Research on Attention Networks as a Model for the Integration of Psychological Science

Michael I. Posner and Mary K. Rothbart[1]

Psychology Department, University of Oregon, Eugene, Oregon 97403-1291;
email: mposner@darkwing.uoregon.edu, maryroth@darkwing.uoregon.edu

Annu. Rev. Psychol. 2007. 58:1–23

First published online as a Review in Advance on October 9, 2006

The *Annual Review of Psychology* is online at http://psych.annualreviews.org

This article's doi:
10.1146/annurev.psych.58.110405.085516

0066-4308/07/0110-0001$20.00

[1]We appreciate the invitation of the editors of the *Annual Review of Psychology* to submit a prefatory essay to this year's volume. We have taken the opportunity to propose a unified basis for psychological science based upon an effort to combine experimental and differential approaches to the field. This article is an improved and expanded version of an earlier one along these lines (Posner & Rothbart 2004), and its developmental aspects are further expanded in a book (Posner & Rothbart 2007).

Key Words

attention, candidate genes, orienting, neural networks, temperament

Abstract

As Titchener pointed out more than one hundred years ago, attention is at the center of the psychological enterprise. Attention research investigates how voluntary control and subjective experience arise from and regulate our behavior. In recent years, attention has been one of the fastest growing of all fields within cognitive psychology and cognitive neuroscience. This review examines attention as characterized by linking common neural networks with individual differences in their efficient utilization. The development of attentional networks is partly specified by genes, but is also open to specific experiences through the actions of caregivers and the culture. We believe that the connection between neural networks, genes, and socialization provides a common approach to all aspects of human cognition and emotion. Pursuit of this approach can provide a basis for psychology that unifies social, cultural, differential, experimental, and physiological areas, and allows normal development to serve as a baseline for understanding various forms of pathology. D.O. Hebb proposed this approach 50 years ago in his volume *Organization of Behavior* and continued with introductory textbooks that dealt with all of the topics of psychology in a common framework. Use of a common network approach to psychological science may allow a foundation for predicting and understanding human behavior in its varied forms.

Contents

INTRODUCTION

Can psychology be a unified science, or must it remain fragmented and subject to transient research interests rather than cumulative development? Is psychology teachable or must psychology textbooks remain encyclopedias of often unrelated findings? In this article, we examine research on attention to suggest ways of looking at psychological questions and findings that might lead to hopeful answers to these questions. We offer a model based on Hebbian psychology that reaches out from biological roots to tackle questions of emotion and thought as well as behavior. We, with many of our colleagues, see different levels of analysis in psychology as informing each other, with each level of equal scientific validity. Bridging these levels can allow a higher level of understanding and prediction.

Attention: the regulating of various brain networks by attentional networks involved in maintaining the alert state, orienting, or regulation of conflict

Neural networks: a number of brain areas that when orchestrated carry out a psychological function

We argue that D.O. Hebb (see **Figure 1**), beginning with his monograph in 1949 and continuing through a series of introductory textbooks (1958, 1966), has convincingly presented the basis for such integration. This integration lies in understanding how genes and experience shape neural networks underlying human thoughts, feelings, and actions.

At the time Hebb wrote his monograph, relatively little was known about how the structure and organization of the central nervous system contribute to the functions observed in psychological studies. This led Hebb to talk in terms of the conceptual nervous system, that is, ideas about its structure that might be imagined or inferred from psychological studies. We suggest that the methods available to Hebb, mostly animal research and behavioral human experiments, were not sufficient to provide empirical methods for linking his conceptual nervous system to real events in the human brain. This methodology has now been provided by neuroimaging. Although Hebb also recognized the importance of studying individual differences in intelligence and affect, at that time there were no methods for exploring the specific genes that are an important source of these differences. The human genome project has provided new methods for exploring this issue.

In Hebb's time, the idea of a network (cell assembly or phase sequence) was a rather vague verbal abstraction that did not allow for models that could produce specific predictions. As a result of the rapid changes in cellular biology (Bullock et al. 2005) and in the mathematics of multilevel networks, this too has changed (Rumelhart & McClelland 1986). Although early versions of these networks were inspired by simple versions of neurons as all-or-none elements, more recent versions (O'Reilly & Munakata 2000) have begun to use the details of neuroanatomy and cellular structure as provided by imaging and cellular studies to develop networks that take more realistic advantage of the structure of the human brain. Hebb's basic idea, together with the new methodological tools and new disciplines (e.g., cognitive, affective, and social neuroscience), all based on network views, give abundant evidence of the value of employing the converging operations strategy advocated by Sternberg (Sternberg 2004).

It is important to recognize the need for integrating cognitive, affective, and social neuroscience with psychology because many of

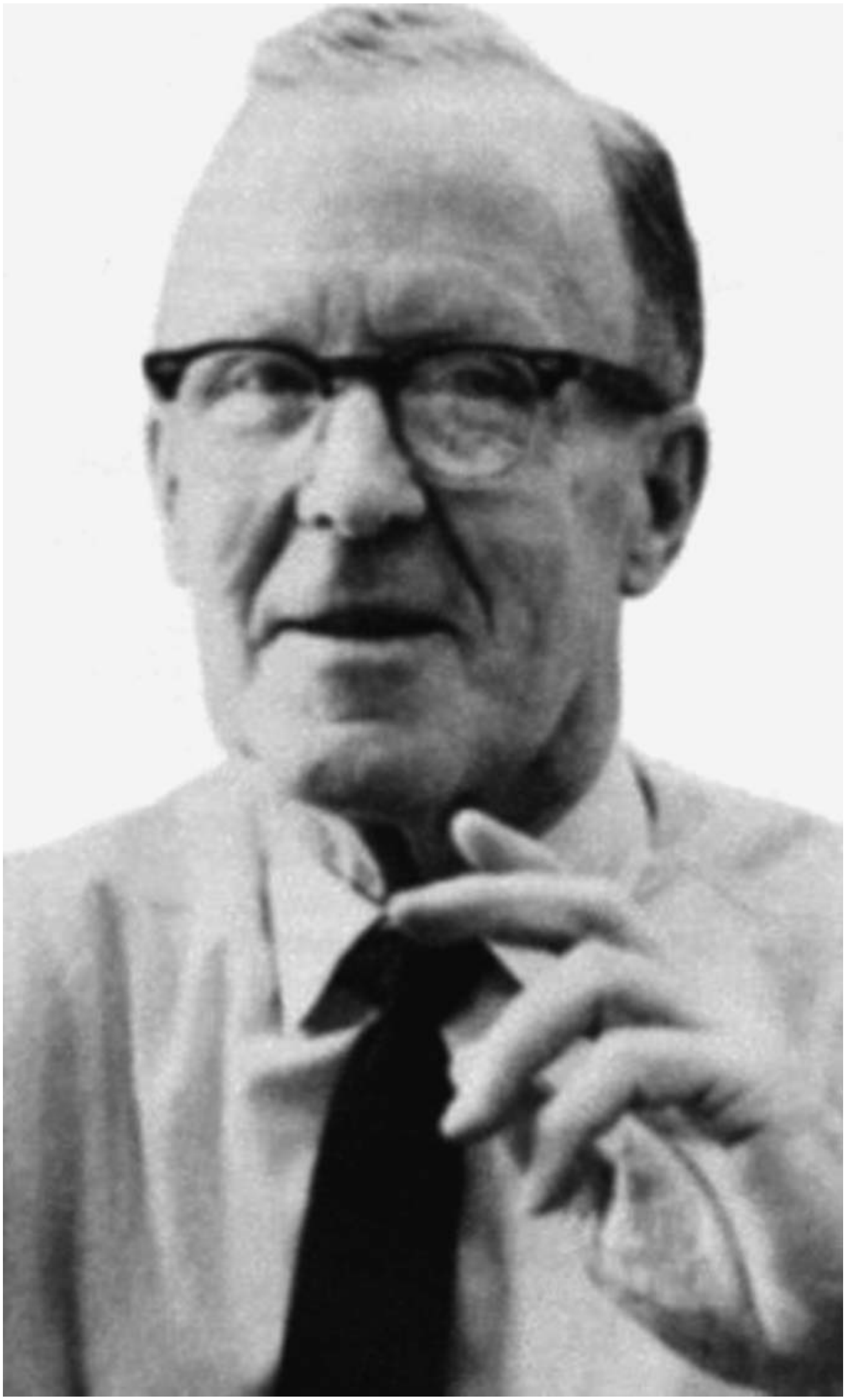


Figure 1

Photograph of Professor Donald O. Hebb.

the theoretical questions that need to be addressed by neuroimaging and genetic studies are exactly those that a century of psychologists have explored. The neuroscience approach provides crucial constraints for psychological theories, but it also benefits when a closer connection is made with the psychological level of analysis.

HEBB'S NETWORK APPROACH

In 1949, D.O. Hebb published his epic work, *The Organization of Behavior*. His book was immediately recognized as providing the potential for an integrated psychology. One reviewer (Attneave 1950, p. 633) wrote:

> I believe *The Organization of Behavior* to be the most important contribution to psychological theory in recent years. Unlike those of his contemporaries who are less interested in psychology than in some restricted aspect thereof to which their principles confine them, Hebb has made a noteworthy attempt to take the experimentally determined facts of behavior, as they are, and account for them in terms of events within the central nervous system.

