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Cumulative Development of Attentional Theory

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The goal of every science is a cumulative development of its theoretical structure so that a larger part of its subject matter is explicable in terms of simpler principles. This traditional view of science has been challenged in psychology from many sources. One argument has been that it is better to view psychology in terms of shifting paradigms (Kuhn, 1962). It often seems to be accepted, almost as a matter of course, that in psychology no cumulative development will take place. A different challenge to the view of psychology as a cumulative science is the notion that nothing new is discovered while the views of Helmholtz, Wundt, or some other elder of the field are being reworked, with no apparent gain in either insight or scope. These two challenges to the cumulative nature of psychological theory are persuasive, but they are not consistent. If we shift from paradigm to paradigm, it seems puzzling that the current paradigm would so exactly mirror that of 100 years ago. On the other hand, if the solutions of 100 years ago remain, what has happened to paradigm shifts? Another criticism that has been applied to the study of attention is that psychological theories are sterile, in that they do not illuminate important natural behavior or provide a perspective on the nature of mind (Neisser, 1976).

The contention in this article is that one can see emerging from psychological research in the area of attention a cumulative development of theoretical concepts that rely on principles, some over 100 years old, that are now elaborated in ways that were essentially unavailable to earlier researchers. Moreover, taken as a whole these ideas do provide insight into the skills of daily life.

If this contention is correct, why is it that the cumulative development of psychological theories of attention are so obscure, even to researchers in the field? I believe that several facts about the nature of psychological inquiry make its cumulative development obscure even to those who read the psychological literature.

The first difficulty in perceiving the cumulative nature of theories arises because much work in psychology is fueled by tests between complex theoretical views that differ in only subtle ways. These theories often have common assumptions, but similarities between them that amount to a common core of agreed principles are overlooked. The view of experiments as tests among competing, well-specified theories can be contrasted with the more cumulative theoretical

Source: *American Psychologist,* 37(2) (1982): 168–179.

approach outlined by Broadbent (1958):

> The proper road for progress then is to set up theories which are not at first detailed, although they must be capable of disproof. As research advances the theory will become continually more detailed, until one reaches the stage at which further advance is made by giving exact values to constants previously left unspecified in equations whose general form was known. It is a highly inefficient strategy to state postulates and deduce predictions unless the postulates have been reached by the gradual narrowing down of possibilities. (p. 312)

A second difficulty in perceiving the cumulative nature of theories of attention stems from the fact that many important ideas are now so deeply a part of the methods by which attention is studied that it is often difficult to see that they result from previous empirical findings. Such findings go back to the last century. In my own research four are most important. First is the idea that every mental operation requires a period of time for its accomplishment. This view emerged from the empirical demonstration by Helmholtz in 1850 that the rate of nerve conduction was not infinitely fast, but only a relatively slow 100 meters per second, and its elaboration by Donders (1868/1969) into the subtractive method for studying mental acts.

Only a few years later, Wundt demonstrated that two mental events occurring closely in time are handled successively (Wundt, 1912). The interference produced on one task by another concurrent task was used as a measure of the common capacity they require (Welch, 1898). The nature of this capacity and the form of the interference occurring between tasks remain important elements of efforts to develop a psychological theory of attention.

Another set of ideas that has become a central feature of many efforts to study attention goes back to the work of Pavlov (1960). Pavlov described two basic internal aspects of behavior, or cortical function as he called it, facilitation and inhibition. He argued that internal events could be studied in terms of the pattern of facilitation and inhibition to which they give rise. Sechenov had argued even earlier that the highest levels of the nervous system exercise inhibitory control over lower levels. Thus one might expect inhibition to be associated with central attention.

A final idea lies in Sokolov's (1963) elaboration of the orienting reflex into a general view about the alignment of central systems with sources of stimulation. The orienting reflex biased organisms toward fresh or novel sources of stimulation. This reflex combined outward signs and inward systems designed to improve processing of selected signals.

It remained, however, for events that occurred following World War II to provide a general language by which these various ideas could be brought together into a systematic analysis of attention. That general language for the discussion of stimulus events has been called information processing. Although the information processing language can be associated both with telephone engineering and with computers, these aspects are less important for our purposes than its providing common concepts for dealing with events as disparate as the processing of a series of letters into a meaning and the processes occurring at individual synapses. Both in neurophysiology and psychology the information processing language provided a vehicle for the discussion of computational operations at every level of the system. The common language of information processing together with the ability to measure mental operations in terms of time and capacity and to deal with both inhibition and facilitation have become indispensable elements of theoretical views of attention.

