Mind and Brain Sciences in the 21st Century

edited by Robert L. Solso

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Imaging the Future

MICHAEL I. POSNER AND DANIEL J. LEVITIN

One thousand years ago it was not universally held that the mind was located within the brain. One hundred years ago, the firm conviction that brain and mind were related led phrenologists to map the topography of the scalp and face (figure 6.1). In the last 10 years, cognitive psychologists studying mental operations have embraced neuroimaging techniques to localize mental operations in the brain, and to study their orchestration as humans perform a variety of tasks (figure 6.2). What will we find as scientists explore and chart the brain in the next 10 years, 100 years, or 1000 years?

Extrapolating the Current Scene

Before speculating about the future, it seems appropriate to begin with a brief account of what we already know (or at least the two of us think we know) of the brain through current methods (Posner & Raichle, 1994). As we reach the last half decade of the 20th century it still amazes us that we can see pictures of our own minds at work. If a thought process can be sustained for only a few seconds, the snapshot revealed positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) can show us which parts of our brain anatomy are active and to what degree. We know already that there are specific brain anatomies for reading (Posner & Raichle, 1994), listening to music (Marin, 1982; Sergent, 1993), mentally practicing your tennis serve (Roland, 1994), calculating numbers (Dehaene, 1995), and imagining a friend's face (Kosslyn, 1994). The methods for revealing the macroanatomy (in the range of millimeters to centimeters) of any mental process are clearly available.

Figure 6.1 A picture of classic phrenology. The areas of the brain come from studies of bumps on the head and the cognition represents the faculty psychology common at the turn of the century. (From Krech, D., and Crutchfield, R., *Elements of Psychology*. © 1958 by David Krech and Richard S. Crutchfield. © 1969, 1974 by Alfred A. Knopf, Inc.)

