What is the relationship between cognitive experiments and cognitive processes?

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ABSTRACT
Human neuroimaging such as PET and fMRI are used to study cognitive function in human subjects. The Cognitive Paradigm Ontology builds on the experience of the BrainMap database in describing and storing cognitive neuroimaging experiments, to present a basic ontology of experimental paradigms, conditions, stimulus types, and related terms. The relationship between the cognitive experiment and the behavioural domain or cognitive process under study, however, is left undefined. We present some considerations about this possible relationship, based on the fact that an experiment is an operationalization of many levels of inference. Cognitive experiments have hypotheses about cognitive process, the physical conditions of the experiment which in part operationalize those hypotheses, results which summarize the physical outcomes, and interpretations which link the physical outcomes to the models of cognitive processes. Pragmatically, this complexity has led to experimental databases tagging experiments as being “about” various cognitive domains and behaviours, while leaving the precise relationship open-ended.

1 INTRODUCTION
Cognitive neuroscience is an experimental discipline that establishes correspondences between brain structure and brain function through the integrated application of experimental psychology, human neuroscience, and non-invasive neuroimaging. Cognitive neuroscience is a highly productive, rapidly growing research field that aims to localize the underlying neural systems in virtually every mental domain. In the last two decades, research in cognitive neuroscience has resulted in an enormous amount of functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) data. Functional brain mapping is being pursued in healthy populations, as well as patients with neurological or neuropsychiatric disorders.

This scientific enterprise has spawned several efforts to facilitate integrating the vast array of results and publications regarding brain function under different conditions and diseases. The BrainMap database (www.brainmap.org, (Fox et al., 2005; Laird, Lancaster, & Fox, 2005)) is one of the oldest and best-curated of the efforts to pull together human neuroimaging results for ease in comparison across papers. It has developed a basic, hierarchical tagging schema for experimental results which has evolved into a data model of experiment, contexts, and behavioral domains. This model formed the backbone for the Cognitive Paradigm Ontology (CogPO; (Turner & Laird, 2012)). CogPO builds on BrainMap by making explicit the experimental paradigm terms, definitions, and their relationships. CogPO works within the context of BFO, RO, and the Information Artifact Ontology (IAO); the full details are explained in (Turner & Laird, 2012). In summary, the model is that a Behavioral Experimental Paradigm is a planned process which has_part at least two Behavioral Experimental Paradigm Conditions. The subclasses of paradigms are often well-known, named experimental paradigms such as the Stroop experiment, the Sternberg experiments, Auditory Oddball, etc. An experimental condition consists of the stimulus type presented to the subject (e.g., a dimly flashing light or moving random dots), the response the subject is supposed to give (e.g., pushing a button), and the instructions given to the subject for that condition (e.g., lie quietly or make a decision about the stimulus). Each stimulus and response also has a modality, such as the visual modality for a dimly flashing light, and the use of the hand or foot to push a button.

The BrainMap schema includes all the CogPO terms as annotations for the papers and results it includes. While not explicit in CogPO, the relationship between the data and the experiment can be modeled as in the Ontology of Biomedical Investigations (OBI; (Brinkman et al., 2010)); the data are the outcome of the planned process. There has not been a need to date to model that relationship more thoroughly (see, however, the NEMO model for a more explicit representation; http://nemo.nic.uoregon.edu/).

With relevance to mental function, however, BrainMap also includes an initial taxonomy of behavioral domains, or cognitive processes (see Figure 1). Each experiment in the database is related to a behavioral domain, based on the judgment of the human curators; the behavioral domains and subdomains have evolved both from a priori understanding of cognitive science, and as needed by the literature. It is neither complete nor fully defined, and is open for expansion if new experiments do not fit these categories. Each experiment is tagged with one or more of these behavioral domains. The precise relationship between the experiment and the cognitive process under study, however, is not currently defined in CogPO or other ontologies. At the moment, the best guess is that the data from that experiment

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“is about” that behavioral domain, with no further constraints. In attempting to make that relationship more precise, several issues arise.

2 COGNITIVE EXPERIMENTS

Cognitive experiments do not arise in a vacuum; they are designed to answer a scientific question, usually. That scientific question assumes a certain framework for thinking about cognitive processes. A basic example from psychophysics is an experiment to measure how bright a light has to be before someone can see it. This is a basic sensory perception example about the limits of the visual system: a light of varying intensity in a dark room, a human with a button to indicate whether or not they saw it—the experiment doesn’t get much simpler. But questions exactly like that have spawned decades of development in signal detection theory, because the link between internal processes and external behavior is convoluted. In cognitive neuroscience, where we include the covert physiological response of the brain in the experiment, in concert with the individual’s overt response, the links become even more complex.

2.1 Cognitive processes and behavior

In the psychophysical example above of the limits of light detection, a classic experiment would be to have a healthy human subject sit in a completely dark room for 15 minutes or more; then with their head fixed, so that the light was always aimed at their eye, lights of varying intensity would be flashed, and the subject would indicate if they saw the light. Assuming a subject who is not malevolent but actually trying to do the task, the proportion of times the subject reports seeing each light level is an increasing function of the intensity of the light. At very low levels, the subject will never report seeing the light; at very high levels, they can’t miss it and will always report seeing it. In the middle, there is uncertainty—from the subject’s point of view, many times they aren’t sure if they saw it or not, and they have to guess. And that is where the link between external measures (did they report detecting the light) and internal processes (they actually perceived it) becomes complicated. It becomes a probabilistic relationship.

