Attention and Perception

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Abstract

This essay discusses several key issues concerning the study of attention and its relation to visual perception, with an emphasis on behavioral and experiential aspects. It begins with an overview of several classical works carried out in the latter half of the twentieth century, such as the development of early filter and spotlight models of attention. This is followed by a survey of subsequent research that extended or modified these results in significant ways. It includes work on various forms of induced blindness and on the capabilities of nonattentional processes. It also covers proposals about how a "just-in-time" allocation of attention can create the impression that we see our surroundings in coherent detail everywhere, as well as how the failure of such allocation can result in various perceptual deficits. The final section examines issues that have not received much consideration to date, but that may be important for new lines of research in the near future. These include the prospects for a better characterization of attention, the possibility of more systematic computational explanations, factors that may significantly modulate attentional operation, and the possibility of several kinds of visual attention and visual experience.

INTRODUCTION

Whenever we open our eyes, we experience an ever-changing world of colors, shapes, and movements. This experience is so vivid and so compelling that we rarely stop to consider whether the underlying mechanisms may have limitations. Instead, we simply have a strong impression that we always perceive everything in front of us. Although we may need to scrutinize something on occasion, for the most part our visual system appears to operate in an automatic and seamless way, providing us with a complete and detailed representation of whatever is in our field of view.

But however appealing it may be, this impression cannot be correct. Suppose someone wants to keep track of various players in a sports game. A single player can usually be tracked without problem. Three or four can also be tracked, although with some effort. But as the number increases further, simultaneous tracking of all the selected players becomes impossible. Performance evidently depends on a factor which enables certain kinds of

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perception to occur, but which has a clear limit to its capacity. This factor is generally referred to as *attention*.

Work on human vision is providing increasing evidence that visual perception is the result of several interacting processes, most of which are quite sophisticated, and many of which have definite limits to their abilities. And rather than the outputs of these processes accumulating in a detailed *construction*, much of our perception results instead from the *coordination* of these processes. In particular, much of our visual experience appears to depend on managing attention so that it is sent to the right item at the right time. As such, attention is more than something that simply modifies or assists our perception on occasion—it is instead a factor central to our awareness of the world around us.

FOUNDATIONAL RESEARCH

It was recognized long ago that we need to pay attention to adequately perceive our surroundings. But only recently have we obtained a better understanding of what attention is and how it relates to perception. Building upon the proposals of philosophers of the seventeenth and eighteenth centuries, researchers in the nineteenth century began to map out several of its main characteristics. For example, Hermann von Helmholtz discovered that an observer could attend to (in the sense of recognizing) letters at locations outside of where the eyes were aimed (or "fixated"), showing that attention is not equivalent to eye fixation. Meanwhile, William James distinguished "sensorial" from "intellectual" attention—the former concerned with concrete objects such as particular sports players, the latter with more abstract structures such as the quality of the game. James also associated sensorial attention—in particular, visual attention, the focus of this review—with clarity of perception, intensity of perception, and visual memory. Many of these concerns became an enduring backdrop for subsequent work.

FILTER MODELS

A more rigorous approach to understanding attention was developed during the middle decades of the twentieth century, when researchers began focusing more on its selective aspects, and—in line with the "cognitive revolution" of that time—replaced the original emphasis on subjective experience with an emphasis on objective models. Donald Broadbent proposed an influential "filter" model, in which perception was carried out via a sequence of processes in a single pathway, with an attentional filter that gated selected aspects of a stimulus through to later processes. An important issue was the locus of this filter: whether it was *early* (selection affecting the initial stages, which measured simple properties such as color and motion) or *late* (selection appearing only at the highest levels, gating properties such as semantic category).

The work undertaken to settle this issue resulted in a great deal of information about the ways various operations were affected by attention. However, the complete resolution of this issue eluded researchers, and continues to do so to this day. This strongly suggests that some of the original assumptions were incorrect: there may be, for example, more than one filter in the pathway (not to mention more than one pathway), making questions concerning a single filter somewhat ill-founded. To get further insights, a different approach was needed.

Spotlight Models

Despite the failure to determine whether selection was early or late, investigations into this issue resulted in a variety of new methodologies and new frameworks. Over time, concerns about the nature of filters receded, and were replaced by an emphasis on how attention affected the representations themselves.