A third impediment to understanding the cumulative nature of the psychology of attention is the several different levels of analysis, each with different goals, involved in the study of attention. Each level is only somewhat predictable from the levels below. We are familiar with separation of levels between disciplines, for example, the argument that sociology is not reducible to individual behavior or that psychology is not explicable from a knowledge of the properties of individual neurons. Even though psychological theory provides important insights and constraints about sociology, there are new emergent principles as well. Similarly, although the properties of neurons do not allow us to constrain a psychological theory, knowledge of their operations can be helpful in constraining views of perception.

There are at least three different levels by which attentional theory has been approached. First is the level of performance, concerning our ability to deal with more than one task at a time. The second is the level of subjective experience, involving separation of conscious from unconscious events. Even if one fully understands the nature of consciousness, such understanding might not allow us to understand how two complex skills can be time shared. The third is the connection between aspects of conscious attention and the neural systems that underlie it.

I believe that each level has been associated with important cumulative development of methods, practical applications, and theory. Because the levels represent different questions about attention, the analysis of any one level provides only weak constraints on theories at the other levels. Increased efforts at relations between levels may develop, but even a detailed understanding of the neural basis of attention may provide us with only the barest help in understanding the processing steps necessary to perform complex skills at a high level of practice.

In this article I will often focus on my own research and related work, particularly studies that provide important qualifications to views presented in my 1978 book. I hope it will illustrate efforts to link studies of attention to complex natural skills and to investigations of neural systems. The particular studies I describe could be replaced by others that reveal the same principles. I begin with performance of complex skills, then turn to the question of whether we can separate conscious and unconscious mental acts and, finally, to an effort to understand the neural systems underlying the simple mental act of orienting to visual events. Space permits only a brief consideration of each area. I believe there are important issues and applications within each of these levels and will try to point them out in the course of reviewing each level.

Performance

Although the problem of attention began with issues of subjective awareness, like other psychological questions, it could only survive the behavioral revolution phrased in terms of experimental operations. Early work on attention within an information processing framework focused on the ability of people to perform simultaneous tasks. In studies involving the psychological refractory period (Bertelsen, 1966), people were required to process a signal that was presented during the reaction time to a prior signal. In studies of shadowing (Broadbent, 1958), subjects were given simultaneous messages and required to focus attention on one message by repeating it back. In general, these experiments were designed to focus full attention on one signal to discover what happened to other signals arriving at the same time.

These experiments showed that the people were limited in their ability to process information. There was abundant evidence of delays or exclusions of information from the secondary source during processing of the primary source. The idea that there was a single, limited capacity channel (Broadbent, 1958) corresponded with the phenomenology of attention and with the 19th-century studies of prior entry.

Nonetheless, there were many cautions about the single channel viewpoint (Broadbent, 1977). It was well-known that tasks requiring uncertain, discrete information from the environment, to which rapid responses were made, produced a great deal of interference, whereas continuous tasks in which there was little uncertainty and high levels of practice produced relatively little interference. These findings were congenial to the language of information theory. It could be argued that the channel limitation was not for number of tasks or items but for amount of information. As the uncertainty of the arrival times or the complexity of the processing of information in one task grew, the degree of interference increased. Though it was somewhat of an embarrassment that dual tasks could be performed more easily following practice, since the formal information content did not change, it was clear that effective uncertainty was reduced by allowing the subject to have a better knowledge of the statistical characteristics of the signals involved.

Partly in reaction to a strong single channel viewpoint, a number of studies were conducted showing that people could process information in a second task even when deeply engaged in the primary task. Some of these studies centered on the fate of information arriving on unattended channels. In general, when tasks became more difficult, they interfered more with each other. However, sometimes more difficult tasks could be time shared more easily than less difficult tasks. This finding led Keele (1973) to argue that some kinds of task difficulty did not require the limited capacity mechanism. Moreover, it was found that even in very demanding tasks like shadowing, information from the excluded channel was not lost all together. The meaning of an unattended word might influence the reaction time to stimulus on the attended channel (Lewis, 1970), bias the meaning of a sentence processed on the attended channel (MacKay, 1973), or produce a galvanic skin response if it had previously paired with shock (Corteen & Wood, 1972). Although all of these findings have been disputed, it is usually agreed that unattended information is not completely excluded even from complex semantic processing habitual to that stimulus.

There have been a number of demonstrations that at high levels of practice, people can time share two tasks as well, or almost as well, as they can perform a single task. (See Allport, 1980, for a review.) These studies show clearly the capability of people to perform two tasks at once. Predictable signals, self-pacing, continuous tasks, and high levels of practice are important in the development of these skills.