The most important basic idea that Hebb presented was the cell assembly theory outlined in chapters 4 and 5 of his book (Goddard 1980, Harris 2005). Hebb argued that every psychological event, sensation, expectation, emotion, or thought is represented by the flow of activity in a set of interconnected neurons. Learning occurs by a change in synaptic strength when a synapse conducts excitation at the same time the postsynaptic neuron discharges. This provided a basis for the modification of synapses and showed how neural networks might be organized under the influence of specific experiences. The Hebb synapse plays a central role in modern neuroscience (see Kolb 2003, Milner 2003, Sejnowski 2003). There are important new developments in the study of synapses and in the discovery of other influences among neurons and between neurons and other brain cells (Bullock et al. 2005). These developments have reduced the gap between networks revealed in imaging studies and the complex intracellular activity that underlies them. In particular, they show that learning may reflect the activity of interactions at many time scales and may be modified by aspects of the organism's overall state.

Hebb also introduced the concept of the phase sequence involved in the coordination of multiple cell assemblies. He recognized the importance of the temporal correspondence between assemblies. In recent years these ideas have been supported by studies showing that synchronization of brain areas may be critical to detecting stimuli (Womelsdorf et al. 2006) and for transfer of information between remote areas (Nikolaev et al. 2001). In later years, Hebb (1958) developed an introductory psychology textbook that integrated much of psychology using the framework provided by his 1949 theory. He applied his network theory to heredity, learning and memory, motivation, perception, thought, and development. In later editions, he extended his approach to emotions in their social contexts, individual differences in intelligence, and abnormal psychology.

Despite his efforts and those of his followers at McGill and elsewhere, Hebb's work was unsuccessful in providing a fully integrative psychology, and many still seek to develop such an integration (Sternberg 2004, Sternberg & Grigorenko 2001). One of the major problems with Hebb's framework was that it left no clear empirical path for the acquisition of new knowledge about how human brain networks develop, how they differ among individuals, why they break down, and how they can be restored to functioning. Most of the research by Hebb and his associates was performed on nonhuman animals, while most of psychology concerns human behavior, brain, and mind.

In 1955, Hebb argued for the utility of a conceptual nervous system inferred from psychological studies of motivation. This idea remains of key importance. Despite our growing understanding of the function and structure of the nervous system, psychological knowledge needs to be used to propose hypotheses about how the central nervous system (CNS) works to support feelings, thoughts, and behaviors. We argue that only within an integrated field of psychology can knowledge at all levels be used to develop and constrain these hypotheses.

New Tools

Several major late-twentieth century events give improved prospects for an integration of psychological science around the ideas introduced by Hebb. Cell assemblies and phase sequences are names for aspects of neural networks. Now, thanks to work on the computational properties of neural networks (i.e., Rumelhart & McClelland 1986), we are in a much better position to develop detailed theories integrating information from physiological, cognitive, and behavioral studies.

In addition, new neuroimaging methods now allow us to examine neuronal activity in terms of localized changes in blood flow or metabolism in positron emission tomography (PET) or changes in blood oxygenation by functional magnetic resonance imaging (fMRI). By using tracers that bind to different transmitters, PET can also be used to examine transmitter density. By measuring electrical (electroencephalogram, or EEG) and magnetic (magnetoencephalogram) signals outside the skull, the time course of activation of different brain areas localized by fMRI can be measured (Dale et al. 2000). Pathways of activation can also be imaged by use of diffusion tensor imaging, a form of MRI that traces white matter tracts. In addition to the study of naturally occurring lesions, interrupting information flow by transcranial magnetic stimulation (TMS) can produce temporary functional lesions of pathways (see Toga & Mazziotta 1996 for a review of these and other methods). These methods provide a toolkit that can be used either alone or together to make human brain networks accessible for detailed physiological study.

Some have thought that the influence of imaging has been merely to tell us where in the brain things have happened (Utall 2001). Certainly many, perhaps even most, imaging studies have been concerned with anatomical issues. As **Figure 2** illustrates, several functions of attention have been shown to involve specific anatomical areas that carry out important functions. However, imaging also probes neural networks that underlie all aspects of human thought, feelings, and behavior. The full significance of imaging for (*a*) viewing brain networks, (*b*) examining their computation in real time, (*c*) exploring how they are assembled in development, and (*d*) their plasticity following physical damage or training is a common theme in current research that is just beginning to reach its potential.

A third development, the mapping of the human genome (Venter et al. 2001), offers the potential for an increased understanding of the physical basis for individual differences, including individual differences in temperament and personality. Many genes exhibit a number of relatively high-frequency variants (polymorphisms) that can code for different physical configurations. These in turn can alter the efficiency of a network. For example, different types of genes (alleles) forming dopamine receptors can lead to different efficiency in binding to dopamine and thus differences in underlying neural networks. In a number of cases, it has been possible to relate these genetic differences to individual performance in tasks involving the network (see Fossella & Posner 2004 for a review). Genetics-based research also provides an important approach to the development of characteristics of neural networks common to all members of the species.

We recognize that not all topics of psychology have been sufficiently explored to illustrate this framework and that limitations in our knowledge prevent us from exploring all of the areas where these developments can be applied. However, attention and

PET: positron emission tomography

fMRI: functional magnetic resonance imaging

Temperament: relatively enduring biological characteristics of individuals that include both reactive and self-regulatory (attentional) aspects

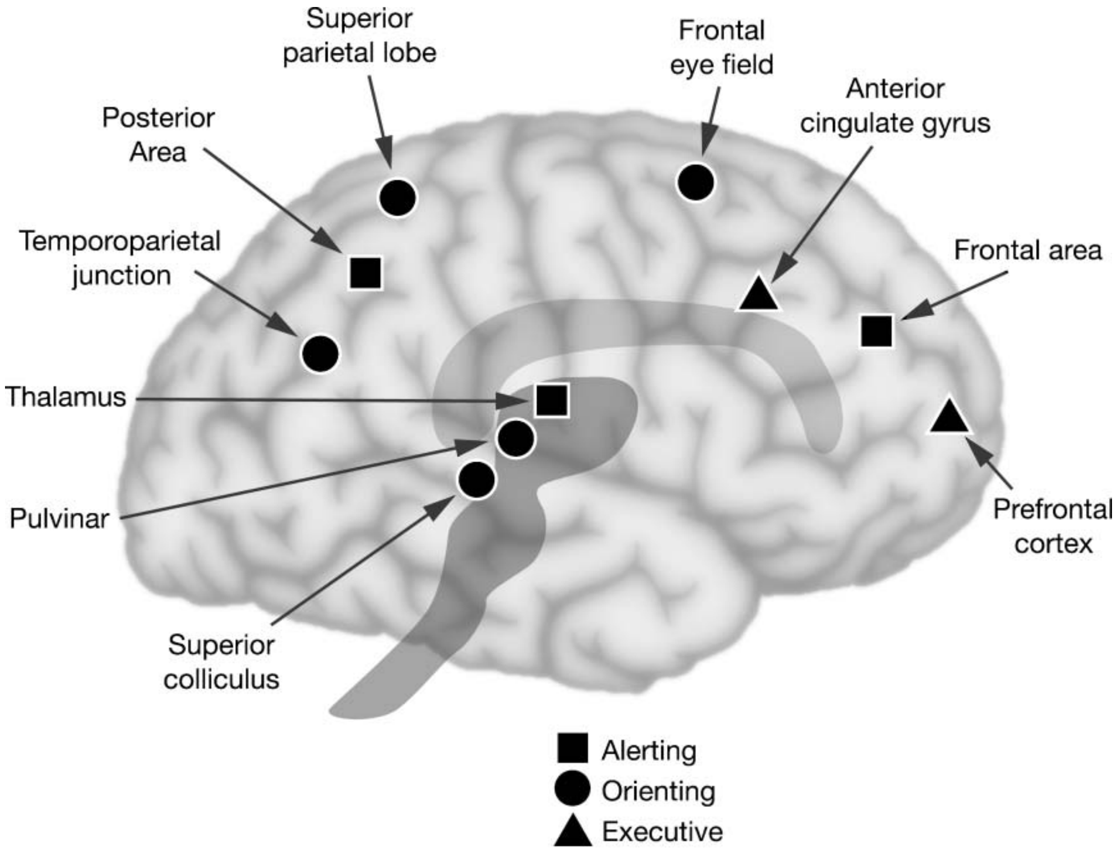


Figure 2

Anatomy of three attentional networks: alerting, orienting, and executive attention (from Posner & Rothbart 2007).

temperament, areas of our study, can be used to consider how a large number of psychological questions can be explored using the neural network framework outlined by Hebb. Attention serves as a basic set of mechanisms that underlie our awareness of the world and the voluntary regulation of our thoughts and feelings. The methods used to understand attentional networks in terms of anatomy, individual differences, development, and plasticity can be applied readily to explore networks related to other aspects of human behavior.

