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FINAL REPORT

Project Title: *Computational and fMRI Studies of Visualization*
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a. Scientific and Technical Objectives

The main goal of this research was to determine the role played by visual imagery and spatial thinking in high level cognition, such as in problem-solving and reasoning. In conjunction with the experimental work, the project developed a computational modeling system (4CAPS) as well as the development of 4CAPS models for particular tasks. The cognitive level of 4CAPS accounts for human errors and performance times in various tasks, whereas the cortical modeling accounts for the time course and amplitude of the brain activation in a number of cortical areas (focusing on association cortex).

The overall scientific objectives were to characterize the brain activation and cognitive processes underlying mental imagery and visual thinking, particularly as they apply to the use of vehicle navigation systems. The research explored display technologies and task variables that affect human performance and brain activity.

b. Approach

The approach uses a cognitive neuroarchitecture to interpret and predict the brain activation in a network of cortical areas that underpin the performance of a visual thinking task. The experiments systematically manipulate various types of cognitive demand that are hypothesized to draw on particular subnetworks of the large-scale cortical network underlying the task. For example, one of the studies investigated the impact of the orientation of the map display (Heading at the top of the display versus North at the top) in various types of navigation tasks, where the key is to find the best match between the display type and a particular type of task. When the match is suboptimal, the cortical and performance costs can be calculated.

c. Accomplishments

Cognitive modeling. The main accomplishment of this project was the development of a new neuroarchitecture, 4CAPS, that accounts for both the brain activity and the behavioral performance of people performing various cognitive tasks, particularly tasks involving spatial thinking or visual imagery, and the concurrent execution of two complex tasks (multitasking).

4CAPS is a distributed computational system whose component centers correspond to particular cortical areas that activate (as measured with fMRI) when the task is being performed. Each center is modeled as a hybrid activation-based production system. The centers collaborate by contributing their own specializations to the performance of a complex task. Each center is characterized by a "computing style" (such as geometric, propositional, temporal) which it can perform with high efficiency. The centers communicate through a shared working memory (in the production system sense) where representational elements can be recognized and operated on by various centers. The amount of processing activity in each center is generally proportional to the amount of fMRI-measured activity in the corresponding brain area.

A new area of 4CAPS modeling examines the relative autonomy versus collaboration among the cortical centers performing a cognitive task. (This can be thought of as an exploration of cognitive modularity within a computational model of the cortical system). The autonomy issue arises in the context of automaticity, where automaticity is neurally defined as the absence of executive control (mainly prefrontal). In this view, automaticity consists of autonomy from the frontal executive system. The initial modeling explorations have examined the ability to perform Tower of London problems of intermediate difficulty based on a parietally-controlled perceptual strategy, and independently of frontal executive input. The initial results from this modeling make the interesting prediction that functional connectivity (synchronization of activation) between the perceptual/parietal areas and the frontal/executive should be lower when the person is operating in this autonomous/perceptual/automatic mode.

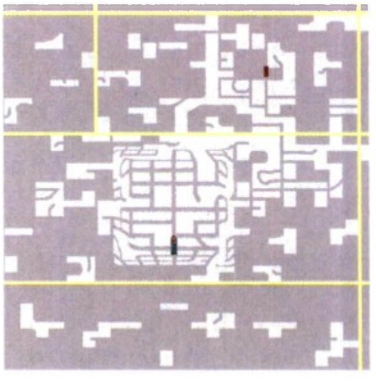
The value of the 4CAPS system is its use as a theoretical framework for understanding cognitive and brain function in a large number of contexts. In many military applications, an operator using a computer interface is faced with a demanding cognitive task, and one of the limiting factors are typically the constraints on the operator's own brain function. Understanding how such constraints may apply can be useful in optimizing the computer interface, re-structuring the task, and in selecting personnel who are cognitively suited to the task. Moreover, 4CAPS modeling may be useful in predicting the performance in new tasks. Like most scientific theories, 4CAPS provides a set of analytical tools for understanding and modifying a phenomenon of nature.

