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Attention

Attention, endowed with a rich set of empirical findings, is a central theme in psychological research. Since the 1980s, human neuroimaging studies have allowed examination of the whole brain during tasks involving attention and, consequently, have provided much information on how the brain houses attentional processes. Brain networks subserving attention have been identified and described both anatomically and functionally. It is now possible to use these networks as model systems for the exploration of symptoms arising from various forms of pathology. This article outlines selective attention, its phenomenology, and its constituent attentional networks.

GLOSSARY

alerting	Achieving and maintaining a state of high sensitivity to incoming stimuli.
attention	The mental ability to select stimuli, responses, memories, and thoughts that are behaviorally relevant among a host of others that are behaviorally irrelevant.
attentional networks	Neural circuits subserving attentional processing that preserve a degree of anatomical and functional independence but interact in many practical situations.
cognitive control	Processes such as conflict resolution, error correction, inhibitory control, planning, and resource allocation.
executive	The mechanisms for monitoring and resolving conflict among thoughts, feelings, and responses (e.g., an attentional system concerned with such tasks as working memory, planning, switching, and inhibitory control).
neuroimaging	Technological advances, often noninvasive, that permit tapping neurophysiological aspects of the behaving brain.

orienting	The selection of information from sensory input.
top-down modulation	A downstream (vs bottom-up) effect (e.g., cognitive control).
self-regulation	Key mediator among genetic predisposition, early experience, and adult functioning (e.g., in controlling the reaction to stress, the capacity to maintain focused attention or the ability to interpret mental states both internally and in others).

HISTORICAL CONTEXT

Attention, one of the oldest and most central issues in psychological science, is the problem of selecting for active processing certain aspects of the physical environment (e.g., objects) or ideas in a person's mind (which are stored in his or her memory). Many great minds have wrestled with the definition of attention. In 1890, William James wrote, “Everyone knows what attention is. It is the taking possession of the mind in clear and vivid form of one out of what seem [to be] several simultaneous objects or trains of thought.” James's account heavily joined attention with subjective experience. Moreover, James's effort to deal with both attention to objects and attention to “trains of thought” is important for understanding current approaches to sensory orienting and executive control. However, because attention in the sense of orienting to sensory objects can actually be involuntary and can occur unconsciously, attention is not, as the quote from James implies, the same as being aware.

Behavioral psychology postponed research into the internal mechanisms of attention after 1900. The quest for attentional mechanisms resumed following World War II, when Donald Broadbent proposed a filter, limited for the amount of information (in the formal sense of information theory), that was located between highly parallel sensory systems and a limited-capacity perceptual system. This view was of immense aid in making possible objective studies of limitations in the human ability to deal with more than one signal at a time in a variety of practical tasks.

As psychology moved toward the study of cognitive mechanisms, the new objective methods made it possible to ask about the processes of selection. It was found that words could activate their semantic associates even when there was no awareness of the words' identities (i.e., priming). The highly parallel organization found for sensory information extended to semantic processing. The act of selecting a word meaning for active attention appeared to suppress the availability of other meanings of the selected item and of competing items. More recently, it became increasingly clear that although attention can be contextualized as a form of “alertness” as well as an index to resource allocation/limitation, it has been viewed less as a filter or bottleneck and more as a mechanism for providing priority for motor acts, consciousness, and some kinds of memory.

Although the psychology of attention furnished a number of interesting results about the limits of performance and of unconscious processing, there was no agreement on whether attention involved separate mechanisms from those used to process data, let alone any analysis of what these mechanisms might be in neural terms. Advances in the understanding of neural systems underlying attention developed from experimental paradigms involving selection of sensory information and more recently from the technological innovation of noninvasive tools for imaging the living brain.

Brain imaging has forged an impressive link between psychology and neuroscience. As early as 1990, some scholars suggested that the human brain entertains several attentional systems of different but interrelated functions (e.g., orienting, target detection, alerting). More recently, it has been demonstrated that distinct brain areas indeed mediate different attentional processes and that it is possible to examine selective attention as an organ system with its own functional anatomy, circuitry, and cellular structure. Although still incomplete, this information has illuminated multiple important questions in cognitive science and has provided insights into neurological and psychiatric disorders of both children and adults. Attention allows humans to exercise voluntary control over thoughts, feelings, and actions. Variations in the operational efficiency of these attentional systems serve as a basis for differences in self-regulation and emotional control, and they promise to help describe mechanisms of volition and sustained effort.