Any approach based on neural networks raises the issue of crude reductionism. Many agree that all human behavior must ultimately be traceable to brain activity, but correctly argue for the importance of cognitive experiments, behavioral observations, and self-report as important elements of psychological science. We hope to illustrate in this article how important such psychological methods are and how they can be integrated within a brain network framework, as Hebb (1955) illustrated in his *Textbook of Psychology*.

IMAGING ATTENTION NETWORKS

Functional neuroimaging has allowed many cognitive tasks to be analyzed in terms of the brain areas they activate, and studies of attention have been among those most often examined (Corbetta & Shulman 2002, Driver et al. 2004, Posner & Fan 2007). Imaging data have supported the presence of three networks related to different aspects of attention (Fan et al. 2005). These networks carry out the functions of alerting, orienting, and executive attention (Posner & Fan 2007). A summary of the anatomy and chemical modulators involved in the three networks is shown in **Table 1**.

Table 1 A summary of the anatomy and chemical modulators involved in the alerting, orienting, and executive attention networks.

Function	Structures	Modulator
Orient	Superior parietal Temporal parietal junction Frontal eye fields Superior colliculus	Acetylcholine
Alert	Locus coeruleus Right frontal Parietal cortex	Norepinephrine
Executive attention	Anterior cingulate Lateral ventral Prefrontal Basal ganglia	Dopamine

Alerting is defined as achieving and maintaining a state of high sensitivity to incoming stimuli; orienting is the selection of information from sensory input; and executive attention involves mechanisms for monitoring and resolving conflict among thoughts, feelings, and responses. The alerting system has been associated with thalamic as well as frontal and parietal regions of the cortex (Fan et al. 2005). A particularly effective way to vary alertness has been to use warning signals prior to targets. The influence of warning signals on the level of alertness is thought to be due to modulation of neural activity by the neurotransmitter norepinephrine (Marrocco & Davidson 1998).

Orienting involves aligning attention with a source of sensory signals. This may be overt, as when eye movements accompany movements of attention, or may occur covertly, without any eye movement. The orienting system for visual events has been associated with posterior brain areas, including the superior parietal lobe and temporal parietal junction, and in addition, the frontal eye fields (Corbetta & Shulman 2002). Orienting can be manipulated by presenting a cue indicating where in space a target is likely to occur, thereby directing attention to the cued location (Posner 1980). It is possible to determine the anatomy influenced by the cue separately from that influenced by the target by using MRI to trace changes in the blood that specifically follow the cue. This method is called event-related functional magnetic resonance imaging, and its use has suggested that the superior parietal lobe is associated with orienting following the presentation of a cue (Corbetta & Shulman 2002). The superior parietal lobe in humans is closely related to the lateral intraparietal area (LIP) in monkeys, which is involved in the production of eye movements (Andersen 1989). When a target occurs at an uncued location and attention has to be disengaged and moved to a new location, there is activity in the temporal parietal junction (Corbetta & Shulman 2002). Lesions of the temporal parietal junction lobe and superior temporal lobe have been consistently related to difficulties in orienting (Karnath et al. 2001).

Orienting: the interaction of a brain network with sensory systems designed to improve the selected signal

Executive control of attention is often studied by tasks that involve conflict, such as various versions of the Stroop task. In the Stroop task, subjects must respond to the color of ink (e.g., red) while ignoring the color word name (e.g., blue) (Bush et al. 2000). Resolving conflict in the Stroop task activates midline frontal areas (anterior cingulate) and lateral prefrontal cortex (Botvinick et al. 2001, Fan et al. 2005). There is also evidence for the activation of this network in tasks involving conflict between a central target and surrounding flankers that may be congruent or incongruent with the target (Botvinick et al. 2001, Fan et al. 2005).

Recently, the role of the anterior cingulate in modulating sensory input has been demonstrated experimentally by showing enhanced connectivity between the anterior cingulate cortex and the sensory modality to which the

ANT: attention network test

RT: reaction time

ACT-R: adaptive control of thought-rational

person is asked to attend (Crottaz-Herbette & Menon 2006). This finding supports the general idea that anterior cingulate cortex activity regulates other brain areas, at least for sensory areas. Experimental tasks may also provide a means of fractionating the contributions of different areas within the executive attention network (MacDonald et al. 2000). In accord with the findings in recent neuroimaging studies (Beauregard et al. 2001, Ochsner et al. 2001), we have argued that the executive attention network is involved in self-regulation of positive and negative affect as well as a wide variety of cognitive tasks underlying intelligence (Duncan et al. 2000). This idea suggests an important role for attention in moderating the activity of sensory, cognitive, and emotional systems.

Simulating Attention Networks

Quantification has had a high value in psychological research. An advantage of the network approach is that it lends itself to the development of precise computer models that allow both summarization of many findings in the field and prediction of new findings. Currently, symbolic models, such as rule-based systems (Newell 1990), appear to be a good way to capture data from reaction time and other psychological findings. In these models, cognitive functions are represented as chains of production rules and can be identified with the mental operations postulated by cognitive studies. On the other hand, subsymbolic models, such as connectionist models (e.g., O'Reilly & Munakata 2000), permit a more biologically realistic implementation of the operations and closer links to imaging studies.

We have developed the attention network test (ANT) to examine individual differences in the efficiency of the brain networks of alerting, orienting, and executive attention discussed above (Fan et al. 2002, Rueda et al. 2004). The ANT uses differences in reaction time (RT) between conditions to measure the efficiency of each network. Each trial begins with a cue (or a blank interval, in the no-cue condition) that informs the participant either that a target will occur soon or where it will occur, or both. The target always occurs either above or below fixation, and consists of a central arrow, surrounded by flanking arrows that can point either in the same direction (congruent) or in the opposite direction (incongruent). Subtracting RTs for congruent from incongruent target trials provides a measure of conflict resolution and assesses the efficiency of the executive attention network. Subtracting RTs obtained in the double-cue condition that provides information on when but not where the target will occur from RTs in the no-cue condition gives a measure of alerting due to the presence of a warning signal. Subtracting RTs to targets at the cued location (spatial cue condition) from trials using a central cue gives a measure of orienting, since the spatial cue, but not the central cue, provides valid information about where a target will occur.

The attention network task has now been simulated in the framework of the adaptive control of thought-rational (ACT-R) theory (Wang et al. 2004). The ANT task is divided into subroutines. Cue processing involves switching of attention to the cued location. Target processing involves detection of the direction of the arrow in the center and involves an attention switch and response initiation. Each of these operations is implemented by a chain of production rules. The operations are similar to those discussed in most psychological studies and localized in neurological studies. For example, the switching of attention based on the peripheral cue or target is thought to be implemented by the temporal parietal junction (Corbetta & Shulman 2002).

A connectionist simulation of the ANT (H. Wang & J. Fan, manuscript in preparation) is based upon a local error-driven and associative, biologically realistic algorithm (LEABRA) (O'Reilly & Munakata 2000). The subroutines of ACT-R are now replaced by specific connections between hypothesized neurons. These neurons are somewhat realistic, and are designed to represent the known properties of specific brain areas. Thus, the orienting network can be designed to reflect the known properties of the frontal eye fields, superior parietal lobe, and temporal parietal junction, and they can be connected within the simulation. As shown in **Figure 3**, simulations do a reasonable job of fitting with the known ANT data, although improvement can be expected in the future. The symbolic model makes contact with the mental operations related to imaging, whereas the connectionist framework allows a strong treatment of the underlying biology. Together they illustrate how network views provide a computational means for summarizing many findings within psychology, allowing novel predictions reflecting properties of the network.

INDIVIDUAL EFFICIENCY

Psychology is often divided into two approaches that are almost completely separate in the literature (but see Gardner 1983 for an effort at integration). The discussion above focused on general features of the human mind, such as the ability to attend. Another approach deals with differences among individuals. These differences may involve cognition, as in the measurement of intelligence, or they may involve temperamental differences, many of which relate to energetic factors such as the expression and control of the emotions. Almost all studies of attention have been concerned either with the general abilities involved or with effects of brain injury or pathology on attention. However, it is clear that normal individuals differ in their ability to attend to sensory events, and it is even clearer that they differ in their ability to concentrate for long periods on internal trains of thought.

We used the attention network task to examine the individual efficiency of the alerting, orienting, and executive networks (Fan et al. 2002). In a sample of 40 normal persons, each of these scores was reliable over repeated presentations. In addition, we found no correlation among the orienting, alerting, and executive scores.

The ability to measure differences in attention among adults raises the question of the degree to which attention is heritable. To explore this issue, the ANT was used to assess attention in monozygotic and dizygotic same-sex twins (Fan et al. 2001). Strong heritability was found for the executive network, some heritability for the orienting network, and no apparent heritability for the alerting network. These data support a search for genes in executive attention and in orienting of attention.

