USING fMRI IN CARTOGRAPHIC RESEARCH

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ABSTRACT:

In this paper we summarize findings to date from a project that had subjects performing navigational map tasks on a computer and again while they were being scanned in a magnetic resonance imaging machine. By comparing activity levels in each voxel with an expected function, the images were converted to *functional* ones (fMRI), and involvement or non-involvement of the brain area in doing the task was indicated. We will raise some fundamental questions that arise in such research, including "Should cartographers be collaborating with colleagues in other disciplines to carry out work of this sort?" and "So what?" We argue that yes, we should be so involved, even if in the end we find little useful. There could be important implications for some very hard questions that overlap between psychology, physiology, and cartography/GIS such as which tasks use similar brain regions even though the tasks themselves seem to be very different or which tasks use different brain regions even though the tasks seem to be very similar.

INTRODUCTION AND BACKGROUND:

For years, cartographers and psychologists conducted research in the area of map reading and spatial abilities. But, until recently, collaborative research was rare. Arguably, such collaborative research brings together the strengths of each discipline, resulting in more meaningful, reliable, and valid results. Similar to the beginning of spatial/map abilities research, fMRI based experiments are currently not commonly conducted collaboratively. But, such collaboration would likely improve the breadth and depth of the research.

Any review of fMRI-related spatial abilities research would reveal many results that address map *related* issues. However, in many cases, even though the study questions may mirror similar ones asked by cartographers, the test instruments do not include maps. Therefore, results may be generalized to suggest they may potentially be related to similar cartographic questions; but, unless the test instruments include maps and the questions address cartographic research, the extent to which results may be generalized is unproven. One way to bring the map or cartographic questions into the body of fMRI research is for cartographers to include this technology in their research. Arguably, map-related research may be considerably more fruitful when undertaken by collaborative teams. In the case of fMRI research, such teams may involve more than the cartographic/psychological groupings that are becoming more common in cognitive map research. Because of the technology and processes involved in fMRI studies, radiology and physiology researchers are part of the research team. Each participant potentially brings to the project a unique and valuable perspective.

fMRI Research:

A brief review of fMRI-based research is presented below. All of these experiments address cartographic related questions and some may seem more cartographically meaningful than others. But, in each case, the researchers are not cartographers and, in fairness, some of the researchers make no intentional correlation with map or navigational importance.

While not yet abundant, map-related fMRI literature is available and published in several psychology and physiology journals. But, because many of these studies may not be obviously map-related, the cartographer searching for such literature must be fairly flexible in the search process. In addition, the cartographer must be educated to the types of tasks, strategies, and cognitive processes that may be involved in map reading or navigation (Lobben 2004). Studies may focus on research questions regarding: visual search, spatial attention, object rotation, and navigation. The last one is clearly map-related; but, theother topics are as well.

Visual Search and Spatial Attention are tasks that are required while using virtually any map for any purpose. Visual search refers to the ability to scan a graphic (or specifically, a map) for the object in question. For example, assume someone is traveling in a new environment to a final destination and they are using a map. They must locate their final destination on the map. At this point, only locating the destination is relevant; the person may be making no attempt to relate the map to the environment. But, in finding the location on the map, they must sort through what at the time may be graphic 'noise' (though that noise may be used during the navigation task). Such a locational task involves visual search. Moreover, the task involves spatial attention, or the ability to sort through all of the momentarily irrelevant objects on the map without getting distracted (keep in mind the task is only to locate the final destination, regardless of the objects that one may encounter while navigating to it).

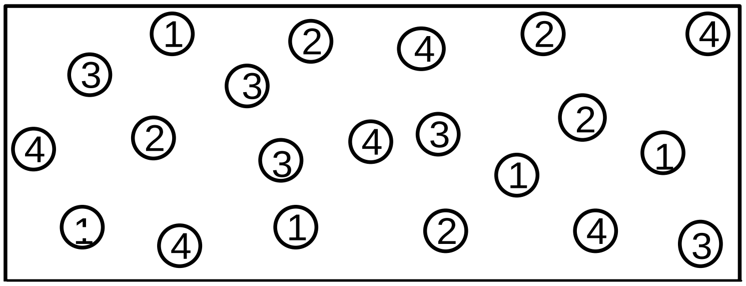


Figure 1. Spatial Attention Graphics (re-drawn from Gitelman et al. 2002)