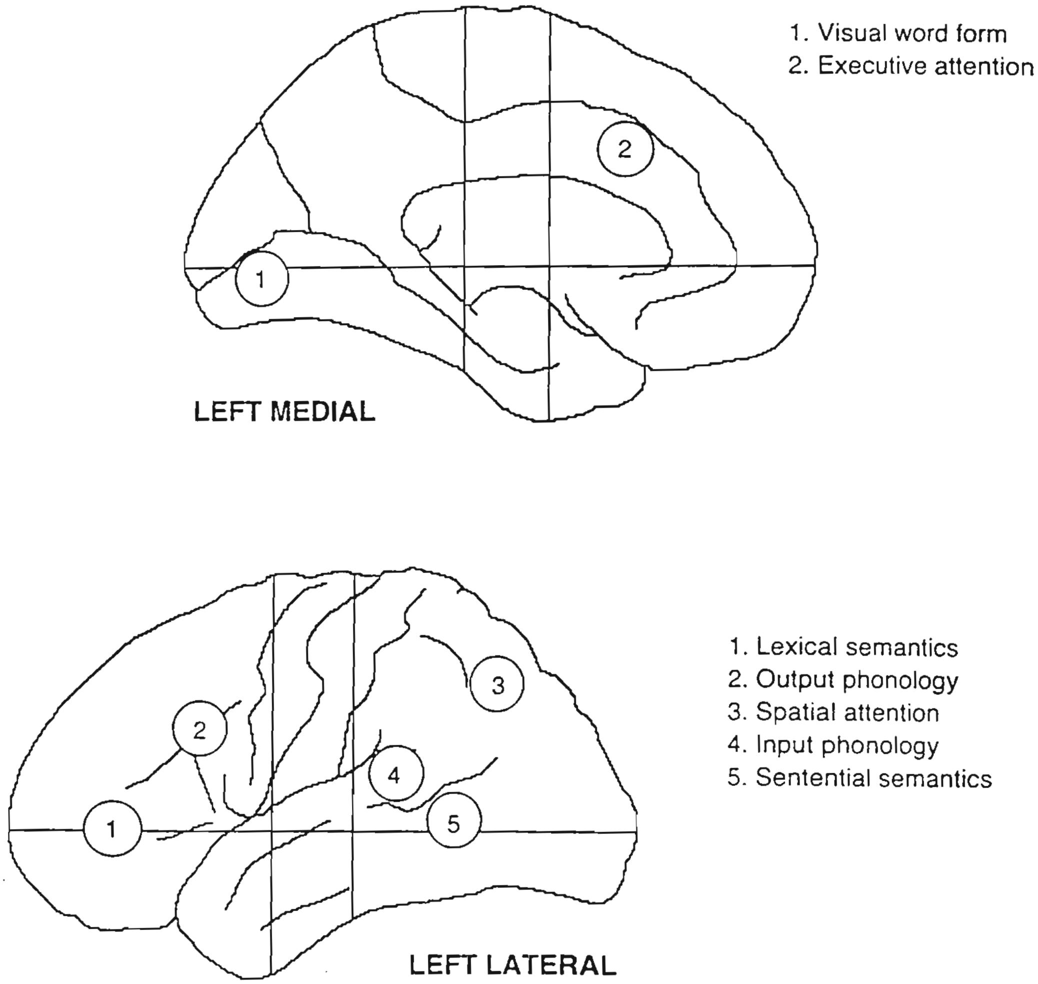

Figure 6.2 Modern phrenology. The areas of the brain summarize studies using PET and fMRI to observe changes in blood flow under experimental and control conditions. The cognition represents ideas of the types of computation involved in many cognitive tasks.

ANATOMY

One clear finding that emerges from these methods is that every cognitive task entails a particular network of brain areas; often we can link these brain areas to a specific computation required by the task. Some brain areas are very specific to a given cognitive domain so that they are only active if the task involves language or recognizing a face. Other brain areas appear to carry out very general computations that may be important in any task domain. For example, the lateral cerebellum appears active in both sensory and motor timing, as if it represented a central clock (Ivry & Keele, 1989).

In the coming decades, we can expect our maps of brain anatomy to yield greater detail and spatial resolution, even if no new methods are invented. However, the attraction of young physicists formerly working on military problems to the study of the brain is such that we can be fairly certain that new and unanticipated ways of imaging brain activity will arrive. How should we use this increased resolution? Not just to make finer and finer maps! Rather, we need to seek principles of how important cognitive activity becomes distributed in brain regions.

In neuroscience, the cortical column is seen as the basic unit of organization of the human brain. Imaging methods have already shown that adjacent brain areas seem to become active as tasks change slightly. This forms the starting point for a principled approach to cortical organization at a macro level. The parietal lobe is involved in shifts of covert attention, but high up in its most superior regions it is active when the shift is to a purely visual event for which little response is required. When the shift of attention involves more detailed analysis of the nature of the visual event, or when overt orienting is allowed, the areas of activation appear to involve more inferior areas of the parietal lobe. When the task is purely one of recognition and no shift of attention is needed, the mid- to inferior temporal lobe is active.

Similarly, when a task is mostly passive (listening to a voice or music) different areas of the frontal midline show activity than those active when one begins to respond rapidly to a task (such as shadowing a word). Moreover, practicing a task can alter the brain areas involved. In one type of experiment, subjects are shown a noun and asked to respond with a word describing how it is used (e.g., "pound" to the word "hammer"). During this task, there are strong activations in the anterior cingulate, and in the left lateral posterior and anterior cortex. These activations disappear with practice but this is accompanied by an increase in activation in other brain areas that appear to be involved in automated (or "overlearned") tasks such as reading a word (Posner & Raichle, 1994). Perhaps our colleagues in the 21st century will be able to integrate these findings into a set of principles that will describe the organization of the brain for cognition.

COMPARATIVE ANATOMY

As principles emerge in the study of the human brain these areas of activation can be viewed in relation to the known areas of primate brains to advance evolutionary analysis of cortical development. Some advances in this area have already taken place. For example, the visual word form area appears to involve portions of the brain that are also important for processing color. This relatively recent evolution suggests that the processing of visual words takes advantage of the high spatial frequency analysis available with the parvocellular areas of the visual system. Similarly, there is reason to think that the grammar of human language may take advantage of brain areas originally developed for hierarchical mechanisms of motor programming (Greenfield, 1991).