Candidate genes: genes that may be involved in the development of utilization of attentional networks

We then used the association of the executive network with the neuromodulator dopamine (see **Table 1**) as a way of searching for candidate genes that might relate to the efficiency of the networks (Fossella et al. 2002). To do this, 200 persons performed the ANT and were genotyped to examine frequent polymorphisms in genes related to dopamine. We found significant association of the dopamine 4 receptor and monoamine oxidase A genes. We then conducted a neuroimaging experiment in which persons with different alleles of these two genes were compared while they performed the ANT (Fan et al. 2003). Groups with different alleles of these genes showed differences in performance on the ANT and also produced significantly different activations in the anterior cingulate, a major node of the executive attention network.

Recent studies have confirmed and extended these observations to other dopamine genes and to the orienting network. In two different studies employing other conflict tasks, the catecholamine-O-methyltransferase gene was linked to the mental operations related to resolving conflict (Blasi et al. 2005, Diamond et al. 2004). Different alleles of cholinergic genes were also related to performance on orienting tasks such as visual search (Parasuraman et al. 2005), thus confirming the link between orienting and the neuromodulator acetylcholine (see **Table 1**).

Hebb (1955) thought that most of the networks involved in higher functions were shaped primarily through experience. We now know that there is a great deal in common

	ALERT	ORIENT	CONFLICT
EXPERIMENTAL RESULTS	47	51	84
ACT-R SIMULATION	55	45	86
LEABRA SIMULATION	70	33	67

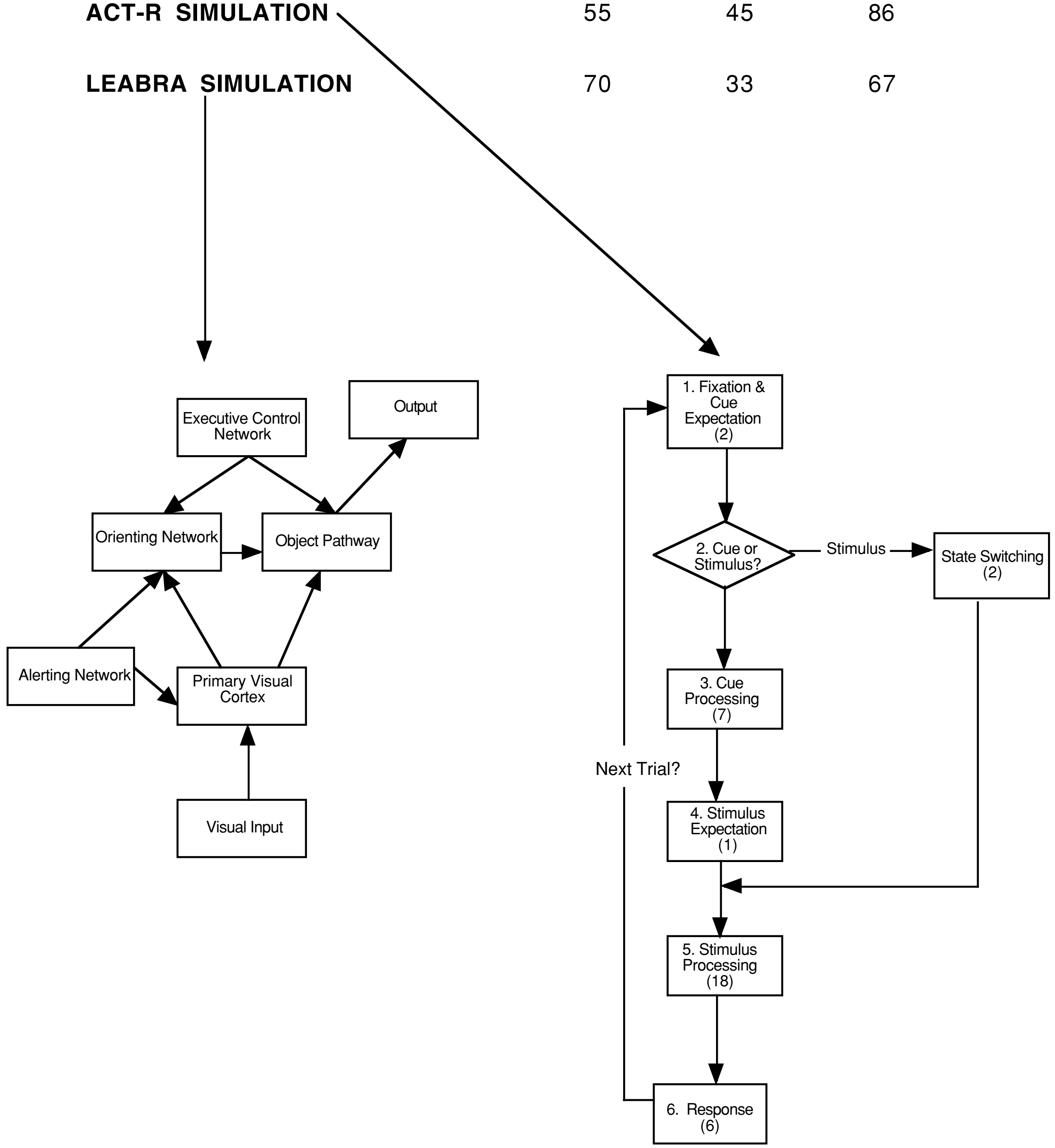


Figure 3

Experimental results compared with simulations of attention networks from ACT-R (Wang et al. 2004) and from a connectionist model (H. Wang & J. Fan, manuscript in preparation). The network scores are in milliseconds.

among humans in the anatomy of these high-level networks, and thus that they must have a basis within the human genome. It seems likely that the same genes that are related to individual differences in attention are also important in the development of the attentional networks that are common among people. Some of these networks are also common to nonhuman animals. By examining these networks in animals, it should be possible to test these assumptions further and to understand the role of genes in shaping networks.

Of importance for this effort is the development of methods to manipulate relevant genes in specific anatomical locations that are important nodes of a particular network. Usually genes are expressed at multiple locations so that changes (e.g., gene knockouts) are not specific to one location. However, using subtractive genomics, a method is currently being developed to do this (Dumas et al. 2005). We believe that this kind of genetic analysis of network development will become a very productive link between genes and both normal and pathological psychological function.

NETWORK DEVELOPMENT

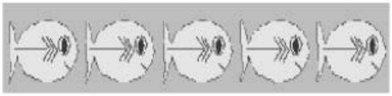
Every parent of more than one child recognizes that from birth, infants are individuals with their own distinct characteristics and dispositions. These include reactive traits such as emotionality, activity level, and orienting to sensory events, and regulatory traits like attention focusing and shifting and inhibitory control. We believe that these early developing temperamental differences reflect the maturation of particular neural networks. We have studied individual differences in attention and related these differences to emotional and behavioral control (Rothbart & Rueda 2005, Ruff & Rothbart 1996).

A major advantage of viewing attention as an organ system is to trace the ability of children and adults to regulate their thoughts and feelings. Over the early years of life, the regulation of emotion is a major issue of development. The ability of attention to control distress can be traced to early infancy (Harman et al. 1997). Early in life, most regulation depends on the caregiver providing ways to control infant reactions. In our study, we first induced a mild level of distress, and then showed how attentional orienting calms that distress while the infant remains engaged with the object. When the orienting is broken, distress returns to the level present prior to the introduction of the object. It is likely that the distress remains present and is held by networks in the amygdala. Parents often use manipulation of the infant's orienting to control distress, and the infant also exhibits coping behaviors involving orienting to form the basis for one aspect of early self-regulation (Rothbart et al. 1992).

Developmental changes in executive attention found during the third year of life are correlated with parent reports of temperamental effortful control (Gerardi-Caulton 2000). Effortful control is a broad variable identified in temperament research; it includes the ability to inhibit a dominant response in order to produce subdominant response and to detect and correct errors (Rothbart & Rueda 2005). Because children of this age do not read, the location and identity rather than the word meaning and ink color served as the dimensions in a spatial conflict task. In one study (Gerardi-Caulton 2000), children sat in front of two response keys, one located to the child's left and one to the right. Each key displayed a picture, and on every trial, a picture identical to one of the pair appeared on either the left or right side of the screen. Children were rewarded for responding to the identity of the stimulus, regardless of its spatial compatibility with the matching response key. Reduced accuracy and slowed reaction times for spatially incompatible trials relative to spatially compatible trials reflected the effort required to resist the dominant response and to resolve conflict between these two competing dimensions. Performance on this task produces a clear interference effect in adults and activates the anterior cingulate (Fan et al. 2003). Children 24 months of age tended to perseverate on a

Table 2

Flanker task for children: Behavioral results



Congruent

Incongruent

Age	Overall RT	Overall %errors	Conflict effect RT (ms)	Conflict effect %errors
4.4	1443	6.8	273	8.9
6	930	13	95	15.6
7	835	5.6	70	0.5
8	811	4.8	70	-0.2
9	740	2.4	67	1.6
10	643	2.2	72	2.1
adults	492	1.2	63	1.6

single response, whereas 36-month-old children performed at high accuracy levels, but like adults, responded more slowly and with reduced accuracy to incompatible trials.

