The Image of Complexity

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Functional magnetic resonance imaging (fMRI) has had a major impact on cognitive science but most of the research has looked at rather simple tasks. However, a number of methodological considerations make fMRI use particularly appropriate for certain complex tasks:

1. The dependent measure, the BOLD (blood oxygen level dependent) response, principally reflects a compensatory hemodynamic response to metabolic activity that is lagged in time from the actual event and is distributed over time. A typical response may reach a peak 4-5 seconds after the actual activity and be distributed over 10 seconds or more. This results in a smearing of the activity structure and a loss of temporal resolution. For a brief cognitive task there seems little hope of recovering its temporal structure and one is left to simply compare magnitudes of responses in different conditions. However, it is possible to discriminate some of the temporal structure of events that take place over many seconds.
2. Complex tasks also tend to engage different brain regions for long periods of time and differences among conditions can often be more than a second rather than effects of 100 msec or less seen in simple tasks. This produces much larger hemodynamic responses and better signal-to-noise ratios.
3. Because reliable fMRI data typically require aggregating many individual trials, there is the danger that different strategies on different trials will blur the results. However, for some complex tasks participants can be instructed on a strategy for performing the task and the time scale of the task makes it relatively easy for them to comply.

These considerations imply that fMRI data are particularly appropriate for understanding long, complex tasks with large effects where participants can be instructed to do the tasks in a consistent way. These kinds of routine cognitive tasks have been the major focus of our laboratory where we have studied problems like Tower of Hanoi, algebra equation solving, and air traffic control.

In studying these tasks in a scanner, four central regions keep showing up: a prefrontal region, a parietal region, and anterior cingulate region, and the head of the caudate. (Each region is an area a little more than 1 cm^3 and the same anatomical definition is used in all experiments.) These regions show up independent of the choice of input or output modality. These regions tend to correlate with task structure in many experiments and so correlate with one another. However, there are systematic differences in the factors that these regions respond to. Moreover, the exact BOLD responses in these regions can be predicted from the activity of different modules in the ACT-R theory. In particular, the prefrontal region reflects retrieval activity in the declarative module of ACT-R, the parietal region reflects representational activity in the imaginal module, the anterior cingulate reflects control activity in the goal module, and the caudate reflects activity in the procedural module.

We have now performed a number of experiments looking at the response of these regions and other regions in complex tasks that take minutes to perform. This has required development of new analysis techniques for dealing with the wide variability in the time that participants take to perform these tasks and relating these data to model predictions. Once we have estimated time parameters by fitting the behavioral data we are able to make parameter-free predictions for the activity of these regions over the time course of the task. Moreover, this methodology is not confined to the ACT-R theory and can be used to provide strong converging data for any information-processing theory.

The outcome of such predictions derived from the ACT-R theory have sometimes been supportive of the existing theory, but there have also been surprises that have guided the development of the ACT-R theory and our understanding of the function of these brain regions. The analysis methodology has also uncovered other brain regions that behave regularly in such tasks and we are beginning to understand how their activity can be used to guide the theory.

Newell noted that human action could be analyzed on different time scales. Up until now, imaging research has mainly provided information about activity at Newell's Cognitive Time Band that spans periods from roughly 100 ms to 10 s. We are now able to penetrate into at least the lower end of his Rational Time Band that spans periods from minutes to hours.