GROSS CHARACTERISTICS OF ATTENTION

Humans are largely visual animals, perhaps due to a common adaptation to visual predation generally found in primates. Researchers and clinicians have investigated the optics, anatomy, development, pathology, and underlying neural processes of the visual system, making it the most widely studied perceptual system. Therefore, it is didactically advantageous to discuss attention within the visual realm. Visual attention allows humans to move attention around to various areas of the visual field and to change the detail with which they look at any given area. For example, a reader can look at this page and pay attention to its setup as a whole, or he or she can zoom in on specific words and certain letters therein. If the reader is paying attention to single characters, he or she can glean a lot of information about punctuation marks, catch typos, and even spot minute imperfections on the physical sheet. But in that case, the reader might miss the idea that a paragraph is trying to convey. A person has the ability to change the location of attention and also to change the size of the attentional focus. This has been called the “zoom lens” idea, or the “attentional spotlight,” and relates to humans' common experience concerning the kind of attention needed for reading versus proofreading.

Given a large visual array of individual features, a person can have a choice of examining it globally or instead examining its specific features. The person can shift back and forth between them by changing the focus. Some patients have difficulty in examining the local features; these patients usually have damage to the left temporo-parietal lobe. Other patients may do well with the local features but fail to get the overall contour; they usually have damage to the right temporoparietal lobe. The parietal lobe tends to emphasize the shifting between local and global, whereas the temporal lobe seems to determine whether one can actually examine a local feature or a global feature of the stimulus.

People usually foveate, or look at, exactly the thing in which they are interested, and that generally relates people's attention to where they fixate. However, it is easy to dissociate the two: to cue people to attend to some location in space other than the center of gaze and then to show that they are very sensitive (i.e., have a low threshold or fast response time) to information that occurs at the cued location and are relatively slow or insensitive to information that occurs at the fovea. These covert shifts are believed to be used to select the part of the visual field to which people usually want to move their eyes. In everyday life, people usually follow covert shifts of attention with eye movements. Attention to visual elements can also apply to other modalities (e.g., auditory).

When multiple people talk simultaneously, it is sometimes necessary to select one of these streams of conversation to follow it in detail. An individual usually does that based on the location of the other person by visually orienting toward the person and/or honing in on the frequency of his or her voice (e.g., it easier to separate a male voice from a female voice than to separate two male voices) or on the content of the information (e.g., following by content). When an individual attends to one stream, the other information goes into the background; it is present but does not reach focal analysis.

There are data indicating that much of this unattended information is processed in subtle and complicated ways. Unattended information can suddenly get interesting because a person's name is mentioned or because something happens that is related to the conversation he or she is following and the person then finds himself or herself orienting to the new information. These phenomena have been studied experimentally in some detail.

ATTENTION AND PERCEPTION

The psychophysics literature provides good accounts of how visual thresholds correlate with attentional investment. However, improvement in “visual acuity” is not synonymous with altered thresholds for detection, better performance, or faster reaction times. For example, acuity requires the resolution of detail, whereas detection thresholds and reaction time can involve the summation of luminance, and this might obscure detail.

There is evidence that attention improves performance in spatial resolution tasks. Cognitive scientists draw a distinction between how attention may be useful for simple detection of events and how performance can improve at those events. Although performance may improve on increased attentional investment, there has been great controversy over what orienting attention to a sensory (e.g., visual) stimulus actually does. There is general agreement that the attended stimulus receives priority, so that reaction time to it is usually faster. For example, in the visual modality, there is evidence of enhancement of brain electrical activity over extrastriate visual areas by approximately

90 milliseconds after visual presentation. On the other hand, attention is not a panacea to perception, and there is a great deal that attention cannot do. For example, it is clear that attention to a peripheral stimulus does not compensate for the lack of acuity that would be present for a foveal stimulus. Stimuli in the fovea always have an advantage in detail, although the priority for processing the input has been placed elsewhere. Thus, while orienting to a location, attention can give priority to that location (i.e., targets that appear there will be perceived more rapidly and with lower thresholds), but it cannot substitute for the acuity provided by the fovea. Although the fovea is critical for acuity, the costs in reaction time for an unexpected foveal stimulus are just as great as those for an unexpected peripheral event. Thus, visual attention influences priority or processing preference.