There are other advantages of exploring relationships between neuroimaging in human and animal models. The neuroimaging methods have been confined to an anatomy in the millimeter range, while cortical columns are in the micron range. The *micro*anatomy is important for understanding how *computations* are made by neurons. We already have some idea of the power of this method from studies of how mental rotations are computed in the monkey motor system (Georgopolis et al., 1989) and how perceptual motions are computed within area MT of the monkey (Newsome, et al., 1994). The coming period should confirm and expand our knowledge of these mechanisms. We can then build on what we know about the details of neuronal computation in animals as additional constraints in the development of models of complex human tasks. As such models emerge it will be important to be able to examine the circuitry involved in human cognition to confirm predictions from models and to shape the agenda for the kinds of animal studies that will be needed.

CIRCUITRY

Today it is also possible to observe the orchestration of many brain areas in real time. So far this has been accomplished mainly by relating the distribution of activity visible in event-related electrical and magnetic fields to generators found active in anatomical studies (Snyder et al., 1995).

Circuitry and Reading One of the areas for which the most knowledge is already available is in reading of words. During the reading of a foveal word (Posner et al., in press), computations occur in the right posterior occipital lobe at about 80 ms that relate to *features* of the word. By 130 to 180 ms the "visual word form" of the left posterior cortex is activated. For simple, clearly visible words, this is followed by activity in a frontal midline attention system by 170 ms and in a left lateralized frontal semantic system by 220 ms.

These activations contribute to organizing the saccade for the next fixation which typically begins by about 270 ms (Posner et al., in press). It is known from cognitive studies that the saccade is influenced by knowledge of the meaning of the current word. Therefore, it is necessary that information about the meaning of the word be available before the eyes are moved. Before the saccade begins there is more activation in anterior semantic areas related to word meaning, as well as higher-level frontal attentional areas. We should not think that these activations are purely in the direction of posterior to frontal. Rather there is feedback of information from frontal systems into posterior areas. Thus, in imagining a scene, frontally based attention and semantic systems can be used to activated posterior areas related to the visual form of the scene (Kosslyn, 1994).

While we can expect some of the details of these findings will likely be modified by future work, the way is clearly open for a detailed description of the time courses of mental operations in high-level human tasks.

There is also much scope for improvement in our ability to image non-invasively the circuitry involved in brain activity. While at present, electro- and magnetic activity recorded from outside the head are all that are available, the development of new statistical tools, including Bayesian analyses to constrain the solution space, will allow us to project the probable three-dimensional source of activation deep into the brain (Tucker et al., 1994). Future advances in dense sensory array measurement (e.g., 128 or 256 channels) of the brain's electrical and magnetic fields at the head surface promise new insights into the sources of these fields.

By combining the surface measurement with accurate information on the tissues of the head and brain from magnetic resonance imaging (MRI), the electrical (electroencephalogram or EEG) and magnetic (magnetoencephalogram or MEG) studies may be guided by additional constraints for localizing the neural sources. Unlike metabolic or blood flow (PET or fMRI) methods that have a poor temporal resolution, the EEG and MEG techniques provide a millisecond temporal resolution that is better suited to the time course of cognitive operations performed by neural circuits.

PLASTICITY

In cognitive science there has been a long-standing interest in the nature of expert performance (Chi et al., 1988). These studies show that there are major differences in representation of the same information by novices and by experts, and changes in representation that accompany the development of expertise within an individual. Very familiar to most cognitive psychologists is the impressive achievements of chess masters. Simon has estimated that this skill is based on many thousands of hours of practice and produces an elaborated semantic memory that allows reproduction of the chessboard in lawful master-level games (Chase & Simon, 1973). Chase and Ericsson (1982) have observed these changes in memory with practice in students trained to have numerical digit spans of up to 100 items. In these cases we do not yet know how the brain is altered by the experience involved.

While it has not yet been possible to understand the achievements of chess masters in *neural* terms, some studies of the neural basis of expert performance have already taken place. Familiar to most cognitive psychologists is the phenomenological change that accompanies learning to read. The ability of a skilled reader to recognize each letter of a lawful word at a lower threshold than the letter in isolation shows that learning the skill provides a visual chunk that eliminates the need to scan and integrate the letters. For this effect we already have a candidate neural system in the left medial occipital lobe (Posner & Raichle, 1994) that appears to be involved in performing this recognition function. It appears that this skill requires years of practice and produces signs of an adult "word form system" only at about age 10 (Posner et al., in press).