The actual “threshold of detection” is usually inferred to be the light level at which subjects are reporting seeing it 50% of the time. But that threshold can be manipulated with incentives; the subject can be induced experimentally to be very conservative and only report detection when they are very sure the light flashed, or to be biased to be much more willing to indicate detection. The threshold has to be noted as being measured using a certain experimental design and biasing system (for review, see (Macmillan & Creelman, 2004)). The context of the experiment can move the measured threshold; so we have to update our model of the links between external measurement and internal detection threshold to take that into account.

2.2 Cognitive processes and physiology

Within an fMRI experiment, the relationship between behavior and the cognitive process is often assumed, while the relationship between the cognitive process and brain metabolism (highly indirectly measured, by the Blood Oxygenation Level Dependent or BOLD signal) is what is being studied. Often the connection is fairly straightforward: Within some limits, the BOLD signal increases with increasing light intensity in primary visual areas (Goodyear & Menon, 1998), and with increasing rate of finger-tapping in the motor cortex (Rao et al., 1996), and with increasing number of items to remember, in the dorsolateral prefrontal cortex (Potkin et al., 2009). However, in many other cases it is less clear: In an auditory oddball task, for example, the subject hears a stream of repeating tones, and every so often a different, target tone occurs (the oddball), to which the subject is supposed to respond by pushing a button. The auditory cortex BOLD signal usually increases for the target or oddball tone; in patients with schizophrenia, however, that BOLD signal increase is consistently reduced. Their performance in responding to the oddball tones is equivalent to healthy subjects, indicating they hear the tone. But the link between internal perception and the BOLD signal is broken, and the precise nature of that relationship is of course the subject of research.

2.3 The cognitive experimental framework

2.3.1 Hypotheses

An experiment usually is cast having a hypothesis, or at least a question, about the cognitive process being studied. We want to know the limits of visual sensitivity, or the effects of emotional shock on memory, for example; the questions we ask are formed within the context of current scientific understanding, and our models of cognitive processes. It does not make any sense to ask about how different odors are processed visually, for example; within the framework we use to understand how sensory cognition works, odors are not included in visual processing. They can affect emotions, they can drive memory retrieval, they can enhance attention to visual detail; but they are not part of the accepted model of visual processing. The relationship between the experiment and cognitive processes is formed in part by how we model cognitive processes.

2.3.2 Operationalizing

The experimental conditions are the embodiment of the test of the hypothesis. We have a hypothesis, e.g., that short-term memory is impaired in emotional situations. We create several conditions of various emotional and non-emotional situations, and we ask people to do something—Push this button if this is an item you’ve seen before (memory). The
implicit assumption is that the number of correct responses will be decreased, or the speed of the response will be slower, or both, when memory is impaired; that is the operationalization of impairment. That operationalization works off the assumption that the emotional situation does not affect visual processing, for example, but that the results are specific to memory function. For the effects of emotional manipulations on behavioral domains other than memory, we might ask something else—Respond as quickly as possible when the arrow appears (attention). Name the color, don’t read the word (executive function). Choose which person you’d rather talk to (social cognition). In each case, we measure the overt behavior against the variation experimental conditions which we control, and within our assumed framework about how that links to cognitive processes, we use those results to draw conclusions about the processes we are studying.

2.3.3 Analysis
The “use” of the results, the next step after data collection, is a formative step in linking experiments to cognitive processes. Few cognitive experimental papers simply report results by subject, without attempting to summarize the data in some way. The simple choice of whether to report a mean or a median reflects what kind of response the subjects were asked to give and our understanding of what kind of scale that response should be measured on, and what is the best measure of central tendency for that response (Stevens, 1946). That theoretical framework is just part of what underlies the choice of statistical summaries and analyses we do on the results, even if it is an unquestioned, standard analysis that many research groups use.

2.3.4 Interpretation
The final step is linking the results back to the cognitive processes: In the emotion and memory example, suppose the number of correct responses in the emotional situation was less than in the non-emotional situation, and under the assumptions used in the analysis, it was a difference that is unlikely to have arisen by chance. Or using a non-parametric approach such as bootstrapping, the difference was again fairly extreme and unlikely to have happened randomly. The conclusion would likely be written up for scientific publication as evidence that short-term memory is impaired in emotional situations—with a long list of caveats, limitations on the interpretations, and suggestions for follow-up experiments (i.e., new hypotheses), all of which reflect our understanding of cognitive processes, their characteristics, and the links between external observables and internal processes.

3 DISCUSSION

The question in the title is really asking ontologists to summarize all of the scientific method in one simple relationship. Our underlying model of cognitive processes, their characteristics, limitations, and connections to external observables such as behavior and physiology, is certainly not captured by a simple taxonomy of the sort that BrainMap uses. Hence, we simply tag experiments with behavioral domains or cognitive process labels and a catch-all relationship “is about”. The full modeling of the context of cognitive experimental design requires considering hypothesis identification, operationalization, analysis, and interpretation, and will have to develop in concert with the modeling of our understanding of the characteristics of and relationships among cognitive processes.

![Fig. 1. The current behavioral domains and their subtypes as used in the BrainMap schema.](image_url)

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REFERENCES