Whereas investing attention is frequently associated with looking directly at the scene of interest, covert attention is the ability to select visual information at a cued location, without eye movements, and to grant such information priority in processing. Researchers have shown that the performance improvement at attended locations results, to some extent, from an enhanced spatial resolution at the cued location. Findings from further psychophysical studies support the hypothesis that attention increases resolution at the attended location. Studies exploring the relationship between visual attention and contrast sensitivity show that covert attention not only improves discriminability in a wide variety of visual tasks but also can speed up the rate at which information is processed. There are findings indicating that a person's contrast sensitivity is greater in the lower visual meridian (not the higher one). The bulk of the evidence sets limits to the effects of attention on spatial resolution and specifies that certain visual (not attentional) constraints determine aspects of spatial resolution.

ATYPICAL ATTENTION

Attentional performance is affected by the biological rhythm. Diurnal reductions in attention normally occur during the hours of maximum sleepiness (2—7 AM) when body temperature is at a nadir, and enhanced performance is usually seen during the evening when body temperature peaks. During sleep, voluntary attention is often considered to be markedly attenuated or indeed absent. However, there is evidence to suggest that certain attentional, as well as preattentional, mechanisms remain intact. Dreaming is usually divorced from a sense of controlled awareness, but purported accounts of lucid dreaming (i.e., dreaming while knowing that one is dreaming) suggest that some control mechanisms may be available during sleep. Other common anecdotes include the incorporation of ambient sound into the dream content and the idea of sensitivity to a person's own name.

One of the ways in which to investigate information processing in sleep involves electrical recordings from the scalp (EEG). By averaging the brain's electrical response potentials to stimuli (ERP), it is possible to examine the processing capability of the sleeping brain. One such component to examine is the mismatch negativity (MMN). The MMN is an electrophysiological manifestation of involuntary preattentive processing in response to oddball stimuli. In a typical MMN paradigm, a “deviant” auditory stimulus is infrequently interspersed within a sequence of “standard” auditory stimuli. The MMN is evident in the difference waveform resulting from the subtraction of the ERP elicited by the standard stimulus from that elicited by the novel auditory stimuli (the deviants). The difference waveform, occuring even without attention, normally peaks between 100 and 250 milliseconds from the onset of the deviant event, depending on the dimension of deviance and its magnitude. The MMN is presumably associated with a mechanism that compares the current auditory input with the memory traces formed by previous auditory inputs and signals the occurrence of a mismatch.

In adults, MMN tends to decline during drowsiness. Whether it persists into adult human sleep is still debated, but other EEG components do reflect the brain's reaction to novelty. Although active midbrain inhibition blocks cortical activity in the developed brain, there is reason to believe that the sleeping infant brain is not as capable of blocking and inhibiting information efficiently. Indeed, MMN is obtainable from newborns and young infants, and there are nascent experimental data showing that the brain can learn (e.g., certain language contrasts), even while asleep, during those early developmental stages.

Another special cognitive state sometimes confused with sleep is hypnosis. Some people (e.g., highly hypnotizable individuals) may experience attentional and perceptual changes, which might not typically occur during common awareness, following particular suggestions. Similar phenomena can occur in certain patient populations. For example, within vision, hypnotic suggestions have been demonstrated to induce tunnel vision, color-blindness, hallucinations, alexia, and agnosia. Such phenomena can manifest in other modalities as well (e.g., auditory).

Hypnosis has been used clinically for hundreds of years and is primarily a phenomenon involving attentive receptive concentration. Clinicians practicing hypnosis suggest that when a person is in a hypnotic state, attentional and perceptual changes may occur that would not have occurred if the person had been in a more usual state of awareness. In a responsive individual, hypnotic perceptual alteration is accompanied by reproducible changes in brain action. For example, the activity of the anterior cingulate to painful stimuli or conflict resolution can be modulated by hypnotic suggestion. Most children are highly hypnotizable and are more easily inducted into the hypnotic state than are adults.

SUBSTRATES OF ATTENTIONAL NETWORKS

Attention can enhance neural processing at multiple levels. It is a selective aspect of information processing; some things are privileged and some things are ignored. The modulation of neural response by attention has been studied vigorously. For example, one recent hypothesis suggests that as processing becomes more complex, it becomes advantageous to spread processing across more neural areas (e.g., both hemispheres). Another experimental approach carefully crafted a behavioral task to probe and assess at least three distinct attentional networks: (a) achieving and maintaining the alert state, (b) orienting to sensory objects, and (c) selecting among conflicting actions. Behavioral and imaging data suggest that these networks are independent. It is further possible to identify the neuroanatomy subserving these attentional networks.