Another factor in the ability to time share tasks without interference is the finding that two tasks can be performed together better if they are quite dissimilar. This finding is by no means universal (Peterson, 1969), but it has led in recent years to the idea that there are multiple pools of capacity for different kinds of tasks (Wickens, 1980). A specific form of this hypothesis is that one can predict the degree of interference between any two tasks from their cerebral distance (Kinsbourne & Hicks, 1978). Kinsbourne argues that tasks that interfere when stimuli are presented simultaneously tend to facilitate when stimuli are presented sequentially. This view suggests that while any neural population is occupied by a signal, it will tend to be resistant to a second signal and that the activation of that population will improve subsequent attention.

There is no incompatibility between the idea of structural limits to capacity within particular neural pools (multiple capacity views) and the idea of a more general structure that might coordinate information arising from more limited systems (single channel view). Indeed, it is a frequent trick of the nervous system to employ the same general organization at different levels of generality. If two signals occupying the same position in visual space interfere, as they do in masking, it is not unreasonable to suppose that signals occupying different sensory and motor pathways might also interfere because of the need for a common structure at some more central level of the system. This would amount to a hierarchy of systems of increasing generality, whose activities are governed by similar principles.

It is this combination of multiple resources (isolable processing systems) and single channel (central attention) that I discussed in detail in my 1978 book. The idea was that much complex, even semantic, processing could be accomplished in local isolated processing systems, but that coordination was achieved through a limited capacity system that might be identified with conscious awareness.

To illustrate the operation of these systems within ongoing tasks, it is instructive to turn to recent studies that required subjects to monitor several simultaneous channels for a specific target event (see Ostry, Moray, & Marks, 1976). Results consistently showed that people could monitor channels simultaneously, except on those occasions when a target was present on one channel. At that moment performance on the second channel was greatly reduced.

In this kind of experiment, one could easily argue that the interference between target events was caused by the requirement for overt responses. Thus, it could be held that perception of the events occurred without any interference, and only overt response produced interference. Studies by Shiffrin (1975) and his associates provided some support for this view. These studies showed that people could monitor a large number of simultaneous sources of signals for a single target as well as they could deal with fewer sources. In this view processing could go on in parallel with no central limitations.

I remember pondering very long over these Shiffrin (1975) results, wondering how all of the previous results of the psychological refractory period and shadowing could be consistent with a view in which the human can process any number of signals simultaneously. For many months the literature seemed to me to be in turmoil between single channel and multiple resource views. A resolution was provided by Duncan (1980). He showed what ought to have been obvious – that many processes having to do with signals are carried on automatically without interference, but a specific aspect of signal processing produces interference. He found that as long as a subject monitored brief exposures of letters for a single digit, the number of letters monitored made little difference. However, if there could be more than one digit present in the visual field, performance dropped dramatically. The Duncan experiment was important because he did not require any speeded response to the target. Thus, it was not the output that produced interference but, rather, noting the presence of a target. Even if a subject had only to give an untimed report of the number of targets present, interference between channels was found. The Duncan results provide resolution to the paradoxes that seem to have accumulated between the monitoring studies and those of Shiffrin. People can monitor channels simultaneously because the lookup processes of the items coming over those targets occur with relatively little or no interference. In current terms they occur automatically. However, in order to take note of targets, the subjects must use some capacity that has a rather drastic limit, and signals occupying that capacity interfere. This idea is consistent with many dual task studies.

Thus, in answer to the question of whether people can perform two tasks at once, it is now clear that they can. Moreover, the things that affect their ability to perform are well-known, such as the uncertainty of the signals, compatibility of input and output codes, the amount of practice, and similarity between the components of the tasks. These are principles of the general type, which were formulated in the early days of information processing (Fitts & Posner, 1967). They remain useful and important in the study of many daily tasks. Their elaboration and supplementation is an important goal for psychologists, which is still under way, for example, in efforts to develop precise mathematical formulations of dual task interactions (Navon & Gopher, 1979; Wickens, 1980). Moreover, they have been and are being applied in such situations as design of cockpits and simulators, allocations of function to people and machines and other human engineering situations. In this sense they constitute a macrotheory of attention that summarizes accumulated knowledge about the ability of people to time share among tasks.

However, this level of analysis provides little information on the coordination and central control by attention. Studies like those of Shiffrin and Duncan provide a hint of general attentional mechanisms operating within dual tasks. We turn now to efforts to study such mechanisms in the hope of illuminating the sources of general interference.

Subjective Experience

At the time the information processing approach was being developed, there remained strong inhibitions about the use of subjective concepts. Thus attention was viewed objectively as interference in the ability to perform two tasks at once, and not in terms of the subjective experience that accompanies concentration on a signal.