We have traced the development of executive attention into the preschool and primary school periods (Rueda et al. 2004) by using a version of the ANT adapted for children (**Table 2**). In some respects, results were remarkably similar to those found for adults using the adult version of the task. Reaction times for the children were much longer, but they showed similar independence among the three networks. Children had much larger scores for conflict and alerting, suggesting that they have trouble in resolving conflict and in maintaining the alert state when not warned of the new target. Rather surprisingly, the ability to resolve conflict in the flanker task, as measured by the ANT, remains about the same from age eight to adulthood (see **Table 2**).

There is considerable evidence that the executive attention network is of great importance in the acquisition of school subjects such as literacy (McCandliss et al. 2003) and in a wide variety of other subjects that draw upon general intelligence (Duncan et al. 2000). It has been widely believed by psychologists that training involves only specific domains, and that more general training of the mind, for example, by formal disciplines like mathematics or Latin, does not generalize beyond the specific domain trained (Thorndike 1903, Simon 1969). However, attention may be an exception to this idea. Attention involves specific brain mechanisms, as we have seen, but its function is to influence the operation of other brain networks (Posner & Rothbart 2007). Anatomically, the network involving resolution of conflict overlaps with brain areas related to general intelligence (Duncan et al. 2000). Training of attention either explicitly or implicitly is sometimes a part of the school curriculum (Posner & Rothbart 2007), but additional studies are needed to determine exactly how and when attention training can best be accomplished and its long-lasting importance.

Socialization and Culture

Cognitive measures of conflict resolution have been linked to aspects of children's self-control in naturalistic settings. Children who are relatively less affected by spatial conflict also received higher parental ratings of temperamental effortful control and higher scores on laboratory measures of inhibitory control (Gerardi-Caulton 2000). Questionnaires have shown that the effortful control factor, defined in terms of scales measuring attentional focusing, inhibitory control, low intensity pleasure, and perceptual sensitivity (Rothbart & Rueda 2005), is inversely related to negative affect. This is in keeping with the notion that attentional skill may help attenuate negative affect while also serving to constrain impulsive approach tendencies.

Empathy is strongly related to effortful control, with children high in effortful control showing greater empathy (Rothbart et al. 1994). To display empathy toward others requires that we interpret their signals of distress or pleasure. Imaging work shows that sad faces activate the amygdala. As sadness increases, this activation is accompanied by activity in the anterior cingulate as part of the attention network (Blair et al. 1999). It seems likely that the cingulate activity represents the basis for our attention to the distress of others.

Developmental studies find two routes to successful socialization. A strongly reactive amygdala would provide the signals of distress that would easily allow empathic feelings toward others and a hesitancy to perform behaviors that might cause harm related to fear. These children are relatively easy to socialize. In the absence of this form of control, development of the cingulate would allow appropriate attention to the signals provided by amygdala activity. Consistent with its influence on empathy, effortful control also appears to play a role in the development of conscience. The internalization of moral principles appears to be facilitated in fearful preschool-aged children, especially when their mothers use gentle discipline (Kochanska 1995). In addition, internalized conscience is facilitated for children high in effortful control (Kochanska et al. 1996). Two separable control systems, one reactive (fear) and one self-regulative (effortful control), appear to regulate the development of conscience.

Individual differences in effortful control are also related to some aspects of metacognitive knowledge, such as theory of mind, which is the knowledge that people's behavior is guided by their beliefs, desires, and other mental states (Carlson & Moses 2001). Tasks that require the inhibition of a prepotent response are related to theory of mind tasks even when other factors, such as age, intelligence, and working memory, are factored out (Carlson & Moses 2001). The mechanisms of self-regulation and of theory of mind share a similar developmental time course, with advances in both areas between the ages of 2 and 5.

Efforts to determine the neural network involved in theory of mind tasks reveal some of the reasons for the common developmental time course in self-regulation. Theory of mind tasks activate a network that includes areas of the anterior cingulate that are also involved in self-regulation, as well as temporal lobe areas (Gallagher & Frith 2003). These anatomical links provide further support for efforts to integrate psychological topics at a network level.

Emotion, thought, and behavior form a cluster of temporally associated processes in specific situations as experienced by the child. Single and repeated life experiences can thus shape connections between elicited emotion, conceptual understanding of events, and use of coping strategies to deal with these events. Several theorists have made contributions to this approach (e.g., Epstein 1998, Mischel & Ayduk 2004), but the overall framework is in keeping with the idea of Hebbian learning through network activation. Mischel and his colleagues have recently developed a cognitive affective personality theory, making use of cognitive affective units (CAUs) seen to operate within a connectionist network (Mischel & Ayduk 2004). In their model, CAUs are variables encoding the features of situations, which include environmental features as well as self-initiated thoughts.

When they are repeatedly exercised, temporally linked clusters of thoughts, emotions, and action tendencies to a particular situation can become highly likely to reoccur and difficult to change. Some of the processes may be conscious and others unconscious; in most cases, the thoughts about affectively significant material will be self-referent. Research on the distinction between conscious and unconscious processes has shown that special networks are active only when items are conscious (Dehaene et al. 2003). Studies of self-reference have also suggested activation of specific networks of neural areas (Gusnard et al. 2001).

In applying this approach to the control of distress, one basic question is how to weaken the mental connection between the situation and its component reactions. In the eastern tradition, this is done partly through meditation, when ideas can be brought up in a context of calmness and safety, and partly through changing the view of the self so that situations will become less threatening. Links between thoughts and emotions or action tendencies are also weakened. Western therapy similarly works through the client's patterns of reaction, attempting to rework previously consolidated patterns and to provide new frameworks for meaning. From a developmental view, one would attempt to give the child the kinds of experiences that will form favorable and non-injurious mental habits.

Clusters of reactions are found within the young child's temperament. Later clusters of thought, emotion, and behavior will also be based on individual differences in personality, including emotions, expectancies, beliefs, values, goals, self-evaluations, appraisals, and thoughts about the situation, self, and/or others. These clusters will be influenced by temperamental predispositions, but they will also be influenced by socialization and experience. Coping and the application of effortful control operate when "the subjective meaning of the situation, including its self-relevance and personal importance, are appraised. The appraisal itself activates a cascade of other cognitive-affective representations within the system—expectations and beliefs, affective reactions, values and goals" (Mischel & Ayduk 2004, p. 105).

Different coping strategies follow and may be consolidated or rejected in the future, depending in part on their consequences. To develop this idea, Mischel & Ayduk (2004) give the example of individual differences in rejection sensitivity. When persons are particularly prepared to perceive rejection from others, attention is likely to be narrowly focused on this possibility, and it has been demonstrated that rejection by a social group can influence areas of the anterior cingulate related to executive attention and pain (Eisenberger et al. 2003). Defensive behaviors such as anger or preventative rejection of the other may serve to fend off feelings of rejection. These strategies in turn can also provide further support for the idea that the self is unworthy of positive social relationships. Different levels of generality of these clusters are possible. Rejection sensitivity, for example, might extend to a wide range of human relationships, but the sensitivity may also be more specific, so that only rejection by the child's peers, but not by adults, is sensitized. The reaction may in fact be limited to a single person in a single kind of situation, in which case a particular person, but not other persons, elicits rejection sensitivity.

Socialization in western cultures strongly emphasizes the individual, promoting the pursuit of individual security, satisfaction of individual desires, and achievement of a positive self-concept. In other cultures, the shaping of the child's experienced world can be quite different. Mascolo et al. (2003) suggest, for example, that the biological systems on which pride and shame are based are the same across cultures, yet can be shaped in quite different directions. In the United States, pride reactions develop as parents and others praise the child's accomplishments; shame reactions occur when there is self-referent failure. In China, however, parents downplay or criticize children's performance while other adults praise it, leading to more moderate prideful affect. Shame, on the other hand, is directly encouraged by parents and others when children do not fulfill their obligations to family.

The biological equipment or temperament is thus similar across cultures, but the mental habits and representation of self created as a result of the child's actions varies from culture to culture (Ahadi et al. 1993). By the time a child is a well-socialized member of the society, biologically based responses will have been shaped into a set of values, goals, and representations of the self and others. These representations specify what is good and bad for the person. Even for the child who is not well socialized, cultural socialization may have an effect. In the United States, for example, a child may pursue a positive view of the self even when achievements result from following goals and values that are not socially acceptable.

PATHOLOGY OF ATTENTION NETWORKS

Much of modern psychology is involved in the diagnosis and treatment of mental illness or disturbance, and the network framework may be an ideal one for incorporating ideas related to clinical remediation. An excellent example of this approach has been in the recent studies of Mayberg (2003) on clinical interventions for depression based upon a neural network model. Treatments involved drugs or cognitive behavioral therapy and both forms of therapy were about equally effective, based on the percentage of persons showing improvement. Imaging data, however, indicated that the two therapies involved very different brain networks. The drugs remediated a largely subcortical network of brain areas that might be difficult to control voluntarily. The cognitive-behavioral therapy affected cortical networks, including areas involved in attention that would be more easily subject to voluntary control. These findings show how important network approaches are likely to be in evaluating the outcome of clinical trials.