The studies outlined above suggest the continued plasticity of some aspects of brain circuitry with new learning. However, there is already evidence of critical periods in the learning of skills. Weber-Fox and Neville (1996) studied the learning of English by immigrants from China who came to the United States at ages ranging from 2 years to adulthood. They found that the brain circuitry involved in understanding the meaning of lexical items was similar regardless of age of immigration. However, the circuitry underlying grammatical judgments resembled American natives for those who immigrated as young children, but was very different in those whose immigration was late. A similar critical period has now been reported in learning the violin. Children who begin lessons prior to age 12 show changes in somatosensory cortical representation between the left and right hands that are not present even in expert violinists who began their lessons late (Elbert et al., 1995).

At present we have only a rudimentary understanding of how the anatomy, circuitry, and plasticity of the brain are involved in the performance of high-level human skills. It is clear that the accuracy and replicability of these findings is likely to improve steadily as new methods and more laboratories examine the results. However, it appears unlikely that we will ever be able to describe playing chess, for example, in terms of every brain area of computation that is invoked during a masters game. What will our goals be then and what progress toward their attainment can we expect?

Dynamic Brains

The study of psychology during the period from World War II to the mid-1980s was a study of how information was transferred between people and within a person. Psychology then was the study of the logic of how information was perceived, transformed, stored, and communicated. The brain was a black box, opaque to the physical substrate required to perform the functions specified by psychological models of mental events. A dominant metaphor was that psychologists studied software and for the logic of the programs it really didn't matter what hardware was required to run them. The current scene that we have described above—in which the hardware is also of interest—was ushered in by two related events. First, methods of neuroimaging opened up the human brain to investigation. It was now possible to image parts of the brain and see how they cooperated during performance. Second, a new class of models were developed, based on the idea of complex computations resulting from simple neuronlike units. These two events have allowed psychologists to describe the anatomy, circuitry, and plasticity of higher forms of human performance. In this section we try to speculate on what the consequences of this new opportunity will be.

A series of very important studies by Merzenich and colleagues (Merzenich & Sameshima, 1993) has found that the brain of the sensory systems of higher primates can change with experience. What is new as the century draws to a close is our capacity to also observe these changes in humans as they acquire skills.

We have barely begun to understand the capacity for change in the human brain. In a recent functional magnetic resonance study (Spitzer, Kwong, Kennedy, Rosen & Belliveau, 1995) showed evidence that brain areas that coded the concept "animal" were separate from the brain areas that were responsive to pictures of furniture. Whereas the areas active for these concepts were generally located within brain areas related to semantic processing, the number, the exact location, and the extent of the activation appeared to differ among people. Putting these observations together with the learning-dependent changes in brain maps shown in Merzenich's work, we may expect that spending a month furnishing your apartment would lead to an expansion of "furniture" representational areas in your brain, while working in a zoo might change the extent and depth to which animals are represented in the brain. These findings might well explain the common observation that our thoughts and even our dreams tend to be dominated by events related to current experiences—observations that on a more micro scale are seen in laboratory studies of priming.

LEARNING

Cognitive science, which views humans as intelligent, learning, and thinking creatures, is beginning to have an influence in the field of education. To bridge the gap between theory and practice in this important arena, a number of cognitive psychologists have moved into the classroom. A recent book (Bruer, 1993) describing the significance of cognitive work for classrooms has received an award from the American Federation of Teachers.

We believe that in the future the field of cognitive neuroscience will be likely to also have a large impact on education. This may seem at first a somewhat unrealistic idea. There have been so many false starts, so many pop theories of brain functions, that many people (perhaps even the two of us) are wondering if we can learn things about the brain of sufficient importance to describe to those entrusted with the education of children. Nonetheless, we think that the new methods available to us both in terms of cognitive theory and brain imaging are stronger then ever before and we really must attempt to relate our findings to educational issues.