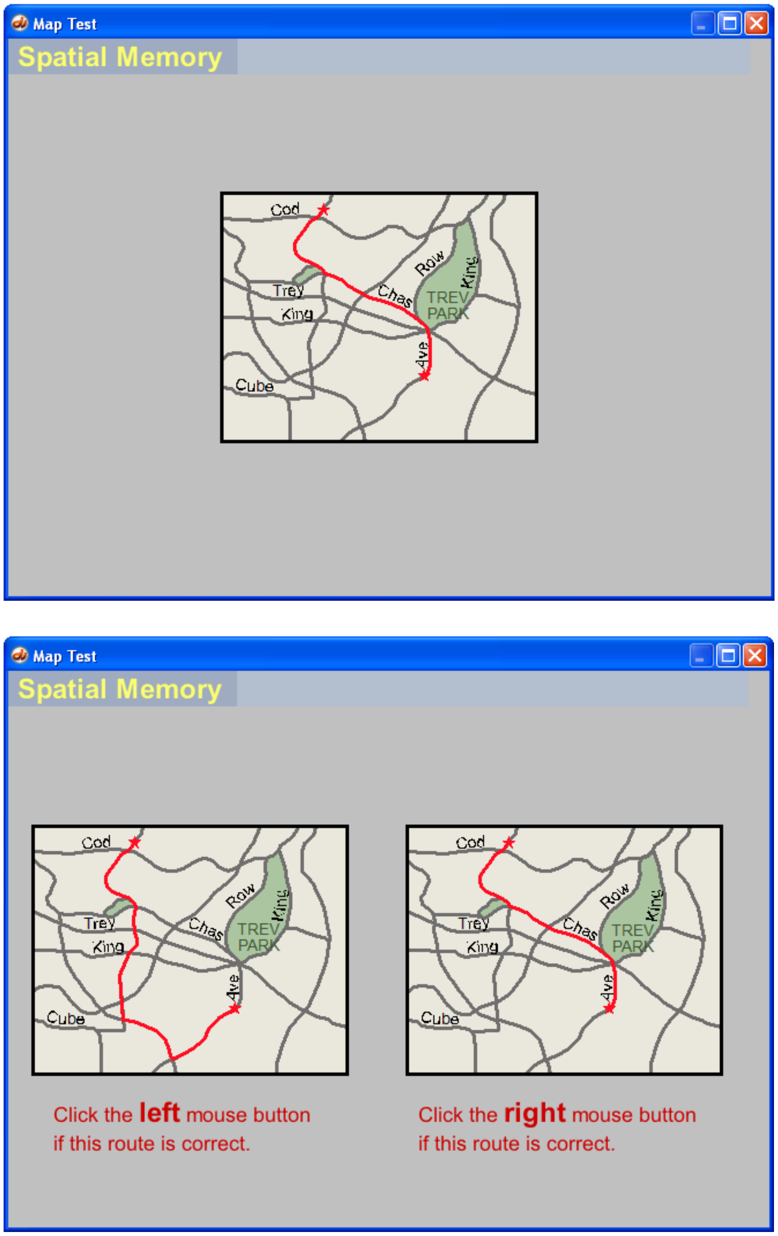
Researchers have investigated visual search and spatial attention using fMRI by asking subjects to view a graphic such as **Figure 1** (re-drawn from Gitelman et al. 2002) during scanning. Using this graphic (as well as other similar graphics), Gitelman et al. (2002) asked subjects to identify the number with a break in it. To accomplish the task subjects must sort through all of the graphic 'noise' before identifying the number with the break. Following analyses of the fMRI images, researchers identified the following areas of brain activation: superior colliculus, frontal eye fields, bilateral parietal and occipital cortices.

Gitelman et al. (1999) identified brain areas involved with spatial attention. They presented subjects with a series of graphics (again, not map related) in which they were required to meander through intentional foils to identify the pairs of objects that met set criteria. The foils served as means to distract subjects' spatial attention. They identified three primary areas of activation: the cingulate cortex, the lateral premotor cortex (frontal eye fields), and the posterior parietal cortex.

Object Rotation has been the subject of substantial attention, primarily by psychologists. Not only have psychologists investigated the relationship between object rotation and spatial ability, but they have begun to study object rotation in fMRI related research. Cartographers have also studied rotation as a map-related task (Levine, Marchon, and Hanley 1984, Lloyd and Steinke 1984, Aretz and Wickens 1992, MacEachren 1992, Lloyd and Cammack 1995). But, with few exceptions (Lawrence 2005, Olson and Lobben 2005), most of the fMRI related rotation experiments have been conducted by psychologists using non-map images. Researchers have found activation in the PPC (posterior parietal cortex) and superior parietal cortex during the rotation of alphanumeric and abstract object rotation (Podzebenko et al. 2005), in the IPS (intraparietal sulcus) separating the superior and inferior parietal lobules during rotation of 3Dimensional cubes and 2Dimensional abstract and letter figures (Jordan et al. 2001), in the PPA (parahippocampal place area) and retrosplenial cortex (Epstein et al. 2005), and in the occipital cortex, the posterior parietal lobe, middle frontal gyrus, and parieto-occipital border during rotation of 3Dimensional cube diagrams (Cohen et al. 1996). The results from such studies are important to cartographers as they use rotation tasks that may be similar to map rotation, a task that is common during navigational map reading. But is rotating a 3Dimensional cube the same as rotating a map?

