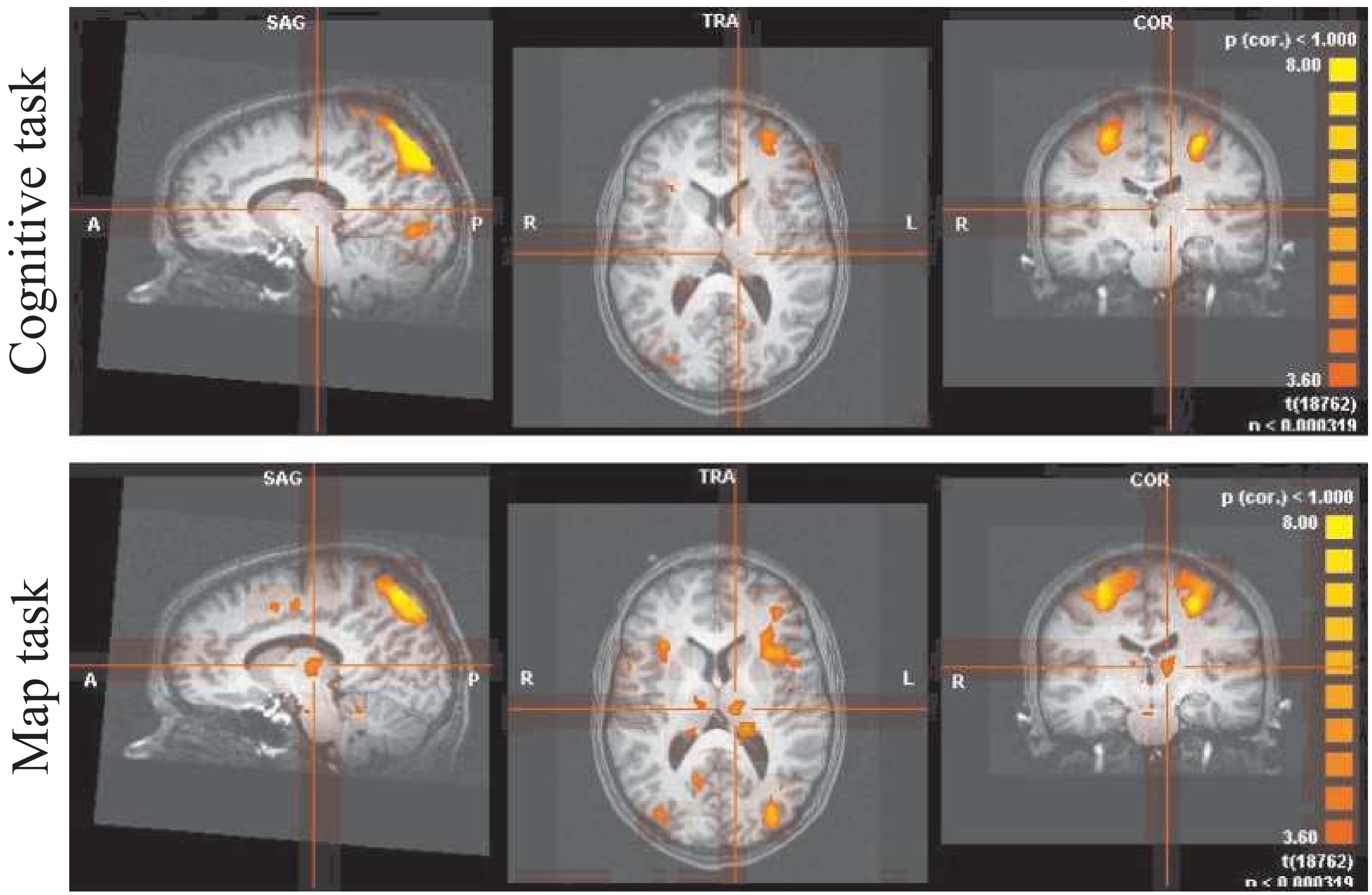


Figure 20. The red cross hairs point to bilateral activation in the dorsomedial thalamus in the spatial relations map task ($p<0.0003$), but not in the spatial relations cognitive task.