RECOVERY OF FUNCTION

Possibly the first area to benefit from the study of brain imaging will be the field of cognitive retraining following strokes or other closed head injuries. There has been evidence of some success in attempting to improve outcome from new forms of learning. However, since the mechanisms of recovery are not known, it has proved difficult to know whether these improvements in behavior are related to the training or due to spontaneous recovery that may also occur with delay after the injury. The ability to image the brain should allow much more detailed evidence of what the learning might do to change the anatomy or circuitry involved in cognitive tasks. In time we should know whether—and under what conditions—the relearning influences recovery within the damaged tissue, allows new areas to take over, or produces wholly new strategies that involve very different brain areas than those involved in the original task.

SCHOOL SUBJECTS

Already some tasks involving reading, music, and arithmetic have been studied in terms of anatomy and circuitry. Is there anything likely to emerge in cognitive neuroscience that will influence how these subjects are taught? One recent report illustrates what might be possible. Dehaene (1996) has argued that areas of the posterior parietal cortex are important for understanding the *quantity* of a number. He argues that this area of the brain is active when subjects are required to compare quantity, and moreover, lesions of this area produce a deficit in comparing and otherwise understanding quantity. Dehaene argues that this area may be common to both humans and animals and underlies our ability to know about quantity.

Griffin and colleagues (1994) has argued that children who are at risk of failing arithmetic in elementary school have a deficit in understanding the quantity of numbers so that they are unable to compare numbers. When this deficit is corrected by intensive education, they show marked improvement in their ability in arithmetic courses. These findings raise the possibility that we may be able to detect difficulties in comprehension related to specific brain areas and perhaps observe changes in activation of these areas that occur following the training. If so, our ability to diagnose a wide variety of learning disabilities in children may improve and benefit from neuroimaging in much the same way as described above for recovery of function following brain damage.

Individuality

The science of human differences has been heavily influenced by psychometric methods on the one hand, and on the other by the promise of twin studies that have suggested the genetic basis of personality. Work at three different levels of understanding in particular hold great promise: (1) genetic approaches, including the human genome project, (2) neuroimaging, and (3) phenotypic approaches to defining personality. As these methods are refined and the different levels related to one another, there is the promise of new excitement in the study of individual differences in cognition, emotion, and personality.

Genetic Level

According to recent estimates, the full sequence of the human genome will be completed ahead of schedule, by 2005. We now know that the brain has 3195 distinctive genes, and that roughly 17% of these are involved with cell signaling. It is conceivable that in the near future we will have found connections between particular genes in the brain and individual differences in personality traits. Whether particular genes will indicate a propensity for certain behaviors or determine those behaviors will undoubtedly be the subject of much popular debate. However, the currently available evidence—based on studies of identical twins separated at birth—is quite convincing that genetics is not deterministic of behavior; it merely provides a statistical model that accounts for only a portion of behavior variability (Lykken et al., 1992, 1993), and then only for the behavior of groups, not individuals. Thus, although certain gene markers might become associated with the potential for particular behaviors, the existence of a particular gene will not likely determine one's behavior.

What we still do not know much about is the way in which genes are translated first into biological substrates in the brain, and then into psychological mechanisms, such as a trait, nature, attitude, or preference. Moreover, we still know very little about the relation between traits and behavior, as the power of situational forces can often confound our predictions based on traits (Malle, 1995; Ross & Nisbett, 1991). The findings of behavior geneticists and personality and social psychologists will need to be integrated in the coming years to advance our understanding of these issues.

Neuroimaging

The genome findings, taken in concert with imaging studies, promise to illuminate the anatomical basis for many types of individual differences. The development of fMRI allows ready superposition of changes in blood flow and brain structure. Thus we can see how activation of brain areas relates to the structure of individual brains. We have already reviewed evidence that the structure and function of the brains of violinists differ if practice is started early enough (Elbert et al., 1995). We should be able to determine which differences depend upon practice and which may involve genetic differences that perhaps lead to the acquisition of high-level skill. In current cognitive psychology both genetic and learning views of individual differences have advocates; it seems likely that the use of imaging methods will provide a basis for separating and relating these approaches.