Navigation has been studied using test stimuli that are more map- or navigation-related. Using simulated or virtual reality environments, researchers have asked subjects to learn or explore a variety of environments, testing both novel and known routes.

Pine et al. (2003) designed an experiment to investigate navigation and memory retrieval in adolescents and adults while performing tasks in a VR and undergoing an fMRI scan. The experiment was conducted in stages, staggered over two weeks. Subjects were first introduced to the VR environment through both a guided tour and then free exploration. Subjects were then asked to navigate to different locations. One week later, they were asked to navigate to the locations again. The following week, subjects performed the tasks again, while undergoing fMRI scanning. Following these tasks, subjects were asked to label as many locations as they could on a 2-D map representing the VR environment. Adults and adolescents performed equally well in the memory navigation exercise. However, adults were better able to construct a more complete and accurate map of the VR environment. Their results indicate that navigation tasks use the right medial temporal region of the brain. Activation was also noted in the cerebellum, frontal cortex, cingulate gyrus, caudate, and thalamus.



Click the **left** mouse button if this route is correct.

Click the **right** mouse button if this route is correct.

Figure 2. Map Memory Sample Question.

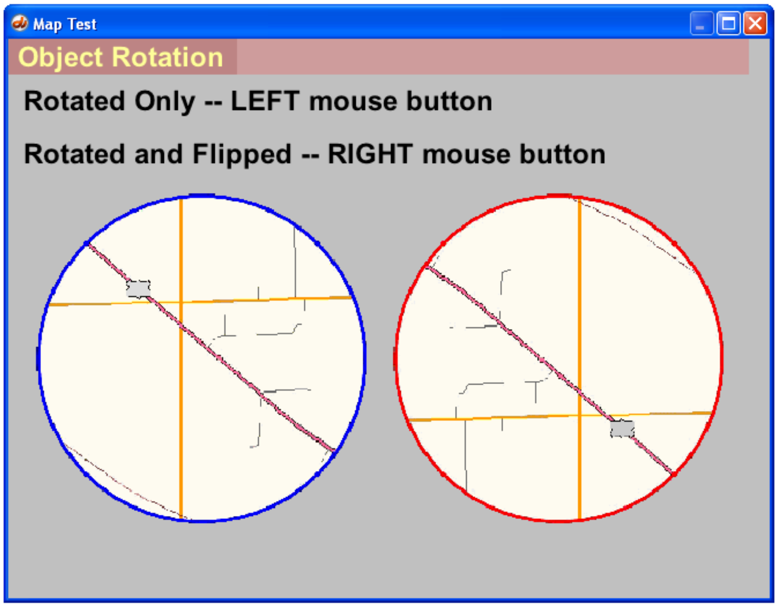
Hartley et al. (2003) constructed an experiment designed to identify the neural basis for both wayfinding (in a novel environment) and route-following (a well-known and frequently traveled route). For the experiment, they designed two VR environments. In one environment, subjects wandered through the town by free exploration. In the other, they repeatedly followed a single route. They found a correlation between performance and activation for the wayfinding task. For the posterior hippocampus and the right insula, increased activation was associated with more accuracy.

Bauman et al. (2003) pilot tested their VR environment, designed for navigational and fMRI experiments. The researchers asked subjects to take a guided tour in a VR environment for 5 minutes. The following day, they underwent an fMRI scan during which they saw a static image from the guided tour, followed by a 2 minute passive guided tour, followed by another static image. They were then asked to navigate to an area in the environment within 3 minutes. They were to use the mental map they formed the previous day during the VR environment tour. The scanning results identified several areas of activation: bilateral sensorimotor, supplementary motor, and cerebellum (these motor areas were activated due to subjects' use of hands during navigation), cingulate cortex (attention area), frontal, dorsolateral prefrontal and parietal (all three known to be involved in memory), and occipital and calcarine (visual areas).

Rosenbaum et al. (2004) investigated navigation and spatial relations ability without the use of graphic stimuli. Instead, they recruited subjects familiar with a large-scale environment (downtown Toronto). Subjects were scanned as they performed tasks such as distance estimates, landmark placement, and route problem solving. They found several regions engaged in the processing of the task: retrosplenial cortex (involved in relative directional assignments to landmarks); medial and posterior parietal (involved in processing imagined movement in ego-centric space); prefrontal cortex (involved in working memory).