The published 4CAPS article (Just & Varma, 2007) provides extensive documentation and explanation of the tenets of the theory. The 4CAPS website provides tools that researchers can use.

Although 4CAPS was developed with the goal of explaining the types of thinking that occurs in military contexts, it has proven to be useful in non-ONR research on autism. The brain imaging findings indicated an underconnectivity among cortical centers in autism. 4CAPS made it possible to develop a computational model of an executive task (Tower of London problem-solving) in which the underconnectivity is modeled as a constriction of the communication bandwidth between frontal and posterior brain areas. This 4CAPS autism model accounts for the individual differences in underconnectivity in participants with high-functioning autism, relating the functional communication constraints (undersynchronization among cortical centers) to the properties of the white matter tracts that carry the communication. The theory provided a framework to develop one of the leading contemporary accounts of autism.

Experimental studies. In addition to the 4CAPS development, the project performed a number of fMRI studies of spatial thinking, within the theoretical framework provided by the neurocognitive architecture. The empirical studies of the use of navigation systems revealed how some of the interface properties affect human performance and brain function. The project developed new paradigms to study how people use in-car navigation systems. The effects of several interface properties were studied in several interesting conditions.

One of the typical studies examined a new dynamic car navigation task in which a pre-planned route had to be modified when an obstruction was encountered during the trip. The main new display feature examined by this research is a dynamic zoom window (an inset) that magnifies the portion of the map containing the vehicle's current position, shown in Figure 1. Both the main display and the zoomed inset dynamically scroll along as the vehicle moves. Participants first plan a global path on a coarser map from a start point to a goal point. They then navigate the vehicle with the benefit of a zoom inset that displays more detail. The inset shows barriers and shortcuts that must be taken into consideration in constructing and executing a more detailed version of the navigation plan.



In one variant of the display, the zoomed window is overlaid over its own position on the main map, which resembles having a square magnifying glass over the vehicle's current position. The advantage of the overlaid window is the overlay removes any uncertainty about the relation of the position of the two maps. The disadvantage of the overlay is that there has to be some distortion in the region where the overlay and the main map meet, where the detail has to be presented at an intermediate level between the two scales.

In the second variant of the display, the zoomed window is presented beside the main display. The advantage of side by side placement of the two map scales is that there is no distortion involved. The disadvantage is that the user occasionally has to look back and forth between the two maps and to relate the position of the inset to the main map. In the task we are studying, participants spend most of their time on the zoomed inset on the side, occasionally looking at the main map to make sure that they are consistent with the global navigational plan.

In addition to the display variable, task conditions varied as to whether or not the participant was required to update their planned route. On half of the trials, obstructions to the shortest possible route were presented, but these were revealed only in the inset display, and were thus not available to the participant during the initial route planning period. In the non-updating condition, no unplanned deviations to the shortest possible route were required.

The fMRI data indicated that the condition in which the inset display was presented to the side of the main map demanded greater visual processing than condition in which it was overlaid. Greater right occipital activation was found for the "inset at side" condition than for the "inset overlaid" condition. The implication is that the overlaid inset reduces the cognitive workload.

As expected, the requirement to update a planned route had an effect on performance of the task. Participants took longer to make turn decisions and made slightly more errors in the update condition relative to the non-update condition. The fMRI data dramatically showed the increase in cognitive workload resulting from the requirement to update, as indicated by increased activation for this condition relative to the no updating condition in bilateral parietal and occipital areas and right dorsolateral prefrontal cortex.

An interaction in the fMRI data between the display factor and the updating factor indicated that the increased cognitive workload in visuospatial areas and right prefrontal cortex resulting from the requirement to update one's route was moderated by the type of display. When updating of the planned route was not required, there were no differences in activation in these areas between the two types of displays. When updating was required, however, greater activation was found in these areas for the display in which the inset appeared at the side of the main map relative to the condition in which the inset was overlaid on the main map. This finding indicates that the advantage of the overlaid zoom window has an impact only if the route has to be dynamically modified.