PHENOTYPIC STRUCTURE

Although we use thousands of words to describe how people differ from one another, mathematical analyses show that our perception of human traits clusters in an orderly fashion, such that most of the traits on which people differ can be described by a location in a five-dimensional coordinate system, the "Big Five" personality model (Goldberg, 1993). This finding seems to hold up across a variety of cultures and languages, adding to the growing body of evidence that the strong version of the Whorf-Sapir hypothesis in untenable.

A subset of work on personality differences concerns one particular constellation of traits, those associated with what we loosely call "intellect." The recent, more inclusionary definitions of "intelligence" that allow for athletic, spatial, artistic, and other "nonacademic" intelligences (Gardner, 1983) broaden our notions of what it means to be intelligent. These new definitions also provide an expanded framework for the study of expertise. The near future may see changes in how we teach our children, as a result of the formal acknowledgment by academia that disparate forms of accomplishment exist.

SOCIOPATHY

An example of how these three levels of research are merging comes from recent studies on criminal and aggressive behaviors. Geneticists have speculated that an "aggression" or "criminality" gene may soon be found. fMRI studies of the brains of murderers have shown clear differences in blood flow between them and normals: murderers tend to show far less frontal lobe activity, a possible indicator that they are less able to regulate feelings of aggression in a normal way. Obviously this evidence is merely correlational, and it does not demonstrate a causal link. Yet, some researchers believe that violent behavior will turn out to be physiologically determined. Raine (1993) predicts that the next generation of clinicians and the public will "reconceptualize non-trivial recidivistic crime as a psychological disorder."

At the phenotypic level, the constellation of traits that seem correlated with criminality appear clustered along the negative axis of one of the Big Five dimensions conscientiousness/undependability. The degree to which criminal behavior is a matter of genetics, anatomy, environment, or personality is a problem that may become subject to scientific resolution. A recent, forward-looking integration of many of these ideas in sociopathy may be found in Lykken (1995).

Some have predicted that within 10 years we will be able to actually diagnose those people with a propensity for committing violent acts before they have committed them, possibly during childhood or preadolescence (Gibbs, 1995). How this information is to be used will undoubtedly become a source of considerable public debate in the coming decades, and psychologists will likely be called upon to participate in this debate. But any "individual differences screening" based on anatomical or genetic markers can yield only statistical probabilities for a group. That is, we might be able to say that *X*% of a group that shows the propensity for violence will go on to commit violent acts, but we cannot predict with any certainty *how a given individual will behave.* Consequently, the most responsible use of such information might be never to gather it in the first place. It is our worst fear that screening information might be used to force medical interventions or incarceration on individuals who have demonstrated only that they are part of a group with a statistical chance of violent behavior, a course that would parallel the ugly history of the eugenics movement in the United States in the early 1930s. A concomitant fear is that future public policy might ignore the findings of science: even seemingly benign interventions that result from the best intuition and intentions can backfire (McCord, 1978).

The one thread common to these three approaches to the study of individuality seems to be an emerging consensus that the brain contains a great deal of "hard-wiring" of systems that are specialized for particular functions, or the expression of particular behaviors. But this hard-wiring is only a framework, one that holds tremendous plasticity, and is malleable as a result of experience and environmental input. Although the range of human differences appears infinite, these differences are contained within a system that is finite in its genetic, anatomical, and phenotypic description.

Theory of Consciousness

The coming decades should hold more interaction among researchers in the various fields that study human behavior. The neuroimaging methods have already brought together many fields in an effort to map the human brain. One theoretical topic that has united philosophy with the sciences is the effort to understand the physical basis of our conscious experience.

The question of what it is to be conscious has recently again become a central one in many serious scientific circles. Proposals range from the anatomical—for example, locating consciousness in the thalamus or in thalamic-cortical interactions—to the physical—for example, the proposal that consciousness must rest on quantum principles. Will all of these speculations provide a basis for understanding the centuries-old philosophical problems of how our mental experiences arise and how they relate to the brain?