OUR FOCUS:

While much of the research presented above (as well as other spatial/environmental fMRI research) is pertinent to cartography, what is generally lacking in such literature is the inclusion (and certainly the focus) of a map.



Object Rotation

Rotated Only -- LEFT mouse button

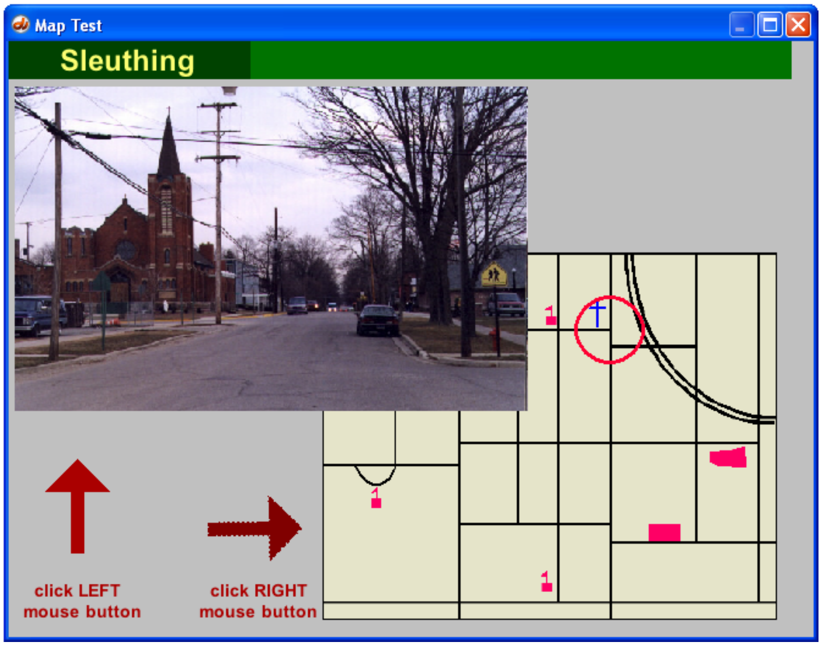
Rotated and Flipped -- RIGHT mouse button

Figure 3. Map Rotation Sample Question.

One reason for the absence of the map in rotation or memory fMRI studies may be complexity. Maps may be considered more complex graphics than an alpha-numeric symbol, for example, and such stimuli are certainly more challenging to construct. But, for cartographers, the map is what is important and we are accustomed to producing them. We designed a navigational map reading study that investigated neurological influences, or differences in performance, on *map-based* tasks.

For several years, we have investigated the tasks associated with map navigation. We have focused on one task, in particular, that we refer to as sleuthing. It is the task of identifying one's location on the map using environmental clues. We have identified this task as one that predicts navigational map reading ability (Olson and Lobben 2003). But, several additional tasks (some known, some unknown) are likely to be influential in map navigation as well. Tasks such as symbol identification, map rotation, map memory, environmental visualization, way finding, and route planning are tasks performed when a person navigates through an environment with the use of a map (Lobben 2004).

Experiment Design--pre-test:



Sleuthing

click LEFT mouse button

click RIGHT mouse button

Figure 4. Map Sleuthing Sample Question.

We designed a pre-test to investigate the relationship between sleuthing, map memory, and map rotation. Specifically, we evaluated performance in each of the three tasks before investigating brain function during task performance with fMRI; we were particularly interested in brain function in high and low task performers. The pre-test allowed us to select the subjects for the fMRI test.

The pre-test was designed and administered in Macromedia Director. Each of the three tasks was assessed individually. Subjects were introduced to the task, interface, and answering options. They were given instructions followed by practice sessions, which they were able to review as many times as necessary until they felt comfortable with the interface and task. When they were ready, they began the actual test. Eight questions were asked in each of the three test sections. During the testing phase, both accuracy and response time were recorded for every question.

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	33	211019	6394.515	14317424
Column 2	33	331297	10039.3	18747941
Column 3	33	71900	2178.788	272164.4

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.02E+09	2	5.11E+08	45.95226	1E-14	3.091188
Within Groups	1.07E+09	96	11112510			
Total	2.09E+09	98				