There has lately been wider use of subjective data in information processing tasks. Problem solving is often studied by the use of verbal protocols (Ericsson

& Simon, 1980), and imagery is studied by asking people to respond when they are satisfied that they have obtained a particular object within the image (Kosslyn, 1980). These studies make it important to have objective methods for isolating those systems capable of providing linguistic commentary or of executing voluntary instructions.

It seems that we have come much closer to answering a fundamental question that has puzzled psychologists and philosophers for many centuries. To what extent are the processes of thought carried on unconsciously? This was the issue that plagued introspectionism in the Wurzburg studies of imageless thought. The problem is addressed by the finding that complex semantic processes can go on outside of attention. They clearly interact with attended processes by biasing certain thoughts or actions. So far such effects have been found only for already well-learned association, indicating that the limits of these largely unconscious complex processes lie in simple, habitual performances, what has been called *automatic processes*. Nonetheless, we do seem to have techniques for a further understanding of the role of conscious and unconscious processes in human mental life that is bound to build on, and hopefully to clarify, issues that have plagued psychology since its very beginning.

I reviewed evidence in 1978 (Posner, 1978) concerning two methods used to investigate the properties of a limited capacity mechanism thought to underlie subjective experience. Both of these methods make use of Pavlovian ideas of the importance of specifying the pattern of facilitation and inhibition as a way of studying higher level processing.

The first method relied directly on the dual task procedure. It involved the use of a secondary probe task to explore the attention demands of a primary task. I reviewed evidence (Posner, 1978) that a wide variety of mental tasks interfered with the secondary probe. I argued that the probe task provided evidence for limitations imposed by a central process.

This view has been challenged at both the stimulus and the response ends. Shwartz (1976) argued that interference effects were clearly evident when the probe and primary task were in the same modality, but not when they were in different modalities. Since that time a more recent study (Proctor & Proctor, 1979) has shown limitations in the methodology used by Shwartz and has concluded that interference provided by probes occurs to nearly the same degree, irrespective of the modality of the probe event. A more serious challenge was provided by McLeod (1978). McLeod argued that probe interference effects occurred primarily when the response to the primary task and the probe involved closely linked motor events. Recently McLeod and I (McLeod & Posner, Note 1) found that strong interference could occur even when the major task and probe were made by different response systems (e.g., vocal and manual). This experiment is of particular interest because McLeod (1977) had shown that in continuous tasks, there was little evidence of interference between vocal and manual responses. When highly compatible stimulus-response loops, such as a vocal response to an auditory stimulus, are used, interference is reduced (McLeod, 1978); but even in this case and in the case of eye movements to a visual stimulus, some evidence of central interference is frequently found (Posner & Cohen, 1980). Recently Papp and Ogden (1981) have confirmed the sensitivity of the probe method by showing that encoding of visual letters, which I had reported as automatic (e.g., not to require central processing), can be shown to give probe interference when an appropriate control condition is used.

A second technique for the study of interference effects due to central processing dispenses with the dual task method. It relies directly on the Pavlovian idea of describing the patterns of facilitation and inhibition. I (Posner, 1978) argued that any stimulus automatically activated habitual pathways related to its interpretation. Once activated such pathways provide enhanced processing of stimuli that share the same pathway. When subjects are induced to pay close attention to a stimulus, however, the facilitation is accompanied by an inhibition of stimuli that do not share the same pathway. This so called *cost-benefit analysis* suggested that conscious attention was closely associated with a general inhibitory process.

Two different experimental investigations seemed to confirm the logic of the cost-benefit analysis. Neely (1977) provided very compelling evidence, using a lexical decision task, that the occurrence of a prime produced both automatic facilitation as well as inhibition tied to an active transformation that was required in some conditions.

Do these techniques really provide evidence for the separation of conscious and unconscious processing? In the three years since I last reviewed this area, considerable evidence in favor of this hypothesis has accumulated. At the time of my last review, I presented evidence from a study by Conrad (1974) showing that both meanings of an ambiguous lexical item are looked up in the nervous system, even when only one of them is available to the subject's consciousness. In the last several years, an overwhelming number of experimental results using a variety of techniques have confirmed the simultaneous activation of lexical meanings, even in situations in which a particular ambiguous word is only used once (Killion, in press; Swinney, 1979).

Further evidence on awareness has arisen in studies of the priming of target words presented for lexical decisions by Fischler and Goodman (1978). They showed that on trials in which the subject was unable to report the prime even two seconds after it occurred, facilitation effects were still present. These facilitation effects were as large as or larger than those that occurred when the subject was able to report the identity of the prime. Even more spectacular are Marcel's (1980) results that automatic priming effects occur even when the subject is unable to discriminate the presence of the prime from a noise background alone. These results have confirmed the idea of unconscious processing of an item that is unattended even at the semantic level.