A similar story may emerge in the study of dyslexia. Many forms of dyslexia involve a difficulty in phonological processing that can be remediated by an intervention targeting the ability to convert visual letters to sound (McCandliss et al. 2003). Following remediation, there is normal activation of a brain region at the boundary between the temporal and parietal lobes related to phonology. However, although these students can now decode words, they do not show fluent reading. This may require development of the visual word form system, which involves an extrastriate visual region (fusiform gyrus) quite distinct from the phonological areas (McCandliss et al. 2003). It is likely that time spent reading is one way to develop

Table 3 Disorders that have been related to attentional networks (from Rothbart & Posner 2006)

Alerting	
	Normal aging
	Attention deficit disorder
Orienting	
	Autism
Executive control	
	Alzheimer's
	Borderline personality disorder
	Schizophrenia
	22Q11 deletion syndrome

this brain area, but it may also be possible to create special training exercises that target the area, as has been done for phonological intervention.

The possibility that aspects of brain networks involved in depression and dyslexia might be remediated by therapies based on training illustrates the close connection between therapeutic interventions designed to correct deficits and education designed to improve the performance of people in general. From the perspective of improving neural networks through specific training, therapy and education can represent similar approaches to improving network efficiency.

The ANT has been applied to a number of forms of pathology in adults, the aging, adolescents, and children. **Table 3** presents classification of a number of disorders that have been related to specific nodes of attentional network; a review by Rothbart & Posner (2006) provides a fuller account.

Plasticity

Executive attention as measured by the ANT and other conflict-related tasks provides a basis for the ability of children to regulate their behavior through the use of effortful control. Executive attention has a well-defined neuroanatomy, and much is known about the role of genes in modulating its efficiency. Difficulties in effortful control provide the basis for problems in child socialization and in a number of disorders of children and adults (Rothbart & Bates 2006). Executive attention represents a neurodevelopmental process in children and adolescents, the alteration of which could affect the propensity for the development of a number of disorders.

It is thus important to link efforts at remediation to the training of underlying brain networks. A central aspect of the executive attention network is the ability to deal with conflict. We used this feature to design a set of exercises for children adapted from efforts to train monkeys to perform tasks during space missions (Rumbaugh & Washburn 1995), which resulted in training monkeys to resolve conflict in a Stroop-like task (Washburn 1994).

Our exercises began by training the child to control the movement of a cat on a computer screen by using a joystick and to predict where an object would move on the screen, given its initial trajectory. Other exercises emphasized the use of working memory to retain information for a matching-to-sample task and the resolution of conflict.

We have tested the efficacy of a very brief five days of attention training with groups of 4- and 6-year-old children (Rueda et al. 2005). The children were brought to the laboratory for seven days for sessions lasting approximately 40 minutes, conducted over a two- to three-week period. The first and last days involved assessment of the effects of training by use of the ANT, a general test of intelligence (the K-BIT; Kaufman & Kaufman 1990), and a temperament scale (the Children's Behavior Questionnaire or CBQ; Rothbart et al. 2001). During administration of the ANT, we recorded 128 channels of EEG to observe the amplitude and time course of activation of brain areas associated with executive attention in adult studies (Rueda et al. 2005).

Five days is of course a minimal amount of training to influence the development of networks that develop over many years. Nonetheless, we found a general improvement in intelligence in the experimental group as measured by the K-BIT. This was due to improvement of the experimental group in performance on the nonverbal portion of the IQ test. Our analysis of the brain networks using EEG recording further suggested that the component most closely related to the anterior cingulate in prior adult studies changed significantly in the trained children to more closely resemble what is found in adults (Rueda et al. 2005).

We also found evidence that prior to training, performance on the ANT, as well as activity of the underlying network, appeared to be related to differences in at least one dopamine gene (Rueda et al. 2005). As the number of children who undergo our training increases, we can examine aspects of their temperament and genotype to help us understand who might most benefit from attention training. Since those with the poorest initial attention seemed to show the most benefit, it is possible that better results will be obtained with children who have more severe attentional disorders.

We are beginning to examine the precursors of executive attention in even younger children, less than one year of age, with the goal of understanding the origin of executive attention. We are also genotyping children in an effort to examine the candidate genes found previously to be related to the efficiency of the executive attention networks. There is already some evidence in the literature with older children who suffer from attention deficit hyperactivity disorder (ADHD) that using attention training methods can produce improvement in the ability to concentrate and in general intelligence (Kerns et al. 1999, Klingberg et al. 2002, Shavlev et al. 2003). As a result, we are also working with other groups to carry out attention training in children with learning-related problems such as ADHD and autism. These projects will test whether the programs are efficacious with children who have special difficulties with attention as part of their disorder. We also hope to have some preschools adopt attention training as a specific part of their preschool curriculum. This would allow training over more extensive periods and testing of other forms of training such as those designed for social groups (Mills & Mills 2000).

We believe that the evidence we have obtained for the development of specific brain networks during early childhood provides a strong rationale for sustained efforts to see if we can improve the attentional abilities of children. In addition, it will be possible to determine how well such methods might generalize to the learning of the wide variety of skills that must be acquired during school.

INTEGRATION OF PSYCHOLOGICAL SCIENCE

In this article, we have tried to cover topics from many areas of psychology, including cognitive, physiological, developmental, individual differences, social, clinical, and quantitative areas. Each of these areas can be shown to be involved as we examine attention networks. Below we argue that most, if not all, of the topics of psychological science can also benefit from a common network approach.

Generality

Fifteen years of cognitive studies using neuroimaging have laid out large-scale networks underlying many cognitive and emotional tasks (see **Table 4** for a partial list). In several fields of research, each area of activity (node) can be associated with a particular function or mental operation (see Posner 2004 for a review). A number of these nodes are active during a given task. The organization of these nodes in real time constitutes a network roughly like Hebb's cell assembly, but involving brain areas rather than individual cells. Of course, not all authors agree on exactly what the function of each node is, and some feel that parts of the brain (e.g., frontal lobes or subcortical areas) are more likely to carry out a number of functions.

We have also attempted to show that the study of attention involves all the branches of psychology. Attention has a detailed anatomy

Table 4 Some networks studied by neuroimaging*

Function	Selected references
Arithmetic	Dehaene (1997, figure 8.5)
Autobiographical memory	Fink et al. 1996
Faces	Ochsner et al. (2006)
Fear	Haxby (2004)
Music	Levitin (2006)
Object perception	Grill-Spector (2004)
Reading and listening	Posner & Raichle (1996)
Reward	Knutson (2003)
Self reference	Johnson et al. 2005
Spatial navigation	Shelton & Gabreli (2002)
Working memory	Smith et al. 1998, Ungerleider et al. 1998

*References cited are illustrative and are not meant to be comprehensive.

that involves large-scale brain areas and details of cellular structure. Nevertheless, the functions of attention are best studied at the cognitive level, which reveals their role in tasks that approximate those of daily life. Networks develop under the influence of social and cultural factors and of genes. The networks support not only the general functions of attention common to all people, but also the individual differences that relate to aspects of temperament and intelligence. We argue that what is true of attention is also true of the many other networks that have now been studied by imaging.

The network approach is general in that it covers the topics of cognitive and emotional mechanisms, and as we have shown above for attention, it allows an approach to issues of socialization and cultural influence, genetics, clinical diagnosis and remediation and their relative individual differences—in short, to all of the traditional areas of psychology.

Results of neuroimaging research also provide an answer to the old question of whether thought processes are localized. Although the network that carries out cognitive tasks is distributed, the mental operations that constitute the elements of the task are localized. A good example is the orienting network. This network carries out a very simple function of providing a priority to a particular source of sensory input, for example, to the particular location at which a visual event will occur. To carry out this function, the superior parietal lobe, temporal parietal junction, frontal eye fields, superior colliculus, and thalamus are all involved. However, they carry out quite different functions, not all of which are fully understood. For example, the temporal parietal junction is involved in interrupting a focus of attention while the superior colliculus and frontal eye fields appear to move the index of attention, with or without eye movements. Building upon the idea of localization of underlying operations, imaging methods are now being applied to studies of the circuitry, plasticity, and individual development of neural networks. Working together with cellular and genetic methods, there is movement toward a more unified view of the role of the human brain in supporting the human mind.

Another general distinction separates conscious and unconscious processes central to psychological thinking. It has been shown that special networks are active only when items are conscious (Dehaene et al. 2003). Studies of self-reference have also suggested activation of specific networks of neural areas when the self is the object of thought (Gusnard et al. 2001).

The study of human and animal genetics is also illuminating the basis for individuality. A view of brain networks developing under combined genetic and experiential control provides a systematic basis for understanding how common networks can be linked through the study of genetic polymorphisms and the socialization of individual differences. By relating task performance to self- and other report questionnaires, as we have done in our work, it is possible to examine the role of cultural and other social processes in the development of these networks.

Hebb provided a basis for viewing brain activity in terms of networks that could compute the various functions underlying human thoughts and feelings. He also attempted to treat all the issues that would normally be included in elementary psychology textbooks in terms of this common framework. With the addition of new methods, we believe that the task of integrating all aspects of scientific psychology in a common framework is even more feasible than when Hebb undertook it.

