Identifying the Modules of the Mind with fMRI: Imaging the Biological Stages in Visual and Language Processing

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In the last three years there have been major advances in brain imaging that provide the ability to look into the brain to identify the biological processes underlying cognition. Functional Magnetic Resonance Imaging (fMRI) allows non-invasive mapping of cortical function with millimeter resolution allowing comparison of cortical activation across many conditions within subject. Experimental results relating to: mapping visual spatial topology, selective attention, attention switching, color & motion perception, motor control, working memory and language processing will be described. Availability and limitations of the methodology will be discussed. Temporal resolution of fMRI is in the seconds range. By combining fMRI with High Density Evoked Response Potential (HD-ERP) techniques we can solve for millisecond temporal activity of fMRI identified generators. Millimeter and millisecond maps detail the biological network interactions. The implications of such maps to the understanding of network cognitive processing will be commented upon.

The network topology of human cognitive processing can be mapped with fMRI brain imaging technique. There are now many reports of fMRI mapping of various regions of cortex (Shulman et. al. 1993). To move beyond imaging experiments which simply activate various areas, a systematic sequence of mapping experiments is required, with careful concern about statistics and artifact rejection. Imaging with fMRI has characteristics that facilitate tracking activation across multiple levels of cognitive processing within a single subject (Schneider, Casey & Noll 1994) including acquisition with near millimeter spatial resolution and the ability to contrast a series of conditions within subject.

We utilize a cortical mapping methodology. This involves 3 steps: 1) determine the number and location of activation areas; 2) determine the topology and replication of processing stages (multiple regions performing the same operation with different receptive fields); 3) determine the exogenous/endogenous specialization of each stage. We illustrate this methodology with mapping of the first 7 stages of the visual system and initial maps of language processing.

In the visual studies, subjects viewed two 10x10 degree apertures in the lower left and lower right visual fields to determine if both stimuli were identical. There were five visual stimulus conditions in the lower visual field including: thick high luminance contrast stripes (2 cycles/degree), thin high contrast stripes (9 cycles/degree), color contrast (isoluminant red/green) thick stripes, fast movement of dots (20 degrees/second) slow movement of dots (2 degrees/second). In addition there was an upper field luminance contrast stripes condition requiring orientation comparison of the upper left and right aperture stimuli. To improve signal sensitivity and reduce artifacts we utilized spiral scans (Noll, in press) on 1.5 T clinical scanners.

Step 1 of cortical mapping identified 7 discrete areas of activation on each side. Each area was statistically defined and separated by a strip of white matter between the fissures, often only a few millimeters thick. Both hemispheres produced the same pattern. The particles were defined as those that statistically had a $p<0.01$ and a particle size > 10 mm^2 utilizing a split half t-test (Schneider, Casey & Noll 1994).

Step two of cortical mapping determined the topology of processing for each area by mapping the activation from input in the upper and lower visual field. We calculated the ratio of activation for each particle as the percent change of the upper visual field activation divided by the lower visual activation. The first two stages had a quadrant representation. Later stages had hemifield representations, and the last stage had a full field receptive field.

Step three of the cortical mapping methodology involves determining the exogenous and endogenous specialization of each of the stages. Activation was greater in the fusiform-lingual area for thin and color bars comparte to fast and slow motion of dots. The opposite pattern occurs for a more superior medial temporal activation with low activation for thin and color stimuli and greater for fast and slow motion.

To identify endogenous influences of each stage, we measured attentional modulation and attentional switching in new behavioral paradigms. The attentional modulation experiments included a comparison of attending to the left and right hemifields. We found evidence for attentional modulation in all regions except V1 (calcarine fissure) suggesting that attention starts at the second cortical level of the visual system. To identify possible locations of attentional control we utilized an attention switching paradigm requiring switching attention every 0.7 seconds. We found a laterallized area in superior right parietal cortex that is active in attentional switching but far less in maintained attentional processing.

Based on these results there are at least seven stages in early visual processing that can be segmented by topology and functions. These results illustrate how a detailed cortical mapping methodology of a cognitive processing system can be carried out with fMRI to identify multiple stages of processing and their specialization. We are applying similar methods to the study of language processing identifying differential activation in the temporal and frontal cortex for rhyme judgements, subject verb agreement and semantic categorization.

The imaging results typically identify a modest number (e.g., 5–15) of interrelated areas the carry out cognitive functions. The networks provide a basis for interpreting and modeling of cognitive processes.

References

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