One of the major criticisms of the attempt to separate conscious effortful processing from more automatic processing has been the supposed sterility of the idea. Neisser (1976) has complained that such a separation provides no real insight into the nature of the human mind. On the contrary, I think recent days have demonstrated that this separation has provided enormous stimulation to explorations of mental processing in a variety of situations. Not surprisingly many of these results have raised questions about the extent to which the simple idea of separation between a parallel automatic pathway system and a limited capacity system could account for details of the data. Let me review some of the more important of these ideas in more detail.

I had associated the general inhibition effect with the limited capacity mechanism. A number of investigators have suggested that inhibition may also occur from repetition or from an active suppression of an unwanted code (Neill, 1977; Reisberg, Baron, & Kemler, 1980). In any case these forms of inhibition are specific to individual pathways and may easily be distinguished from the more general inhibition that occurs with the use of the central processing system.

More troublesome for the theory is the finding that a rapid form of general inhibition may arise (Antos, 1979; Taylor, 1977). Taylor's finding may be limited to specific competition between responses, and Antos showed early inhibition in only one condition. It is not yet clear how general these effects will prove to be and what significance they have.

In many cases there are problems that arise because of special strategies that might be developed in dealing with particular paradigms in which primes are studied. Fortunately there are now a variety of tasks in which priming can be studied, so it is possible to determine what effects are due to special strategies for a given task and what to more general mechanisms.

One of the most complete examinations of such strategy is a series of lexical decision experiments (Becker, 1980) that have shown either a facilitation-dominant pattern with very little evidence of inhibition or an inhibition pattern of results with very little evidence of facilitation. The former arises when the prime is very predictable of the target, whereas the latter arises when there is relatively little predictability between prime and target. Some subjects seem to show the facilitation pattern, whereas others tend to show the inhibition pattern.

There are several ways of accounting for these results that are compatible with my general position. For example, it may be that when the list is highly predictable, subjects do not need to do any active processing but can obtain facilitation passively without producing any interference. With less predictable primes, they may attempt prediction and, since they often fail, will produce an interference-dominant pattern. Becker's (1980) use of a single interval between prime and target may cause him to miss effects that occur very rapidly to the prime. If a quick active prediction is possible, the interference associated with its generation may be over by one second. His data do suggest ways in which active attention is employed with different stimulus material.

Logan (1979) has argued that the central processor in repetitive tasks is involved in setting up a program of analysis of the stimulus, rather than in running off the information processing stages that convert stimulus to response. This has the effect of reducing the role of the control processor in repetitive tasks and may explain why limited capacity central mechanisms may not be of major importance in much of highly skilled performance.

The idea that control processors may not be involved in the execution of responses at a high level of skill was bolstered by results obtained with event-related potential recording. My colleagues and I had shown that the latency of a late positive wave (P-300) was reduced when the second of two letters matched the first and thus finds an already activated pathway. If one assumes, as much of the literature indicates (Donchin, Ritter, & McCallum, 1978), that this wave is related to aspects of stimulus evaluation, our results indicated that priming was not of overt responses but of some internal system that was also responsible for the P-300. The largest objection to this view was that P-300 was frequently too late to be a sign of anything involved in conscious processing. In many cases it followed the overt motor response. This difficulty was relieved by a study reported by Duncan-Johnson (1979). Duncan-Johnson confirmed our finding that P-300 latencies were reduced when primed. She studied the relationship between the P-300 latency and reaction time. Highly primed motor responses to expected stimuli were emitted prior to the occurrence of the P-300 complex. On the other hand, unexpected motor responses emerged following P-300. This dissociation of a limited capacity system, at least so far as it is indexed by P-300, from motor responses explains why the limited capacity system may be relatively unimportant in dual task performance. The commitment of conscious attention seems not to be a necessary condition for highly overlearned responses to stimuli.

What is most impressive in recent studies is that the insights from these rather simple experimental tasks can be applied to more realistic situations. For example, a number of investigators (Becker, 1980; Britton, Holdredge, Curry, & Westbrook, 1979; Davidson, 1978; Ratcliff & McKeon, 1978; Stanovich & West, 1981) have applied these methods to processes involved in reading. By requiring occasional probes or lexical decisions or by the use of priming, it has been possible to shed light on reading activity as it takes place in real time. Davidson has used these methods to show that in rapid reading, the entry of words into meaning relies on the visual representation, and not its phonological code, whereas the representation of prior words presented in the story relies heavily on the phonological code. Britton showed that auditory probes are greatly affected by the presence of a narrative story line, as though the phonological construction is an active process that interferes with the probe. Ratcliff and McKeon have used the priming technique to show how sentences comprising the stories are represented in propositional form following their presentation. I believe that the techniques and theories outlined here are giving new insight into how the past experience of the reader and his or her current attention combine to produce the unique experience we call comprehension.