The fMRI results indicate how a principle of cognitive design manifests itself in terms of brain activity. There often isn't a universally superior cognitive tool (a strategy or display type), but an interaction between the tool and the task. The research has determined some of the tool-task mappings and the specific brain costs of an inferior mapping. The articulation of the new knowledge is guided by the 4CAPS neuroarchitecture.

Individual differences. In most of the fMRI studies, we have examined the relationship between individual differences in spatial ability as measured by the Vandenberg test, with activation in visuo-spatial areas and with functional connectivity (a measure of the synchronization of activation among nodes of the visuo-spatial network). In almost every study, participants with higher spatial ability showed lower activation in frontal and parietal areas; participants with higher spatial ability had a higher synchronization of activation between frontal and parietal areas. The individual differences in cognitive performance are manifested as efficiency differences in brain activity. This approach allows individual differences in cognitive performance to be expressed in terms of the attributes of the individual's neuroarchitecture. The attributes identified so far include 1. efficient use of neural resources efficiency (how much activation is required to perform a cognitive computation); 2. degree of synchronization (coordination) between cortical centers; and 3. adaptation of cortical networks in the face of changing demands.

Publications:

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Honors

Keynote speaker at the *National Academy of Sciences Annual Meeting.* Systems underconnectivity in the autistic brain: Brain function, anatomy, and cognition. April 28, 2008, Washington, D.C.

Testimony on Multitasking with Driving given before the Pennsylvania House of Representatives Transportation Committee Hearing: Teen Driving and Other Distracted Driver Issues, March 5, 2008, Pittsburgh, Pennsylvania.

Presentations

Why just listening on a cell phone degrades driving performance: Brain limitations on multitasking while driving. Keynote address given at the *International Symposium on Distracted Driving*, National Safety Council Annual Meeting, October 14, 2008, Arlington, Virginia.

Identifying thoughts with brain imaging: towards the ultimate interface. Keynote address given at the *International Society for Wearable Computers (ISWC) Conference*, September 29, 2008, Pittsburgh, Pennsylvania.

The 4CAPS Neuro-Architecture of Complex Cognition: A theory driven by fMRI findings. Keynote address presented at the *8th International Conference on Cognitive Modeling*, July 27, 2007, Ann Arbor, Michigan.

Brain activity and workload during multitasking and driving. Presentation at the *ARL/HRED Professional Development Seminar and Lecture Series*, October 24, 2006, ARL Army Research Laboratory, Aberdeen Proving Ground, Maryland.

What brain imaging can tell us about embodiment. Presentation at the *Garachico Workshop - Symbols, Embodiment and Meaning: A Debate*, December 16-18, 2005, Tenerife, Spain.

Neural Connections. Keynote Presentation at the *43rd Annual Briefing of New Horizons in Science* sponsored by the Council for the Advancement of Science Writing (CASW), October 24, 2005, Pittsburgh, Pennsylvania.

Comprehending two language communications concurrently: Multi-threading in the brain. Presentation at the *Conference on Brain, Language and Cognition*, University of Minnesota, October 13, 2005, Minneapolis, Minnesota.

The neuroarchitecture of cognition. Colloquium presented at the University of Santa Barbara, Department of Psychology, May 23-26, 2005, Santa Barbara, California.

Dynamic adaptations in brain activity. Presentation at the *Symposium on Visual Learning and Brain Plasticity*, University of Minnesota, April 7-9, 2005, Minneapolis, Minnesota.

Neuroimaging: A transformative innovation in education. Presentation to the Grable Foundation Board of Trustees, Brain Imaging Research Center, March 23, 2005, Pittsburgh, Pennsylvania.

Posters

Examining the hidden factors that underpin semantic representation: What functional brain imaging reveals about the neuroarchitecture of object knowledge. Poster presented at the *Cognitive Science Society Annual Meeting*, July 2008, Washington, D.C.

Language dual-tasking: listening to two people makes your brain work twice as hard? Poster presented at the *14th Annual Human Brain Mapping Conference*, June 2008, Melbourne, Australia

Brain activation in two types of complex multitasking. Poster presented at the *12th Annual Human Brain Mapping Conference*, June 2006, Florence, Italy.