One aspect of experience that has traditionally been related to or equated with consciousness is attention (James, 1890/1950). The images of human brains at work have revealed brain areas that seem closely related to programming the order of our mental computations. The areas responsible for programming amplify particular computations or suppress others, and they comprise various networks supporting selective attention. So far, these studies have supported three fundamental working hypotheses that together constitute current efforts to produce a combined cognitive neuroscience of attention. First, the brain possesses an attentional system that is anatomically separate from the various data-processing systems that can also be activated passively by visual, auditory, and other input. Second, attention is accomplished through a network of anatomical areas; it is neither the property of a single brain area nor is it a collective function of the brain working as a whole. Third, the brain areas involved in attention do not carry out the same function, but specific computations are assigned to specific areas (Posner & Raichle, 1994).

One major source of our feelings of conscious control involves the act (or illusion!) of voluntary control over behavior and thought. Volitional control is by no means total as the (presumably unwanted) tendency of depressed people to dwell on negative life events clearly shows. Yet all normal people have a strong subjective feeling of intentional or voluntary control of their behavior. Asking people about goals or intention is probably the single most predictive indicator of their behavior during problem solving. The importance of intention and goals is illustrated by observations of patients with frontal lesions (Duncan, 1994) or mental disorders (Frith, 1992) that cause disruption in either their central control over behavior or the subjective feelings of such control. Despite these indices of central control, it has not been easy to specify exactly the functions or mechanisms of central control.

Nonetheless there are some cognitive models of executive control that outline subsystems serving to control cognitive processing (Norman & Shallice, 1986). According to this model, attentional systems involve two qualitatively different mechanisms. The first level of control corresponds to routine selection (contention scheduling) in which the temporarily strong activity wins out. However, when a situation is novel or highly competitive (i.e., requires executive control), another supervisory system would intervene and provide additional inhibition or activation to the appropriate schema for the situation. Norman and Shallice (1980, 1986) have argued that the supervisory system would be necessary for five types of behaviors or situations in which the routine or automatic processes of the contention scheduling mechanisms would be inadequate and executive control would be required. These are (1) situations involving planning or decision making; (2) situations involving error correction; (3) situations where the response is novel and not well-learned; (4) situations judged to be difficult or dangerous; and (5) situations that require overcoming habitual responses.

One of the most interesting findings from the era of neuroimaging is that tasks involving these properties have all activated areas on the midline of the frontal lobe (Posner & DiGirolamo, in press). Moreover, lesions in this general area produce a remarkable loss of spontaneous thought and action. Damasio (1994) has recently described the effects of lesions of this area as follows: "Their condition is described best as suspended animation, mental and external—the extreme variety of an impairment of reasoning and emotional expression. Key regions affected by the damage include the anterior cingulate cortex, the supplementary motor area, and the third motor area." While more recent studies of surgical lesions of this area have not produced the devastating loss of mental function, so we do not know the extent or the neural system involved.

A new debate has emerged over whether consciousness is a function or a process, and thus over whether consciousness will be found to exist in a particular place in the brain. Elsewhere, one of us has argued that the anterior cingulate is likely to be a necessary and important component of tasks that are associated with consciousness (Posner, 1994), but that consciousness is a distributed, multifaceted function. The other of us has argued the not inconsistent idea that consciousness is an emergent property of the brain-as-a-whole, and that it is a *process*, not a *thing* (Luu et al., 1996). Thus, just as we don't expect to find "gravity" at a particular location in the middle of the earth, we shouldn't expect to find consciousness at a particular place in the head.

We can only speculate about the consequences of these new developments in the theory of attention for philosophical views about the relationship of brain to mental experience. Although we feel some confidence about the scientific predictions made in this chapter, we have relatively little idea what effect they might have upon the philosophical disputes that have attended the issue of consciousness. However, we can express our hope that the new developments in neuroimaging that will take place over the coming decades might help psychologists and philosophers to overcome the inhibitions of the hundreds of years of separation between mental and physical events. With an understanding that knowledge of the brain's anatomy provides constraints for more conceptual—or traditional cognitive—models, the psychologist and the philosopher will thus be able to reason, each from his or her understanding of neuroscience and of cognition. This joint approach will provide the basis for understanding the mechanisms of awareness and cognitive control as elements of consciousness.

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