In the late 50s the so-called "new look" in perception also presented evidence of the importance of unconscious processes in governing the structure of current awareness. Many will remember these studies (see Dixon, 1971, for a summary). I believe the current results are consistent with the findings of the late 50s but are more impressive in several ways. First, the current theorists not only find evidence of unconscious priming, but they also show the role of attention in selecting and coordinating the broad range of automatically primed associations. Second, we have available theories of semantic memory showing how conscious and unconscious processes may be combined in determining our interpretation of stimulus events. Recently Bower (1981) and Zajonc (1980) have presented important information on the role of emotion in the interpretation and storage of information. These ideas build on our increasing knowledge of semantic networks to suggest the particular role emotion plays in the priming and storage of ideas. Studies of stereotyping, compartmentalization, and dissonance within social psychology have also begun to draw on our knowledge of the representation of memory in complex concepts and the role of conscious and unconscious processes in determining our current impressions (Higgins & King, 1981).

Complex tasks such as reading are limited to humans. To link the study of attention with the underlying neural systems that may support it, it is useful to have simpler tasks that can also be studied in nonhuman organisms. If the analysis of reading by mental chronometry is correct, it should be possible to study the same attentional mechanism in simpler situations in order to foster integration with physiological investigations. It is to this goal that we turn in the next section.

Neural Systems

It has been an ancient goal of psychology to bring together studies of brain and mind. The integration of sensory physiology and psychophysics provides clear evidence of the potential benefits of such integration. There is also some fear involved in taking this direction. Will a link to neural systems end the need to study phenomena at the level of performance and subjective experience? It seems to me unlikely that even a very fundamental understanding of the neurology of attention will provide sufficient constraints so that performance can be fully understood. This is especially true of attention because of the special connection of the field to human phenomenal experience and linguistic reports. On the other hand, there is much attraction in seeing whether the view of the nervous system based on our ability to make precise measurements of conscious processes and to time lock them to external signals outlined in the previous section can be supported by links to the relevant physiology. To do this, simpler tasks involving the operation of the same attentional mechanisms discussed in the last section seem to be required.

One area in which there has been progress in the development of such links is the study of orienting (Sokolov, 1963). Sokolov suggests a constellation of overt changes in head and eyes, for example, and of covert changes that serve to align the organism's attention to the source of signals. The most studied-example of orienting is the alignment of attention with a source of visual signals. Work with both alert animals and humans suggests that spatial orienting might provide a good model for linking subjective experience to underlying neural systems.

During the last several years my colleagues and I have sought to foster the connections between cognition and neuroscience through the study of orienting in visual space (Posner, 1978, 1980). We have tried to develop paradigms for the study of orienting attention in normal human beings that would make contact with developing neuroscience studies of attention using single cell recording from alert monkeys. In an effort to get beyond demonstrations that models of cognition can be loosely related to problems of brain injury, we have attempted a more detailed analysis of hypotheses arising in both neuroscience and psychology. For example, there has been active interest in the relationship between attention and movement in both neurophysiology (Goldberg & Wurtz, 1972; Mountcastle, 1976) and cognitive psychology (Posner, 1980). For visual events the major interest has been in the relationship between orienting (overtly by eye movements, or covertly via shifts of attention) and the efficiency of detecting (making arbitrary responses, or being aware of) stimuli. In our behavioral work we have been able to explore three general points:

1. Measurement of covert orienting of attention by changes in the efficiency of detecting stimulus events at different spatial positions;

2. The relationship between movements of covert attention and movements of the eyes;
3. The pathways controlling both covert and overt orienting.

Measurement of Covert Attention

We have a variety of methods (e.g., reaction time; probability of reporting near-threshold stimuli) to measure the efficiency of detecting information at various positions in the visual field. Subjects maintain fixation, but if cued to shift attention to places other than the line of sight, they are able to do so (Posner, Nissen, & Ogden, 1977). Such shifts are accompanied by improved efficiency of performance in terms of the latency of responding and probability of detecting signals that occur at the expected position in comparison to those that occur at the unexpected position (Posner, Nissen, & Ogden, 1977). Shifts of covert attention can be time locked so that the changes in efficiency can be traced dynamically as attention is moved across the visual field (Shulman, Remington, & McLean, 1979), suggesting an analog process.