Figure 5. ANOVA Results

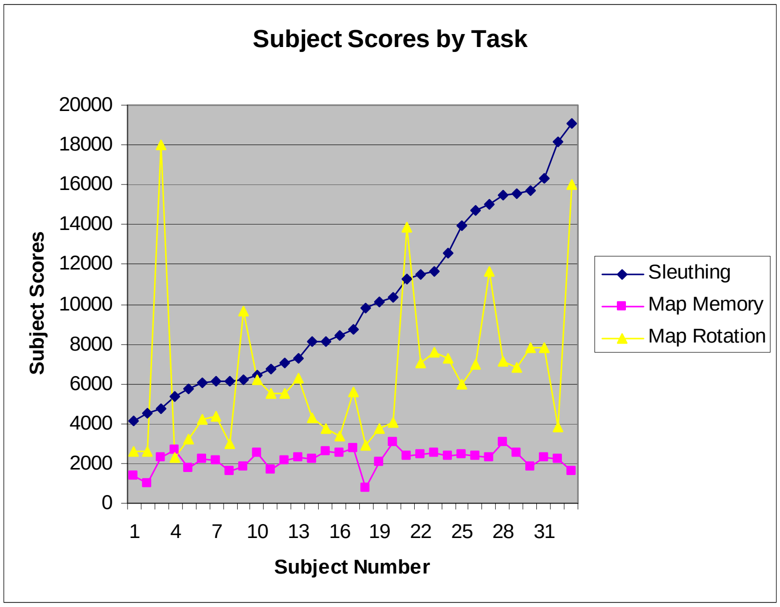


Figure 6. Subject Scores by Task

Map Memory was assessed by showing subjects a map with a highlighted route for 7 seconds, followed by a different map with a different highlighted route for another 7 seconds. After viewing the second map, two versions of the first map were shown side-by-side. Subjects had to determine which map displayed the same route highlighted in the original map. Two versions of the second map were then shown and subjects had to make the same determination. The process was repeated for eight maps.

Map Rotation was evaluated using the classic approach of showing subjects side-by side images (maps in this case) and asking them to determine whether the map on the right was rotated only or rotated and flipped (see **Figure 3**). Subjects were given as much time as they needed to answer each map rotation question.

The sleuthing task was designed to assess subjects' ability to locate themselves on a map using a photograph of an environment. Task design included creating a graphic that included a photograph of an area that is represented on an accompanying map. Subjects looked at the photograph, whose location was noted on the map with a red circle (see **Figure 4**). Subjects were asked to identify which direction they were facing on the map and were given as much time as they needed to answer the question.

Behavioral Data Analyses. Analyses of the behavioral data recorded from subjects' pre-test identified relative performance on three map-related tasks. We conducted ANOVA and correlation analyses on subject scores, which were calculated based on response time and accuracy. These analyses revealed that subjects performed the three tasks in varying degrees of accuracy and time. In fact the ANOVA results (**Figure 5**) reveal a statistically significant difference between performance across the tasks, as the null hypothesis (that all groups are the same) was rejected. Such results indicate that while subjects completed all three map-related tasks, their performance on the different tasks was not equal.

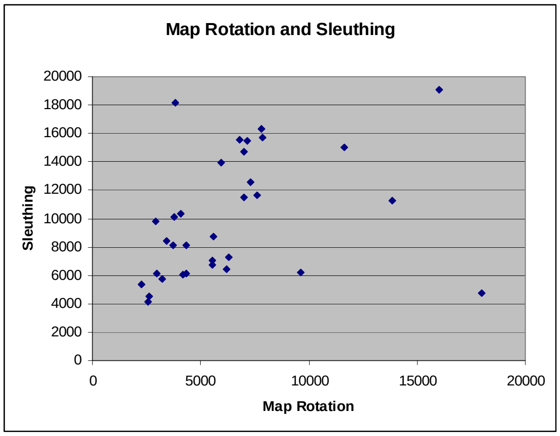


Figure 7. Correlation between Map Rotation and Sleuthing, =.35, p= 0.045206.

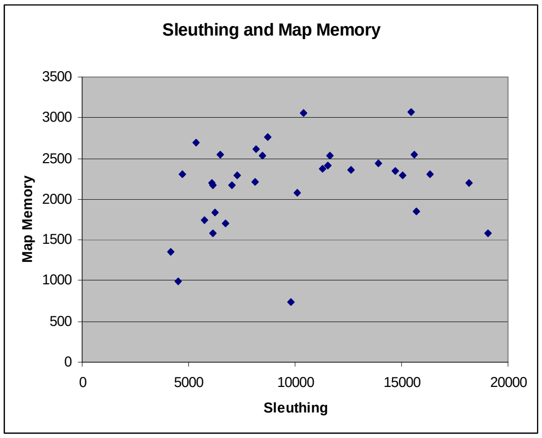


Figure 8. Correlation between Sleuthing and Map Memory = .23, p= 0.195218.

