Can High-Level Cognitive Functions be Localized?

By

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Teaser

Cognitive function – imaging comparisons may represent a new phrenology in which ill-defined cognitive concepts are erroneously localized to narrowly specified regions of the brain.

Keywords

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Abstract

Technical and conceptual difficulties abound in the effort to localize high-level cognitive functions to narrowly circumscribed regions of the brain. Some of the most serious involve the ambiguous definition of the putative mental components that are to be localized and the generally unacknowledged nonlinear complexity of both the mind and the brain. In addition, the imaging techniques themselves are replete with technical difficulties that raise additional questions about this particular application even though these wonderful machines can make extraordinary contributions to our knowledge of brain anatomy and physiology.

Throughout the history of cognitive neuroscience, a persistent goal has been the search for localized regions of the brain that represent or control specific cognitive functions. Prior to the last couple of decades the predominant method was surgical extirpation of brain regions followed by the study of behavioral deficits. For a number of reasons, interest in this kind of study has waned. One reason, not as frequently acknowledged as are the practicalities of cost and ethics of animal treatment, is that progress of the surgical program began to run into what were insurmountable conceptual and logical difficulties. This older approach was doubly challenged. First, cognitive functions were inadequately defined. Second, the surprising lack of appreciation that the brain was a highly complex, heavily interconnected system displaying nonlinear properties that precluded its simple analysis into independent functional units.

Now a new technology holds center stage in the effort to answer the same localization question. Surgical extirpation has largely been replaced by fMRI and other imaging studies that seek to correlate regions of high level of metabolic activity with particular cognitive functions. Because of the noninvasive and nonradiological nature of MRI techniques, this approach initially promised to offer enormous advantages over the surgical techniques. It is estimated that nearly 100,000 fMRI studies have been reported since the discovery of this method by Ogawa and his coworkers [1] only 13 years ago. In spite of their advantages, the new techniques still suffer from many of the conceptual and technical difficulties that bedeviled surgery and related techniques.

Some General Points

Before I present some of the persistent difficulties and challenges still faced by the cognitive imaging enterprise, several general points must be made. First, like all others who are admirers of modern biomedical advances, I am firmly convinced that the various kinds of MRI devices now available or that are under development represent some of the most important medical advances in human history. The MRI technique is likely to be eventually compared with the milestone of anesthesia with regard to its ability to alleviate human suffering. It has already provided opportunities for diagnosis and treatment that would have exceeded the imagination of medical scientists only a few years ago. As the technology progresses, it is also likely to introduce new techniques such as intraoperative imaging, MRI spectroscopy, and microscopic imaging that will open previously closed doors to understanding the structure and biochemistry of the brain, especially in degenerative diseases.

Second, there is little question that some processes and activities are more or less localized in the brain. The location of sensory and motor and some emotional and appetitive regions have been known for years and newer imaging studies has repeatedly confirmed the basic facts of this aspect of brain organization. On the other hand, the idea that high-level cognitive processes such as decision-making or problem solving are uniquely encoded in localized regions of the brain is, some of us suggest, suspect. It seems far more likely that each region of the brain mediates many cognitive processes and that each cognitive process is encoded by activity in widely distributed brain regions.

Third, by no means am I arguing that the brain is a homogeneous mass of undifferentiated, equipotential regions in the sense that Lashley [2] once proposed. Somewhere between that extreme and the concept of a collection of relatively isolated functional modules lies what we must consider to be the truth about brain organization. Most probably a compromise will ultimately appear that accepts distributed encoding with some degree of specialized localization.

What is missing, I now argue, in the excitement of the new technology, is sufficient discussion of the conceptual and technical obstacles that abound in this new endeavor and of possible alternative interpretations of the imaging data. In the remainder of this article I discuss some of these obstacles and make the argument that the enormous commitment of resources and human energy to this particular scientific approach may be ill advised.

On the Definability of "Cognitive Processes"

One of the most profound problems facing those who seek to localize cognitive processes in the brain is the tenuous nature of these "hypothetical constructs" as defined by MacCorquodale and Meehl [3]. Throughout the long history of the interest in classifying mental processes, there has been little agreement on what are the components, modules, faculties, or traits of human thought. Indeed, one of the great unanswered questions of psychology is whether these proposed subdivisions of the "mind" actually exist in any biological sense. It may be that they are only figments of our experimental designs or convenient artifices to organize our theoretical models.

There is, thus, a real but unacknowledged possibility that many of the cognitive components for which brain locales are sought are idiosyncratic to a particular experiment, very poorly defined, or simply names applied to concretize measured behavior. If this turns out to be correct, then many cognitive processes do not represent real isolable entities, but, rather, are simply inferences or "nominal" hypotheses drawn from the measures of the particular results of an experiment. Because of the neutrality of behavior [4], a profound logical difficulty remains cogent – since any behavior may be "explained" by many plausible internal mechanisms, therefore, mental terms cannot, in principle, denote specific internal mechanisms.

In spite of this possibility, hypothetical cognitive modules are often reified as specific "organs", "objects", or "modules" whose mechanisms are narrowly localized in the brain. There is at least a reasonable possibility that the "mind" is a far more integrated, molar, unified entity than a system of quasi-independent faculties. If so, the assumption of localizable cognitive modules is just wrong.