The time locking of attention shifts to external signals allows testing a number of theoretical positions about the relationship between the position of the eyes and covert orienting of attention. We have shown that the occurrence of a peripheral event leads to a shift of covert attention to the area of the target about 150 milliseconds prior to an eye movement (Posner; 1980; Remington, 1980). This occurs even when the subject has a strong incentive to maintain attention at fixation, and its time course resembles that of the selective enhancement of superior colliculus units (Goldberg & Wurtz, 1972). There is no necessary connection between covert attention shifts and eye movement if a central cue is used to instruct subjects to make an eye movement; no evidence for a shift in visual attention prior to the eye movement has been found (Remington, 1980).

These findings (Posner, 1980) suggest that there are strong functional relationships between the shifts of the eyes and shifts of visual attention toward the occurrence of peripheral stimuli, but that there is no identity in the underlying physiological system. Nor can attention be viewed as closely coupled to the programming of the oculomotor system as proposed by efference theories (Wurtz & Mohler, 1976). The close functional relationship between attention movements and eye movements is similar to the relationship between eye movements and hand movements (Posner & Cohen, 1980).

The functional relationship between orienting covert attention and eye movements has allowed us to begin the task of forging links between the known anatomical pathways for eye movement control and the unknown neural systems that are involved in covert orienting and awareness. The goal is not merely localization of the process but development of a model system in which to study the cooperation of different neural systems in controlling a complex cognitive act.

It has been known in the literature that in mammals each eye tends to be linked by predominantly crossed pathways to the midbrain of the opposite side. These retinal-to-midbrain pathways are thought to be very important in the triggering of eye movements by visual stimuli. It seemed useful to test whether adult human beings would show the influence of these anatomical arrangements in their processing. To do this we confronted our subjects with simultaneous stimuli that occurred 10° to the left or right of fixation (Posner & Cohen, 1980). The subjects viewed the display monocularly, with one eye patched. On most trials one of the two stimuli occurred 150 or 500 milliseconds before the other and thus produced eye movements in the direction of the lead stimulus. On a small proportion of the trials, however, both stimuli came on simultaneously. It was these conflict trials that were of interest. According to the anatomical arrangement, one would expect that in such trials the subject's eyes would tend to go toward the temporal visual field, driven by the predominantly crossed retinal collicular pathways. The results conformed to this idea. In general the subject's eyes moved toward the temporal visual field. To see whether the advantage of the temporal visual field was as a general one that governed conscious perceptions as well as eye movements, we also had subjects remain fixated but judge the temporal order of stimuli occurring to the temporal or nasal visual field. Here we found virtually no asymmetry between the temporal and nasal field.

Efforts to link the anatomy with human performance results were also confirmed by findings in the developmental literature (see Posner & Rothbart, 1980, for a review) that show that newborn babies, whose vision is heavily influenced by midbrain structures, show a strong tendency to move their eyes in the direction of the temporal visual field. This result occurs in newborns even when only a single visual stimulus is presented and there is no conflict. This tendency to fixate only in the temporal visual field drops out in the first few months of life but apparently leaves present a dominance of the temporal visual field over eye movements, which remains present in adults.

The ability to predict eye movements based on anatomical organization encouraged our pursuit of the role of midbrain and cortical sites in the control of covert orienting. Some results have begun to accumulate. We (Rafal, Posner, & Walker, Note 2) have been studying a rare neurological syndrome, progressive supranuclear palsy (PSP), in which saccadic eye movements, particularly in the vertical direction, are affected by the degeneration of the superior colliculus and pretectal areas as part of a widespread midbrain disease. We have been able to show that such degeneration leaves patients with the ability to shift covert attention even in directions in which they cannot move their eyes. This suggests that the pathways that control voluntary eye movements are not completely necessary for the shifts of covert attention. It fits with the results with normal people indicating that covert attention can be moved with the eyes fixed. However, we also found some evidence that midbrain pathways were involved in shifts of covert attention. Patients seemed to be slower in shifting attention in the vertical direction, in which the eye movement system was most affected. This finding suggested that the midbrain system was involved in covert attention shifts.

Recently (Holtzman, Sidtis, Volpe, Wilson, & Gazzaniga, 1981) it has been shown more directly that the midbrain plays an important role in the covert orienting task. The study used split brain patients. A cue was presented to one hemisphere indicating the location of a target that might be presented to it or to the other hemisphere. The results showed that spatial information given to either hemisphere facilitates orienting controlled by both the same and the opposite hemispheres. These results argue that the two hemispheres share information provided by the cue about the location of the forthcoming target.