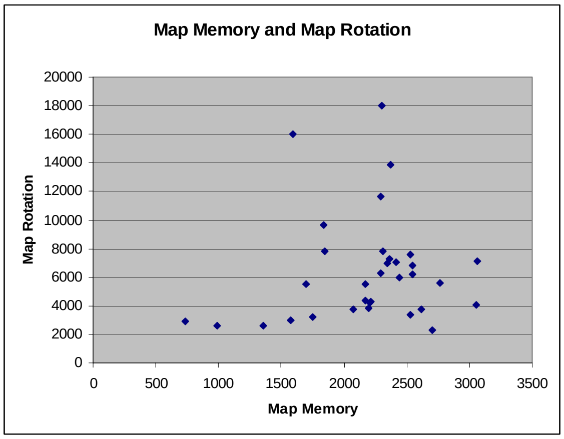


Figure 9. Correlation between Map Memory and Map Rotation = .12, p= 0.501462.

Variation in task performance can also be seen in the Subject Scores by Task graph (**Figure 6**). Upon visual inspection, some remarkable differences are observed between the tasks. Scores on Sleuthing and Map Rotation appear volatile compared to the steady scores on the Map Memory test. The graph also illustrates difficulty level of each task. On the graph, the x-axis represents subject number, whereas the y-axis represents task performance. Lower scores (faster reaction times) indicate better performance on the task; therefore, the lower the score on the y-axis, the better the performance. Along with being most consistent, Map Memory was the easiest task for subjects, while Sleuthing was the most difficult.

The relationship between individual task performance was further investigated through correlation analysis. Each task was correlated against the others. Results revealed weak relationships between all task pairs. The strongest relationship was between Map Rotation and Sleuthing, with a correlation coefficient of only .35, (**Figure 7**), followed by Sleuthing and Map Memory, correlation coefficient .23 (**Figure 8**), and Map Memory and Map Rotation, correlation coefficient .12 (**Figure 9**).

Further Investigation Warranted. We took a relatively traditional approach in the design and analysis of the pre-test phase of our experiment. Cartographers and behavioral geographers have submitted subject scores on different map-related tasks to statistical analyses and have identified the relationship between tasks or relative to an external control, such as psychometric measures. Our approach was similar. We can conclusively report that subjects performed the tasks at varying levels of effectiveness and efficiency. In addition, we can report that, in general, subjects performed the map rotation task more quickly and with greater accuracy than the sleuthing task, i.e. the sleuthing task appears to be a more difficult task.

We were also interested in identifying why these differences exist. We sought to provide some explanations for the disparities in task performance, and to this end, we chose to ask selected subjects (at the high and low ends of performance) to perform the tasks again, while undergoing an fMRI scan. The analyses of the resulting scans would, ideally, identify differences in brain function involved in completing the different map tasks, i.e. are different parts of the brain involved in completing the different tasks. To keep the time in the Imaging device reasonable, we chose to further investigate only Sleuthing and Map Rotation (the two tasks that showed the most variability in the Subject Score Graph).

Experiment Design--the fMRI test:

Figure 10. fMRI Sleuthing Task

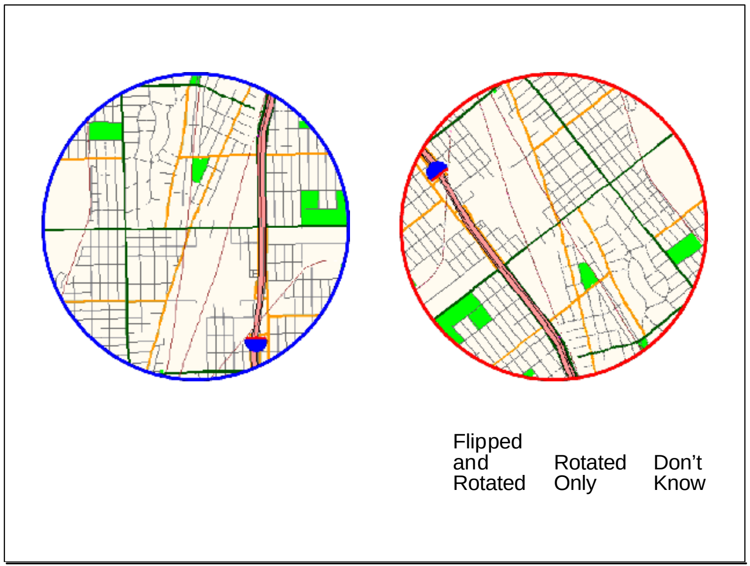


Figure 11. fMRI Map Rotation Task

Administering a map-related test during a scan differs considerably from administering a test using a computer with a standard mouse. For our experiment, the most substantial differences included the necessary change in test content (two tasks instead of three) and change in subject input method. Perhaps even more important, acquiring usable scans requires that the subject spend time on the task, alternating with rest time (method described briefly below) with a consistent amount of time allocated for each. As a result, the amount of time required to administer a test lengthens due to the necessary rest time, as well as time needed to perform anatomical scans. Therefore, our pre-test was essentially re-designed Because any body movement will register activation in the brain (in the best case) or cause head movement resulting in unusable scans (in the worst case), specialized input devices must be used in order to restrict such movement as much as feasible. In our experiment, subjects used a keypad that was molded to the shape of an adult-size hand. The keypad included a button for every finger. Test design required that subjects be able to answer three-choice questions, where answers corresponded to keypad buttons. In the design of the pre-test, we had used two choices, but subjects had unlimited time to answer. Our fMRI version of the test used a third choice (neither or don't know) because only limited time was allowed to figure out an answer and we reasoned that "neither" or "don't know" would help them to answer promptly and not continue thinking about the choice.. **Figures 10 and 11** represent the re-designed test sections. Twenty instances of each task were included in the fMRI test.

Acquiring the Images. Obtaining the brain images was accomplished by the Imaging equipment. The MRI magnet, when spinning, causes nuclei of hydrogen atoms to line up in a certain way. When radio waves are generated, which is what happens in a scan, different areas in the body send signals according to composition. A physical image (of the brain in our case) results. These are called anatomical scans and they are recorded when the subject is not carrying on any particular activity. Functional scans are generated when the subject is carrying out a mental task and the signal during this scan is the Blood Oxygenation Level Dependent (BOLD) haemodynamic response (blood flow), which occurs because the active part of the brain demands more oxygen and glucose than non-active parts.

In our test, subjects carried out an instance of a task (answering either a Map Rotation or a Sleuthing question). Then, after a set length of time, the image disappeared and there was a signal on the screen indicating that they should enter their answer. At this point, the subject entered an answer using the keypad. Subjects were instructed not to think, but rather relax, until presented with the next question.

Scans were being recorded throughout this sequence of events, and from onset of the image to the end of the 'not thinking' period resulted in 120 or 140 scans (depending on task) for a matrix of small regions in each of about 25 horizontal cross sections of the brain. For a given task (rotation or sleuthing), the values at the different times within the sequence were averaged over all the repetitions. For any one pixel within the scan, then, one could plot a graph of the average level of activity, by time. If the cell was being actively used for the task, its excitation would rise rapidly at the beginning of the task, peak, and then decline somewhat more slowly than the original rise. The activity in the voxel, then, the tiny region of the brain being sensed, should reach non-active level when the subject is not thinking if the testing sequence is timed correctly. The comparison of activity during the task and not during the task, then, is not a subtraction of the two values, but rather a look at the sequence of values for a cell to see if its pattern of excitation corresponds to a standard function that describes the ideal sequence of activity level if that pixel in the brain is involved in the activity. For our processing, we selected the gamma function (**Figure 12**), where A is amplitude, t_0 is the time delay (from onset of the stimulus), δ is the rise time (how quickly the function rises), and τ is the width of the function.

$$S(t) = A(t - t_0)^{\delta} e^{-(t-t_0)/\tau}$$

Figure 12. Gamma Function

For each task, a cross correlation coefficient (correlating actual excitation and the ideal function) is calculated for every pixel in every scan level for each subject. Those pixels that correlate highly are the ones the subject used in the task. We used a significance level of .05 to separate the active voxels (volumetric cells) from the non-active voxels. **Figure 13** illustrates a functional scan (on the right) versus an anatomical scan (on the left).

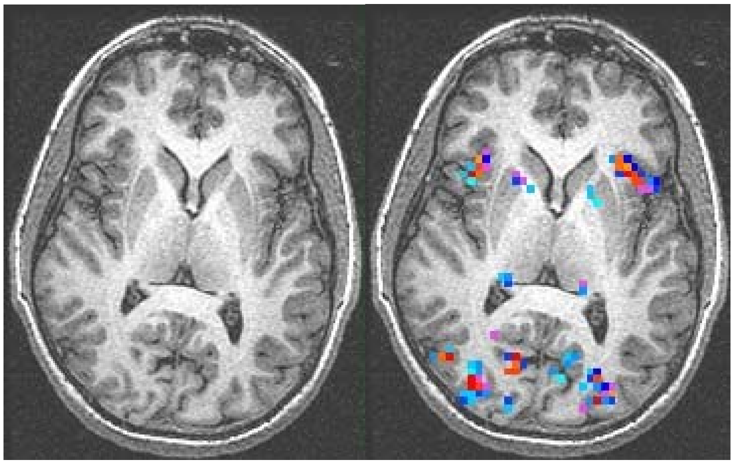


Figure 13. Anatomical and Functional Images

Image Analyses. The processed fMRI images were interpreted using AFNI (Analysis of Functional NeuroImages). This is the program that allows simultaneous display of the different views (parasagittal, coronal, and axial) as well as the turning off and on of the functional image over the anatomy. By studying the scan in each view, we are able to identify the location in the brain where the activation is observed.