At a scientific level, Hebb's dream of an integrated psychology is coming about. Sternberg & Grigorenko (2001) laid out the political and social impediments that any effort at an integrated psychology faces, such as identifications of scholars with psychological subdisciplines (e.g., clinical, social) rather than with the phenomena they study, creating unnecessary boundaries. These factors may unfortunately lead to a failure to realize the old dream of an integrated science, but the opportunities are clearly there. New tools are helping, and Hebb's efforts have led the way.

ACKNOWLEDGMENTS

We acknowledge the support and aid of many people at the University of Oregon, the Sackler Institutes, and Washington University in this work. Grant support was provided by NIMH and the McDonnell and Dana Foundations.

LITERATURE CITED

Ahadi SA, Rothbart MK, Ye R. 1993. Children's temperament in the U.S. and China: similarities and differences. *Eur. J. Personal.* 7:359–78

Andersen RA. 1989. Visual eye movement functions of the posterior parietal cortex. *Annu. Rev. Neurosci.* 12:377–403

Attneave F. 1950. Book review of D.O. Hebb's *Organization of Behavior*. *Am. J. Psychol.* 63:633–35

Beauregard M, Levesque J, Bourgouin P. 2001. Neural correlates of conscious self-regulation of emotion. *J. Neurosci.* 21(RC165)1–6

Blair RJR, Morris JS, Frith CD, Perrett DI, Dolan RJ. 1999. Dissociable neural responses to facial expression of sadness and anger. *Brain* 1222:883–93

Blasi G, Mattay GS, Bertolino A, Elvevåg B, Callicott JH, et al. 2005. Effect of catechol-*O*-methyltransferase *val*[158]*met* genotype on attentional control. *J. Neurosci.* 25(20):5038–45

Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. 2001. Conflict monitoring and cognitive control. *Psychol. Rev.* 108:624–52

Bullock TH, Bennett MVL, Johnston D, Josephson R, Marder E, Fields RD. 2005. The neuron doctrine, redux. *Science* 310:791–93

Bush G, Luu P, Posner MI. 2000. Cognitive and emotional influences in the anterior cingulate cortex. *Trends Cogn. Sci.* 4(6):215–22

Carlson ST, Moses LJ. 2001. Individual differences in inhibitory control in children's theory of mind. *Child Dev.* 72:1032–53

Corbetta M, Shulman GL. 2002. Control of goal-directed and stimulus-driven attention in the brain. *Nat. Neurosci. Rev.* 3:201–15

Provides an excellent review of the neural areas involved in orienting of attention.

Crottaz-Herbtte S, Menon V. 2006. Where and when the anterior cingulate cortex modulates attentional response: combined fMRI and ERP evidence. *J. Cogn. Neurosci.* 18:766–80

Dale AM, Liu AK, Fischi BR, Buckner R, Beliveau JW, et al. 2000. Dynamic statistical parameter mapping: combining fMRI and MEG for high-resolution cortical activity. *Neuron* 26:55–67

Dehaene S. 1997. *The Number Sense*. Oxford, UK: Oxford Univ. Press

Dehaene S, Artiges E, Naccache L, Martelli C, Viard A, et al. 2003. Conscious and subliminal conflicts in normal subjects and patients with schizophrenia: the role of the anterior cingulate. *Proc. Natl. Acad. Sci. USA* 100(23):13722–27

Diamond A, Briand L, Fossella J, Gehlbach L. 2004. Genetic and neurochemical modulation of prefrontal cognitive functions in children. *Am. J. Psychiatry* 161:125–32

Driver J, Eimer M, Macaluso E. 2004. Neurobiology of human spatial attention: modulation, generation, and integration. See Kanwisher & Duncan 2004, pp. 267–300

Dumas T, Hostick U, Wu H, Spaltenstein J, Ghatak C, et al. 2005. Maximizing the anatomical specificity of native neuronal promoters by a subtractive transgenic technique. *Soc. Neurosci. Abstr.*

Duncan J, Seitz RJ, Kolodny J, Bor D, Herzog H, et al. 2000. A neural basis for general intelligence. *Science* 289:457–60

Eisenberger NI, Lieberman MD, Williams KD. 2003. Does social rejection hurt? An fMRI study of social exclusion. *Science* 302:290–92

Epstein S. 1998. Cognitive-experiential self-theory: a dual process personality theory with implications for diagnosis and psychotherapy. In *Empirical Perspectives on the Psychoanalytic Unconscious*, ed. RF Bornstein, JM Masling, 7:99–140. Washington, DC: Am. Psychol. Assoc.

Fan J, Flombaum JI, McCandliss BD, Thomas KM, Posner MI. 2002. Cognitive and brain mechanisms of conflict. *Neuroimage* 18:42–57

Fan J, Fossella JA, Summer T, Posner MI. 2003. Mapping the genetic variation of executive attention onto brain activity. *Proc. Natl. Acad. Sci. USA* 100:7406–11

Fan J, McCandliss BD, Fossella J, Flombaum JI, Posner MI. 2005. The activation of attentional networks. *Neuroimage* 26:471–79

Describes the brain areas activated for each of the three attention networks using fMRI data.

Fan J, McCandliss BD, Sommer T, Raz M, Posner MI. 2002. Testing the efficiency and independence of attentional networks. *J. Cogn. Neurosci.* 3(14):340–47

Fan J, Wu Y, Fossella J, Posner MI. 2001. Assessing the heritability of attentional networks. *BMC Neurosci.* 2:14

Fink GR, Markowitsch HJ, Reinkemeier H, Bruckbauer T, Kessler J, Heiss WD. 1996. Cerebral representation of one's own past: neural networks involved in autobiographical memory. *J. Neurosci.* 16(13):4275–82

Fossella J, Posner MI. 2004. Genes and the development of neural networks underlying cognitive processes. *The Cognitive Neurosciences III*, ed. MS Gazzaniga, pp. 1255–66. Cambridge, MA: MIT Press. 3rd ed.

Fossella J, Sommer T, Fan J, Wu Y, Swanson JM, et al. 2002. Assessing the molecular genetics of attention networks. *BMC Neurosci.* 3:14

Gallagher HL, Frith CD. 2003. Functional imaging of "theory of mind." *Trends Cogn. Sci.* 7:77–83

Gardner F. 1983. *Frames of Mind*. New York: Basic Books

Gerardi-Caulton G. 2000. Sensitivity to spatial conflict and the development of self-regulation in children 24–36 months of age. *Dev. Sci.* 3(4):397–404

Goddard GV. 1980. Component properties of the memory machine: Hebb revisited. In *The Nature of Thought: Essays in Honor of D.O. Hebb*, ed. PW Jusczyk, RM Klein, pp. 231–47. Hillsdale, NJ: LEA

Grill-Spector K. 2004. The functional organization of the visual ventral pathway and its relation to object recognition. See Kanwisher & Duncan 2004, pp. 169–93

Gusnard DA, Akbudak E, Shulman GL, Raichle ME. 2001. Medial prefrontal cortex and self-referential mental activity: relation to a default mode of brain function. *Proc. Natl. Acad. Sci. USA* 98:4259–64

Harman C, Rothbart MK, Posner MI. 1997. Distress and attention interactions in early infancy. *Motiv. Emot.* 21:27–43

Harris KD. 2005. Neural signatures of cell assembly organization. *Nat. Neurosci. Rev.* 6:399–407

Haxby JV. 2004. Analysis of topographically organized patterns of response in fMRI data: distributed representation of objects in the ventral temporal cortex. See Kanwisher & Duncan 2004, pp. 83–97

Hebb DO. 1949. *Organization of Behavior*. New York: Wiley.

Hebb DO. 1955. Drives and the C.N.S. (conceptual nervous system). *Psychol. Rev.* 62:243–54

Hebb DO. 1958. *A Textbook of Psychology*. Philadelphia, PA: Saunders

Hebb DO. 1966. *A Textbook of Psychology*. Philadelphia, PA: Saunders. 2nd ed.

Johnson SC, Schmitz TW, Kawahara-Baccus TN, Rowley HA, Alexander AL, et al. 2005. The cerebral response during subjective choice with and without self-reference. *J. Cogn. Neurosci.* 17(12):1897–906

Kanwisher N, Duncan J, eds. 2004. *Attention and Performance XX: Functional Brain Imaging of Visual Cognition*. London: Oxford Univ. Press

Karnath HO, Ferber S, Himmelbach M. 2001. Spatial awareness is a function of the temporal not the posterior parietal lobe. *Nature* 411:950–53

Kaufman AS, Kaufman NL. 1990. *Kaufman Brief Intelligence Test Manual*. Circle Pines, MN: Am. Guidance Serv.