There are marked differences in the effect of the midbrain and cortical lesions we studied on subject's awareness of the target. Though the mid-brain lesions of PSP may prevent overt orienting and slow covert shifts of attention, they do not keep the subject from becoming aware of the target. On the other hand, unilateral lesions of the parietal lobe can cause a complete absence of awareness when a cue misdirects the subject's attention to the side of the field ipsilateral to the lesion. We are currently pursuing the role of mid-brain and cortical control over the orienting response (Posner, Cohen, & Rafal, Note 3).

These experiments provide evidence that regional neural systems exercise control over our ability to shift attention around the visual field, independent of overt changes in the position of the eyes or peripheral musculature. In cognitive science people presently wonder whether studies of mental chronometry can tell us anything about mechanisms (Neisser, 1976). The results of our orienting of attention work show clearly that the mechanisms of attention studied by chronometric techniques can be interfered with in different ways by brain injury. We are at the very beginning of developing an understanding of the underlying neural systems that support shifts of attention. The use of the same experimental methods in normal and brain injured people and the close connection between studies of humans and single cell work in nonhuman animals both provide the basis for developing links between what have too often been completely separate levels of analysis.

Do the methods we have adopted to study spatial orienting shed any light on more naturalistic behavior? Can we gain any insights into the skills of daily life from our analysis of the mechanisms of covert attention? In our current work Yoav Cohen and I (Posner & Cohen, Note 4) uncovered an inhibitory effect produced by a peripheral cue. We found that when the subject's attention is drawn to a place in space by a peripheral cue and then returned to fixation, processing at the cued position is inhibited with respect to other positions in the visual field. Our experiment showed that this inhibition effect was not a result of the attention shift to the cued position but of the sensory stimulation arising from the cued position. A demanding mental task interferes with covert orienting to the peripheral cue and thus reduces the facilitation of information from that spatial position, but it does not affect the amount of inhibition at that position caused by the cue (Hockey & Posner, Note 5). Each peripheral stimulus event has two opposed processes. It sets up a sensory inhibition rendering that position in space less sensitive to information that follows, but it also produces an orienting of attention that acts to counter the inhibitory effect. This reciprocal relation between sensory events and attention is reminiscent of the system governing overt movements through the programming of relative tensions between opposed muscle systems. It now seems clear why covert orienting is more effective when initiated by a central cue presented afresh on each trial than when it results from either a peripheral cue or from blocks of trials in which a single spatial position is made probable (Posner, Davidson, & Snyder, 1980). Only in the former case do we get a pure measure of the facilitation without inhibitory effect. We believe that this system at the microlevel may help us to understand why concentration on a sustained source of sensory signals is so difficult. Rather than being best understood in terms of a filter that eliminates unselected signals, such concentration appears to require an active orientation that must work against the basically inhibitory sensory process.

This article has attempted to go from more global studies of sustained performance in dual tasks to microprocesses related to them. The insights obtained from the study of these microprocesses must be tested in complex performance to determine their role in such skills. A fruitful interplay between the study of microprocesses and performance in realistic natural tasks now seems possible.

Conclusions

Work on attention has developed over more than 100 years. Our current knowledge and techniques owe much to Wundt, Helmholtz, Pavlov, and others. I have tried to convince you that we now know more because of current developments in the field. It seems to me that these studies provide genuine insights into aspects of human cognition.

It is difficult to summarize any more than I have the progress that has taken place at the three levels I have tried to describe in this article. Yet I recognize fully how far we really are from a complete theory at any level or from a deeper theory that ties together the different threads that I have tried to describe here. Perhaps we can derive some encouragement in our search for cumulative development from Glashow's (1980) recent article in *Science*, comparing the situation in particle physics in 1956 with the situation today:

> When I began doing theoretical physics, the study of elementary particles was like a patchwork quilt. Electrodynamics, weak interactions, strong interactions were clearly separate disciplines, separately taught and separately studied. There was no coherent theory that described them all. Developments such as the observation of parity violation, the successes of quantum electrodynamics, the discovery of haydron residences and the appearance of strangeness were well defined parts of the picture but they could not easily be fitted together. Today we have what has been called a standard theory of elementary particle physics in which strong, weak, and electromagnetic interactions all arise from a local symmetry principle. (p. 1323)

I hope that important steps toward such a theory of attention will take place. In the meantime those of us who work within and between the various levels of attention can feel that progress is being made. Although in the future we may see more shifts bringing to the fore new global questions in psychology, I suspect that the empirical work of the last century will remain an important part of whatever psychology should follow us.

Note

This article was presented as a Distinguished Scientific Contribution Award address at the meeting of the American Psychological Association, Los Angeles, September 1981.

This work was supported by a series of National Science Foundation grants to the University of Oregon. I am most grateful to the many students and colleagues who have contributed to this work, and to Mary Rothbart for assistance in writing it.

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