Alerting involves a change in the internal state in preparation for perceiving a stimulus. The alert state is critical for optimal performance in tasks involving higher cognitive functions. Neuroimaging studies have shown activity in the frontal and parietal regions, particularly of the right hemisphere, when people are required to achieve and maintain the alert state even for a brief period. Lesions of these areas will reduce the ability to maintain alertness. Right frontal lesions have been shown to impair ability to voluntarily sustain attention, producing a larger number of errors over time than is found for left frontal patients in tasks involving continuous performance. Right parietal patients show deficits in maintaining the alert state and difficulty in attentional orienting that together produce a profound neglect in the visual field opposite the lesion. Alerting is thought to involve the cortical distribution of the brain's norepinephrine system arising in the locus coeruleus of the midbrain.

The orienting network involves the selection of information from sensory input. Cholinergic systems arising in the basal forebrain play an important role in orienting. The pulvinar, superior colliculus, superior parietal lobe, and frontal eye fields are often activated in studies of the orienting network. Orienting can be reflexive (e.g., when a sudden target event directs attention to its location), or it can be more voluntary (e.g., when a person searches the visual field looking for some target). Orienting typically involves head and/or eye movements toward the target, that is, overt orienting. However, it can also be covert. A few dorsal brain areas, including the superior parietal lobe and temporo-parietal junction, serve as a common source of attention to sensory stimuli. They produce effects within a network of areas that depend on modality (e.g., ventral visual areas in the case of visual input). The strongest evidence for localization of mental operations stems from the area of attentional orienting toward sensory stimuli, where a confluence of methods and experimental sophistication has demonstrated how separate brain areas can be invoked to organize a simple attentional shift. There is agreement that orienting of attention to a visual stimulus produces amplification in prestriate regions and that this affects processing in all subsequent regions and feeds back to influence processing in the primary visual cortex and perhaps in the lateral geniculate nucleus of the thalamus.

Executive control of attention involves more complex mental operations in monitoring and resolving conflict among computations occurring in different brain areas. Executive control is most needed in situations that involve planning or decision making, error detection, novel (or not well-learned) responses, and conditions judged to be difficult or dangerous as well as in overcoming habitual actions. The anterior cingulate and lateral frontal cortex are target areas of the ventral tegmental dopamine system. Brain imaging data have shown repeatedly that the anterior cingulate cortex (ACC) is an important node in this network. Toward that end, a number of neuroimaging studies have shown activation of the dorsal anterior cingulate in tasks requiring people to respond either to a prepotent response or to a rather strong conflicting dimension. For example, in the classic Stroop task, experienced readers name the ink color of a displayed word. Readers are usually slower and less accurate in responding to the ink color of an incompatible color word (e.g., the word “red” displayed in blue ink) than in identifying the ink color of a control item (e.g., the word “lot” displayed in red ink). Another task involves participants responding to the direction of a central arrow when flanking arrows could point in either the same (congruent) direction or the opposite (incongruent) direction. The Attention Network Test uses this flanker task to measure conflict and shows strong activation in the dorsal ACC. Neuroimaging studies have shown that these conflict tasks activate midline frontal areas (e.g., ACC), lateral prefrontal cortex, and basal ganglia. These experimental tasks provide a means of fractionating the functional contributions of areas within the executive attention network. Chiefly, the ACC was more active on incongruent trials than on congruent trials. This result could reflect the general finding that lateral areas are involved in representing specific information over time (i.e., working memory), whereas medial areas are more related to the detection of conflict.

Patients with focal brain lesions of the ACC initially display deficits of voluntary behavior. The notion of ACC involvement in cognitive control and volition has been a topic of much interest recently. Based on behavioral, optical, and neuroimaging data, it was reported that effective suggestion (i.e., verbal exhortation) prevented word reading and modulated focal brain activity in highly suggestible individuals. This top-down influence was both potent and selective in that it annihilated the Stroop interference effect and reduced ACC activity, respectively. Interpretation of these data implies that, at least in highly suggestible individuals, attentional manipulations can influence aspects of self-regulation by affecting neural activity in specific brain areas. Although attention and self-regulation have arisen within two different research traditions, there have been some recent efforts to integrate these two directions considering hypotheses about specific neural mechanisms involved in both attention and cognitive control. For example, these prospective approaches advocate a synthesis that is likely to be productive in linking brain systems to aspects of child socialization.

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