Kerns KA, Esso K, Thompson J. 1999. Investigation of a direct intervention for improving attention in young children with ADHD. *Dev. Neuropsychol.* 16:273–95

Klingberg T, Forssberg H, Westerberg H. 2002. Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24:781–91

Knutson B, Fong GW, Bennett SM, Adams CM, Homme D. 2003. A region of mesial prefrontal cortex tracks monetarily rewarding outcomes: characterization with rapid event-related fMRI. *Neuroimage* 18(2):263–72

Kochanska G. 1995. Children's temperament, mothers' discipline, and security of attachment: multiple pathways to emerging internalization. *Child Dev.* 66:597–615

Kochanska G, Murray K, Jacques TY, Koenig AL, Vandegeest KA. 1996. Inhibitory control in young children and its role in emerging internationalization. *Child Dev.* 67:490–507

Kolb B. 2003. The impact of the Hebbian learning rule on research in behavioural neuroscience. *Can. Psychol.* 44:14–16

Levitin D. 2006. *This Is Your Brain on Music*. London: Penguin. In press

MacDonald AW, Cohen JD, Stenger VA, Carter CS. 2000. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science* 288:1835–38

Marrocco RT, Davidson MC. 1998. Neurochemistry of attention. In *The Attentive Brain*, ed. R Parasuraman, pp. 35–50. Cambridge, MA: MIT Press

Mascolo MR, Fischer KW, Li J. 2003. Dynamic development of component systems of emotions: pride, shame and guilt in China and the United States. In *Handbook of Affective Sciences*, ed. RJ Davidson, KR Scherer, HH Goldsmith, pp. 375–408. New York: Oxford Univ. Press

Mayberg HS. 2003. Modulating dysfunctional limbic-cortical circuits in depression: towards development of brain-based algorithms for diagnosis and optimized treatment. *Br. Med. Bull.* 65:193–207

McCandliss BD, Beck IL, Sandak R, Perfetti C. 2003. Focusing attention on decoding for children with poor reading skill: design and preliminary test of the word building intervention. *Sci. Stud. Read.* 7(1):75–104

McCandliss BD, Cohen L, Dehaene S. 2003. The visual word form area: expertise for reading in the fusiform gyrus. *Trends Cogn. Sci.* 7:293–99

Presents the original theory of how cell assemblies and phase sequences relate to psychological functions.

Mills D, Mills C. 2000. *Hungarian Kindergarten Curriculum Translation*. London: Mills

Milner P. 2003. The relevance of D.O. Hebb's neural network learning rule to today's psychology. *Can. Psychol.* 44:5–9

Mischel W, Ayduk O. 2004. Willpower in a cognitive-affective processing system: the dynamics of delay of gratification. In *Handbook of Self-Regulation: Research, Theory, and Applications*, ed. RF Baumeister, KD Vohs, pp. 99–129. New York: Guilford

Newell A. 1990. *Unified Theories of Cognition*. Cambridge, MA: Harvard Univ. Press

Nikolaev AR, Ivanitsky GA, Ivanitsky AM, Abdullaev YG, Posner MI. 2001. Short-term correlation between frontal and Wernicke's areas in word association. *Neurosci. Lett.* 298:107–10

Ochsner KN, Ludlow DH, Knierim K, Hanelin J, Ramachandran T, et al. 2006. Neural correlates of individual differences in pain-related fear and anxiety. *Pain* 129(1–2):69–77

Ochsner KN, Kossyln SM, Cosgrove GR, Cassem EH, Price BH, et al. 2001. Deficits in visual cognition and attention following bilateral anterior cingulotomy. *Neuropsychologia* 39:219–30

O'Reilly RC, Munakata Y. 2000. *Computational Explorations of Cognitive Neuroscience*. Cambridge, MA: MIT Press

Parasuraman R, Greenwood PM, Kumar R, Fossella J. 2005. Beyond heritability—neurotransmitter genes differentially modulate visuospatial attention and working memory. *Psychol. Sci.* 16:200–7

Posner MI. 1980. Orienting of attention. The seventh Sir F.C. Bartlett Lecture. *Q.J. Exp. Psychol.* 32:3–25

Posner MI. 2004. The achievements of brain imaging: past and present. See Kanwisher & Duncan 2004, pp. 505–28

Posner MI, Fan J. 2007. Attention as an organ system. In *Neurobiology of Perception and Communication: From Synapse to Society. De Lange Conference IV*, ed. J Pomerantz. London: Cambridge Univ. Press. In press

Posner MI, Raichle ME. 1996. *Images of Mind*. New York: Sci. Am.

Provides an overview of neuroimaging in relation to psychological concepts.

Posner MI, Rothbart MK. 2004. Hebb's neural networks support the integration of psychological science. *Can. Psychol.* 45:265–78

Posner MI, Rothbart MK. 2007. *Educating the Human Brain*. Washington, DC: Am. Psychol. Assoc.

Relates the implications of neural network development for issues of educating children.

Rothbart MK, Ahadi SA, Hershey KL. 1994. Temperament and social behavior in childhood. *Merrill-Palmer Q.* 40:21–39

Rothbart MK, Ahadi SA, Hershey KL, Fisher P. 2001. Investigations of temperament at three to seven years: The Children's Behavior Questionnaire. *Child Dev.* 72(5):1394–408

Rothbart MK, Bates JE. 2006. Temperament in children's development. In *Handbook of Child Psychology: Vol. 3, Social, Emotional, and Personality Development*, book ed. W Damon, R Lerner, vol. ed. N Eisenberg, pp. 99–166. New York: Wiley. 6th ed.

Comprehensively reviews temperament research.

Rothbart MK, Posner MI. 2006. Temperament, attention, and developmental psychopathology. In *Handbook of Developmental Psychopathology, Revised*, ed. D Cicchetti, DJ Cohen, pp. 167–88. New York: Wiley

Rothbart MK, Rueda MR. 2005. The development of effortful control. In *Developing Individuality in the Human Brain: A Festschrift Honoring Michael I. Posner*, ed. U Mayr, E Awh, SW Keele, pp. 167–88. Washington, DC: Am. Psychol. Assoc.

Describes the effortful control temperament variable and how it relates to behavior and underlying networks.

Rothbart MK, Ziaie H, O'Boyle CG. 1992. Self-regulation and emotion in infancy. In *Emotion and Its Regulation in Early Development: New Directions for Child Development No. 55: The Jossey-Bass Education Series*, ed. N Eisenberg, RA Fabes, pp. 7–23. San Francisco: Jossey-Bass

Rueda MR, Fan J, McCandliss BD, Halparin JD, Gruber DB, et al. 2004. Development of attentional networks in childhood. *Neuropsychologia* 42:1029–40

Rueda MR, Rothbart MK, McCandliss BD, Saccomanno L, Posner MI. 2005. Training, maturation, and genetic influences on the development of executive attention. *Proc. Natl. Acad. Sci. USA* 102(41):14931–36

Ruff HA, Rothbart MK. 1996. *Attention in Early Development: Themes and Variations*. New York: Oxford Univ. Press

Rumbaugh DM, Washburn DA. 1995. Attention and memory in relation to learning: a comparative adaptation perspective. In *Attention, Memory and Executive Function*, ed. GR Lyon, NA Krasengor, pp. 199–219. Baltimore, MD: Brookes

Rumelhart DE, McClelland JL. 1986. *Parallel Distributed Processing*. Cambridge, MA: MIT Press

Sejnowski TJ. 2003. The once and future Hebb synapse. *Can. Psychol.* 44:17–20

Shavlev L, Tsal Y, Mevorach C. 2003. Progressive attentional training program: effective direct intervention for children with ADHD. *Proc. Cogn. Neurosci. Soc. NY*, pp. 55–56

Shelton AL, Gabrieli JDE. 2002. Neural correlates of encoding space from route and survey perspectives. *J. Neurosci.* 22(7):2711–17

Simon HA. 1969. *The Sciences of the Artificial*. Cambridge, MA: MIT Press

Smith EE, Jonides J, Marshuetz G, Koeppe RA. 1998. Components of verbal working memory. *Proc. Natl. Acad. Sci. USA* 95:876–82

Sternberg RJ, ed. 2004. *Unity in Psychology: Prospect or Pipedream?* Washington, DC: APA Books

Sternberg RJ, Grigorenko EL. 2001. Unified psychology. *Am. Psychol.* 56(12):1069–79

Thorndike EL. 1903. *Educational Psychology*. New York: Teachers College

Toga AW, Mazziotta JC, eds. 1996. *Brain Mapping: The Methods*. San Diego: Academic

Ungerleider LG, Courtney SM, Haxby HV. 1998. A neural system for human visual working memory. *Proc. Natl. Acad. Sci. USA* 95:883–90

Utall WR. 2001. *The New Phrenology*. Cambridge, MA: MIT Press

Venter JC, Adams MD, Myers EW, Li PW, Mural RJ, et al. 2001. The sequence of the human genome. *Science* 291:1304–35

Wang H, Fan J, Johnson TR. 2004. A symbolic model of human attentional networks. *Cogn. Syst. Res.* 5:119–34

Wang H, Fan J. 2006. Human attentional networks: a connectionist model. Manuscript in preparation

Washburn DA. 1994. Stroop-like effects for monkeys and humans: processing speed or strength of association? *Psychol. Sci.* 5(6):375–79

Womelsdorf T, Fries P, Mitra PP, Desimone R. 2006. Gamma-band synchronization in visual cortex predicts speed of change detection. *Nature* 439:733–36

Annual Review of Psychology

Volume 58, 2007

Contents

Research Methodology

Indexes

Errata

An online log of corrections to *Annual Review of Psychology* chapters (if any, 1997 to the present) may be found at http://psych.annualreviews.org/errata.shtml