An example of such a methodology is *visual search*, where observers are asked to report on a prespecified target item in a visual display. It was found, for example, that some items can be detected immediately and without much attention (e.g., a blue dot among a set of yellow dots), whereas others cannot (e.g., a "T" among a set of "L"s). Among the more prominent frameworks to account for such findings was Anne Treisman's *feature integration theory*. This framework modeled visual processing in terms of two stages. The first is a *preattentive* stage that determines simple properties (features) such as color or motion rapidly and in parallel at each point of the visual field, resulting in a "map" describing the spatial distribution of each feature. The second involves a limited-capacity "spotlight" of attention that travels from item to item at a rate of about 50 ms per item, not only filtering but also *binding* features that correspond to the same item (e.g., integrating the representations of the "blue" and "vertical" properties at a location into a single representation of both). Later refinements included the *guided search* model of Jeremy Wolfe and colleagues, in which items in a feature map could be selectively inhibited or excited to improve the efficiency of search. Other variants examined issues such as the extent to which attention might be allocated in parallel rather than in a serial fashion. All these models had natural connections to other areas of vision science: for example, the features found in visual search could be related in a fairly straightforward way to many of the elements underlying texture perception.

Other approaches yielded similar results. Michael Posner and colleagues did seminal work on *cuing*, showing that if a cue (such as a dot) was shown at the location of a target just before the target appeared, detection could be sped up by several hundred milliseconds. This speedup diminishes as the separation between target and cue increases, something readily accounted for by a model in which the edges of the spotlight are smooth. Meanwhile, Charles Eriksen and colleagues showed that a spotlight mechanism could also account for the ability of nearby items (or "flankers") to interfere with detection; results also suggested that only one spotlight operates at any time, and that it can rapidly adjust its size, "zooming" in or out as required by the task. Owing to its ability to account for a variety of effects, therefore, the spotlight model has become the "classical" explanation of visual attention, forming the basis of much of our current understanding of how it operates.

Multiple-Object Tracking

A rather different approach to studying attention was developed by Zenon Pylyshyn and colleagues, based on *multiple-object tracking*. Here, a set of identical items—dots on a screen, say—is initially displayed. A subset of these is marked (e.g., some of the dots flash) and the marked items then tracked as they randomly move around the display. The ability to track is severely limited: Under most conditions, no more than three or four can be handled. The extent to which multiple-object tracking can be explained by a spotlight mechanism remains unclear. However, there is considerable—although not universal—belief that this tracking does involve a form of attention, if only because of the limited capacity found.

Underlying Mechanisms

One of the more successful quantitative models of attentional filtering and binding was the *Theory of Visual Attention* of Claus Bundesen, which could account for a considerable variety of experimental data. It was also compatible with later suggestions that filtering and binding could be implemented via neural assemblies that inhibit their neighbors when activated. Another (possibly complementary) proposal about implementation was *neural synchrony*, which posited that an attended item could be represented by the synchronized firing of a group of neurons. More generally, many of the classical results could be explained by models based on the dynamics of neural interactions, along with the selective routing of information from various areas of the brain.

In parallel with this, other work focused on understanding attentional *control*. Michael Posner suggested that the movement of attention involved three distinct components: (i) the *disengagement* of attention from the current item being attended, (ii) the *shifting* of its location (e.g., the center of the spotlight) over space, and (iii) the *reengagement* of attention on a new item. Among other things, this model successfully accounted for several perceptual problems encountered in developmental disorders and degenerative diseases. Subsequent work placed an increased emphasis on the extent to which control was affected by properties of the image—for example, the extent to which the size or color of an item differed from that of its neighbors.

CUTTING-EDGE RESEARCH

The late twentieth and early twenty-first century saw the development of several new research directions. Some were direct continuations of classical work, and led to further refinement of earlier results. But others involved new perspectives, and sometimes caused a reconsideration of previous assumptions. Although these investigations have not yet resulted in a coherent, generally accepted account of attention, they have provided a better understanding of its operation, including how it relates to other mechanisms involved in visual perception, and how its limitations can intrude into everyday life.

Induced Blindness

Much of recent work has returned to the issue of how attention relates to conscious visual experience—in particular, the way that an absence of attention can cause a failure to see an item in clear view of the observer. One example is *inattentional blindness*, where an observer fails to see an unexpected object or event, even when these are large and quite visible. This has been taken to indicate that attention is needed to see an object or event. There is some uncertainty as to the extent of its implications at the theoretical level: Does the observer fail to see all aspects of the object, or do they still see its basic features but are blind to its structure or meaning? Either way, inattentional blindness is increasingly recognized as being important at the practical level. For example, many traffic accidents are likely due to a driver failing to see a pedestrian (or another car) because attention was focused on something else.