The Nonlinearity of the Cognitive and Brain Systems.

Let us assume, for the sake of argument that the both the mind and the brain are modular in the way required for the imaging approach to succeed. Is it likely that these hypothetical components are so simply interconnected that they can be dissected and examined in isolation? The brain is hardly likely to meet this criterion; it is an immensely complex organ whose many regions are well known to be heavily interconnected. Indeed, this complexity of interconnection was one of the difficulties that confronted the earlier generation of surgical localizers. What the earliest anatomical studies discovered and the functional studies later confirmed was that the centers and nuclei of the brain spoke to each other along many different pathways. Complex networks existed with feed back, feed forward, and multiple lateral connections.

It is now thought that the task of determining the hierarchical ordering of components of even as relatively simple a system as the visual system may be intractable due to this nonlinearity. Rather, according to Hilgetag et al [5], such a task is mathematically impossible and no additional amount of research can ever overcome this fundamental problem.

Interactions of this kind make it impossible, for example, to determine if a region is sufficient to encode a putative cognitive process, simply a transmission pathway for the flow of critical information, or even an inhibitor of an inhibitor whose surgical removal or activation could produce a simulation of localization. In other words, we may obtain strong evidence of necessity (i.e., participation) without being able to strongly argue that a particular region of the brain is uniquely sufficient to represent or encode a particular cognitive process.

Contrary to current cognitive dogma, psychological functions also are subject to this same kind of nonlinear constraint on our analytical ability. For example, Pachella

[6] argued that certain unrealistic simplifying assumptions were required to fractionate reaction times into components. He argued that it would be necessary to assume that the components were activated in serial order; that the components were stable enough to remain unchanged when task requirements change; and that the data used to choose between alternative processes were sufficiently precise to distinguish between alternative explanation.

In short, the foundation idea of that the mind is a system of quasi-independent modules that can be localized in narrowly circumscribed regions of the brain is at least questionable and probably unsustainable. In mathematical terms, the localization of cognitive processes in the brain is an ill-posed problem! That is, there would not be enough information to solve it even if we possessed all possible data.

The Subtraction Process

The basic methodology used in fMRI imaging of cognitive process is to subtract the image of an experimental condition from a control condition. However, "experimental" and "control" in this case refer to manipulations of thought processes. The degree to which control is possible over the freewheeling way in which humans adapt to instructions will always leave a residue of doubt about what is actually going on in the mind of the subject and thus introduce uncertainty into any drawn conclusions.

More fundamentally, the subtraction of one image for another, even if done with great accuracy, obscures the fact that many other regions other than those highlighted may be active and involved in the cognitive process under study. Even though the cumulative activity in these other regions may appear to be unchanged, this does not mean that the underlying patterns of neuronal activity are identical in the two conditions. Thus, there is a logical flaw built into the subtractive method; it ignores places where activity may be constant in integrated quantity (which is what the fMRI measures) but quite different in microscopic detail.

The Arbitrariness of Statistics and Thresholds

There are a number of other technical and data problems that have to be considered in terms of what has already been accomplished in the quest to localize cognitive functions in the brain. Among the most serious are those that have to do with the massaging of the data by statistical and experimental design protocols. Individual differences can have an enormous impact on the apparent localization of a putative cognitive process. Broadly distributed activity for individuals can, when averaged, produce relatively small apparent regions of activation in the same way that the "common region" of a Venn diagram is much smaller than the individual regions.

Even more important, however, is the arbitrariness with which thresholds can be set to define the boundaries of an activated region. High levels of significance reduce the apparent size of an activated region while low levels broaden it. Injudicious assignment of significance levels and thresholds can, therefore, grossly distort the apparent degree of "localization".

The Question of Data Reliability

As it should be, the reliability of the obtained experimental results should be paramount in evaluating the success of a scientific study. Thus, newly emerging meta-analytical comparisons of the results from a number of experiments are particularly important in evaluating the success of the cognitive imaging enterprise.

What is arguably the most comprehensive meta-analysis yet carried out in the field of cognitive localization is that reported by Cabeza and Nyberg [7]. They compared the regions that were activated by what were assumed to be common cognitive processes. Regions that were associated with some sensory or motor activities (e.g., "perception" or "language") did show relatively narrow localization to the classic visual or Broca and Wernike’s areas. However, when Cabeza and Nyberg compared the results for higher cognitive processes such as “working memory” or “problem solving”, the data from different laboratories were broadly distributed. The reported peaks of brain activity associated with this latter kind of cognitive activity were spread over at least a quadrant and, more typically, half of the brain!

It is clear from Cabeza and Nyberg’s meta-analysis that no narrowly circumscribed region of the brain was uniquely associated with any high level cognitive function. Although individual reports may suggest such a conclusion, the variability of the reports from different laboratories suggests that narrow localization is, to a substantial degree, mythical.

Conclusion

This essay is much too short to permit the presentation of the entire case against the cognitive localization enterprise (for a more complete discussion of the technical and conceptual difficulties facing this field of research see my book [8].) What is clear is that there has been a rather reckless community decision to commit an inordinate portion of psychology’s limited resources to this one research program. Obviously some knowledge will come from this new approach. However, until we consider the basic assumptions, the epistemological constraints, and the forthcoming data in detail, the potential for enormous waste and theoretical misdirection continues unabated.

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