Activation differences for the Spatial Relations Tasks: 4

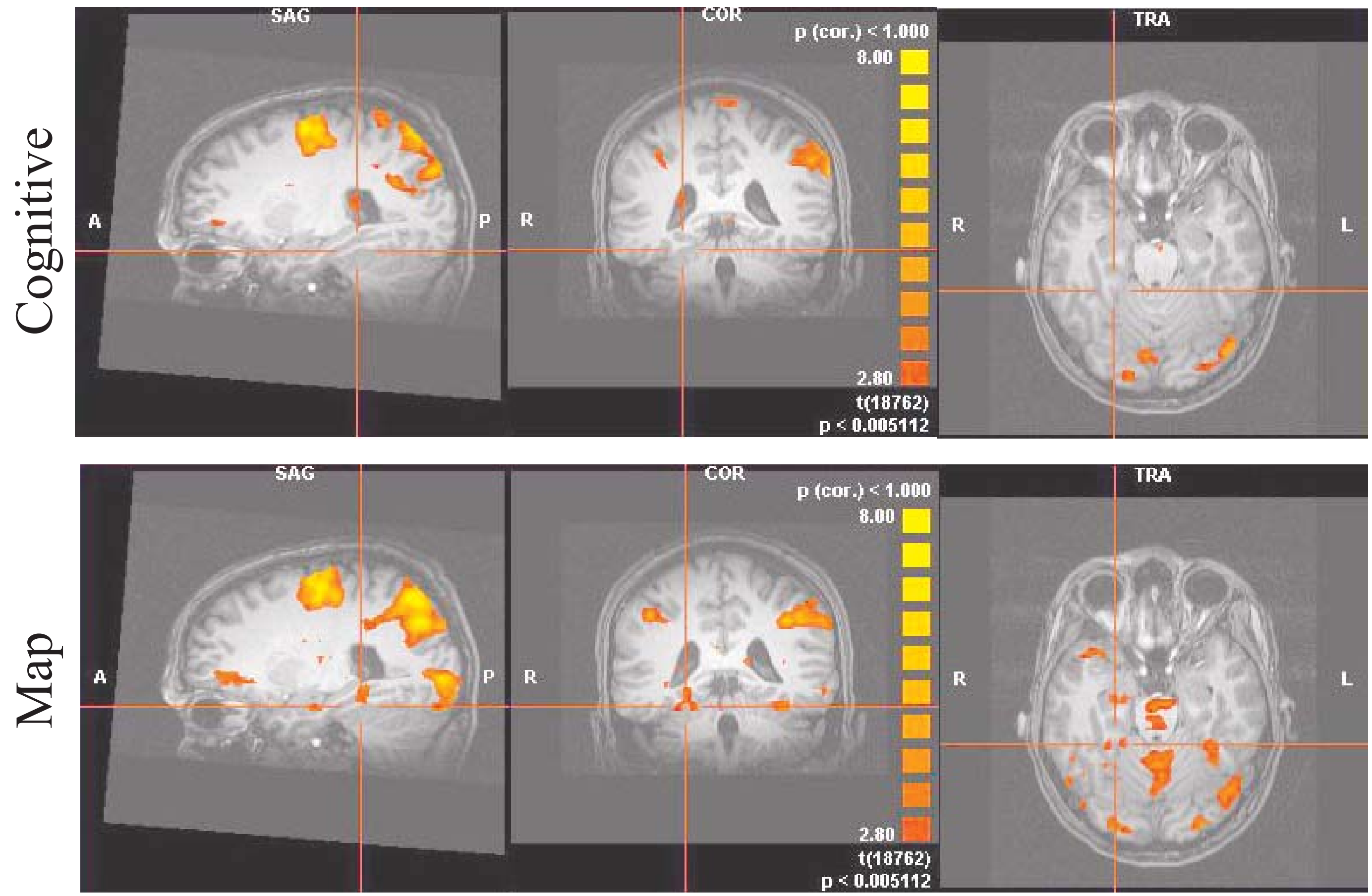


Figure 21. The red cross hairs point to activation in the parahippocampal place area (PPA) for the map task (p<0.0003), but not in the spatial relations cognitive task.

Similarities in activation for the Map Tasks

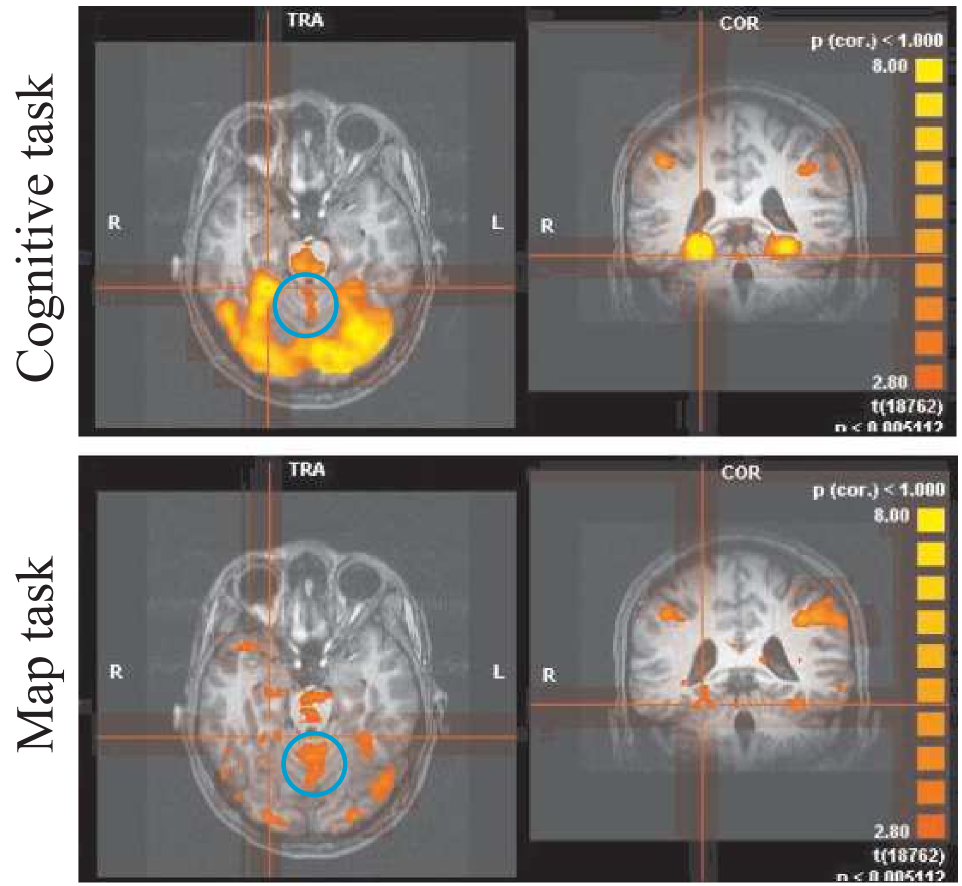


Figure 22. The red cross hairs point to activation in the PPA for both the spatial relations map taskand the spatial scanning map task (p<0.0003). The highlighted circle points to the cerebellum vermis activation found in both map tasks.

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