A variant of this is *continuous flash suppression*. Here, a set of random images is continually flashed into one eye at a rate of about 10 Hz, suppressing the experience of the image shown to the other eye. This can be sustained for several minutes. Various explanations have been put forward for this phenomenon. The predominant hypothesis is that it occurs because attention cannot be sent to the suppressed image, and that no other effects are responsible—that is, that continuous flash suppression is a form of inattentional blindness. If so, it could be a powerful way to study the extent to which perception can occur in the absence of conscious visual experience.

Another phenomenon that has received a great deal of interest is *change blindness*. Here, the observer fails to notice a change that occurs in an object, even if the change is large and can easily be seen once the observer knows what it is. This phenomenon strongly suggests that attention is needed to see change. It appears that attention engages visual short-term memory (vSTM) to create a representation that is *coherent*—that is, is integrated over some extent of space and has continuity over some duration of time. The number of items that can be monitored simultaneously for change is about three or four, a limit similar to the capacity of vSTM. Unlike inattentional blindness, change blindness can occur even when a change is expected. This can lead to severe problems in everyday life, in that people can miss even a large, obvious event if they are not attending to it the moment it occurs.

Other types of induced blindness are also of interest. One of these is the *attentional blink*. This occurs when two different (prespecified) targets in a stream of rapidly presented stimuli appear at slightly different times; under some conditions, the first target will be seen but not the second. This has been explained in terms of attention not being allocated to the second item in time, possibly because the representation for the first has not yet been completed. A related phenomenon is *repetition blindness*, where the observer can miss the occurrence of a repeated item in a stream of rapidly presented images. This is likewise believed to be due to the failure of attention to create sufficiently quickly a representation of the repeated item.

Nonattentional Processing

The earliest stages of visual processing are generally thought to be concerned with simple properties such as color, motion, and orientation. It was originally assumed that attention acted directly on such properties: that they were the preattentive features uncovered in visual search. But later work showed that search can be influenced by relatively complex localized structures—*proto-objects*—created by processes acting before attention. These processes can group line segments, bind features, interpret dark regions as shadows, and perhaps even recover three-dimensional orientation at each location in the image, essentially creating a "quick and dirty" map of scene structure. The strength of cuing and speed of search can be similarly influenced by the inferred structure of the background, being enhanced for items on the same surface and diminished for items on different ones. All these results point to a considerable amount of processing that occurs rapidly (and likely in parallel across the visual field), before attention has had much of a chance to operate.

Recent work has also shown that observers can accurately estimate summary statistics, such as the average size of the disks in an image, even if this image is presented for only a 100 ms or so; more sophisticated properties (e.g., Pearson correlation) can also be estimated this way. Observers can even determine the appropriate category (or *gist*) of a scene under such conditions, possibly based on these statistics. In all of these, there is no time to filter or bind more than a few items, suggesting the existence of processes that operate before—or perhaps in tandem with—visual attention.

The "intelligence" of such nonattentional processes is an open issue. Observers show little inattentional blindness to words and pictures with a strong emotional impact (e.g., the observer's name), indicating that some degree of recognition exists before attention is sent to the item. In general, then, all these results imply that nonattentional processes are capable of more than previously believed. And attention may correspondingly do less: although attention can be used on occasion to bind visual features, for example, it may not be necessary for all aspects of binding.

Connections with Scene Perception

Phenomena such as inattentional blindness and change blindness suggest that attention is necessary for visual experience. And most studies concur that attention is severely limited. Why then do we not experience such limits when viewing a scene? One possibility is that attention can create a representation—a *visual object*—possessing detail and coherence, but only as long as attention is maintained. If this can be done on a "just-in-time" basis—that is, attention is sent to the right item at the right time—the result would be a *virtual representation* that would appear to higher level processes as if it were "real," that is, as if it contained detailed and coherent representations everywhere. An important goal of current work is therefore to understand the nature of the mechanisms underlying such coordination.

One suggestion begins with nonattentional processes providing a constantly regenerating array of proto-objects, which represent simple properties of the scene that are visible to the observer. Attention can select a subset of these, "knitting" them into a coherent visual object. In tandem with this, the statistics of the (unattended) proto-object array could determine gist; this could help access high-level knowledge about the scene, and so guide attention to appropriate parts of the image. In this characterization, then, scene representations are no longer long-lasting structures *built up* from eye movements and attentional shifts, but are relatively temporary structures that *guide* such activities. Among other things, this implies that different observers—with different knowledge, different goals, and therefore different attentional strategies—can literally see the same scene differently.