Once the regions have been identified for all the clusters of functional voxels, the information is compiled into a spreadsheet that lists all brain regions along with number of voxels activated (**Figure 14**). The spreadsheet allows us to compare activation intensity per brain region.

Results for First Subject. Preliminary analysis of the functional images for the first subject are displayed in **Figure 14**. While analysis has been performed to date on only one subject, we are able to identify differences in activation during performance of the sleuthing versus the map rotation task.

Three interesting results are identified. First, overall, more voxels were activated in the sleuthing task than in map rotation. We hypothesized this result, but will see if it bears out across other subjects. Second, a difference in hemispheric activation is observed between tasks. Activation for sleuthing is fairly similar between the right and left hemispheres. However, map rotation initiated more activation in the right hemisphere. These findings are consistent with results reported in similar experiments in which right-hemispheric dominance was observed in subjects performing non-map rotation tasks (Podzebenko 2005, Harris and Miniussi 2003, Podzebenko, Egan, & Watson 2002, Harris, Egan, et al. 2000).

	Rotation				Sleuthing				S-R
	LEFT	RIGHT	Diff.	*Total*	LEFT	RIGHT	Diff.	*Total*	Diff.
	Side of brain				Side of brain				
Precentral gyrus	101	166	-65	*267*	183	148	35	*331*	64
Superior frontal gyrus	59	53	6	*112*	61	72	-11	*133*	21
Middle frontal gyrus	52	29	23	*81*	124	41	83	*165*	84
Inferior frontal gyrus	3	7	-4	*10*	20	19	1	*39*	29
Paracentral lobule	11	2	9	*13*	28	27	1	*55*	42
Cingulate gyrus	5		5	*5*					
Postcentral gyrus	79	49	30	*128*	169	58	111	*227*	99
Supramarginal gyrus	59	69	-10	*128*	73	47	26	*120*	-8
Angular gyrus	19	32	-13	*51*	81	86	-5	*167*	116
Superior parietal lobule	130	140	-10	*270*	124	184	-60	*308*	38
Precuneus	6	58	-52	*64*	31	57	-26	*88*	24
Retrosplenial area	5	2	3	*7*	2	19	-17	*21*	14
Superior temporal gyrus	4	1	3	*5*	0	2	-2	*2*	-3
Middle temporal gyrus	36	11	25	*47*	5	39	-34	*44*	-3
Inferior temporal gyrus	0	1	-1	*1*	1	1	0	*2*	1
Fusiform gyrus	97	46	51	*143*	75	30	45	*105*	-38
Lateral occipital gyri	166	300	-134	*466*	165	222	-57	*387*	-79
Cuneus	48	43	5	*91*	56	68	-12	*124*	33
Lingual gyrus	69	113	-44	*182*	45	102	-57	*147*	-35
Insula	0	19	-19	*19*	6	10	-4	*16*	-3
Splenium of corpus callosums					3	3	0	*6*	6
Cerebellar hemispheres	68	74	-6	*142*	101	89	12	*190*	48
Cerebellar vermis					4	5	-1	*9*	9
Mesencephalon	1		1	*1*	0	6	-6	*6*	5
Caudate nucleus	0	4	-4	*4*	1	0	1	*1*	-3
Thalamus	45	40	5	*85*	42	34	8	*76*	-9
Posterior limb-Internal capsule	0	5	-5	*5*	0	2	-2	*2*	-3
Totals	1063	1264	-201	*2327*	1400	1371	29	*2771*	444

Figure 14. Voxel Activation Spreadsheet

Third, we found differences in areas of activation for the two tasks. In the map rotation task, we observed more activation in the lateral occipital gyri. This finding is also consistent with previous reports by researchers who used fMRI to investigate rotation of non-map objects (Podzebenko et al. 2005 and Cohen et al. 1996). In the sleuthing task, activation was greater in the middle frontal gyrus, postcentral gyrus, and the angular gyrus than it had been in the rotation task.

Clearly some overlap between the two tasks is evident in the activation areas, namely the lateral occipital gyri and superior parietal lobule. The similarities may be due the fact that the sleuthing task required the subject to identify what direction they were facing in the map. Such a task likely requires some mental rotation and as a result, some areas involved in rotation may activate during our sleuthing task. Recall, however, that performance differences were evident in the analysis of the behavioral (pre-test) data, indicating that the tasks are different (at least statistically).

A more thorough analysis of existing as well as analyses of the other 11 subjects' activation maps may reveal more answers (either continue to show similar activation or identify different areas). We believe that this area of study, in the long run, has potential for helping us understand differences in individual performance as well as differences between the processing of different map tasks.

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