Connections with Perceptual Deficits

Given that attention is needed for visual experience, problems with its allocation may explain various perceptual deficits. In *unilateral neglect*, for example, patients with damage to the right posterior parietal cortex (at the top and back of the head) can fail to visually experience whatever is in the left half of the visual field, even if this is directly in front of them. (Oddly, a corresponding deficit does not result from damage to the left side.) A related condition is *extinction*, where such a failure also occurs, but only when an object exists in the right half of the visual field. Such deficits may result from problems in shifting attention to the relevant location (or at least, keeping it there), possibly because of damage to the parietal circuits that control it. Interestingly, words and pictures in the neglected—and presumably unattended—part of the visual field can still affect the observer, consistent with the proposal of intelligent nonattentional processes.

Another condition likely related to these is *simultanagnosia*. Patients with this deficit cannot see more than one coherent object (or coherent part of an object) at a time; the rest of the scene is experienced only in a fragmented way, or not experienced at all. This has been associated with damage to the parieto-occipital areas (at the upper part of the back of the head), which may cause problems in allocating attention to particular objects.

KEY ISSUES FOR FUTURE RESEARCH

Most issues in attention research—both classical and subsequent—are still far from being resolved. For example, what is the relation between attention and vSTM? How many nonattentional process exist, and how intelligent is each? How exactly do the knowledge and goals of the observer determine how attention is allocated? The answers to all of these are necessary for a complete understanding of attention. Finding them will take many more years of work.

Meanwhile, other issues are also beginning to emerge. Part of the reason they have not received much consideration to date is sociological: Given the work still to be done on current issues, little incentive exists to embark upon riskier ventures elsewhere. Part is methodological: It is not clear how some of these issues could be addressed in a productive way. And part is simple ignorance: We did not know enough until recently to realize that some of these issues even existed. But whatever the reason for their previous obscurity, many of these issues are becoming increasingly prominent, and may well form a critical part of future research.

Characterization

One of the most basic—and oldest—issues concerning attention concerns its nature: What exactly *is* it? Over the years, attention has been characterized in various ways, such as the quality of visual experience, or a limited "resource" that enables particular operations to be carried out. But the greatest increase in our understanding seems to have been achieved by focusing on the idea of selection. Could this idea be developed further, ideally in a way consistent with most of the other characterizations that have been applied?

One possibility would be to define an attentional process as one that is *contingently selective, with that selectivity controlled via global considerations* (e.g., tracking a particular person of interest). From this perspective, "attention" is more an adjective than a noun. Any globally controlled process of limited capacity—such as binding visual features, or placing them into vSTM—would be "attentional," because limited capacity implies selectivity of one form or other. This would also be the case for any process that selectively improves the quality of visual experience, provided only that this is done on the basis of some global consideration (e.g., not done reflexively).

Computational Explanation

Even if attention could be described in terms of a particular function or mechanism, our understanding of it would be incomplete: We might know *how* it operates, but not *why*. For example, if some capacity were limited to three items, why should this be? Why not four? Why not one? Of course, such a limit may simply be an accident of history. But it may also reflect the influence of deeper principles.

One possible way of investigating this is to apply the computational framework of David Marr. This framework posits that any (visual) process can be analyzed from three interlocking perspectives: (i) *function* (both description and justification), (ii) *mechanism* (algorithm and representation), and (iii) *neural implementation*. Such explanations have led to deep insights into the nature of processes at early levels of human vision, and have helped develop their equivalents in machine vision. A few studies, such as those of John Tsotsos, have begun applying this approach to attention as well. Such analyses could eventually provide considerable insights into the nature of attention and the exact role it plays in perception.

Modulatory Factors

It is often assumed that attention is governed entirely by the demands of the task and the knowledge of the observer. However, evidence is emerging that other factors also play an important role:

Stress. Stress can cause *tunneling*, where the observer loses awareness of anything beyond the center of the visual field. It can also speed up visual search for simple features (e.g., a particular orientation, such as "vertical"), although apparently not for their combination (e.g., "blue" and "vertical"). Such effects suggest that stress causes attention to improve its selectivity by reducing the range of the properties allowed through. However, it may be that such improvement is obtained at the cost of a slower switching of the underlying mechanisms.

Aging. Another important perspective is how attention changes over lifespan. Different aspects of attention appear to be differently affected: Filtering and binding appear to be largely unaffected, while top-down control (e.g., disregard of irrelevant stimuli, switching speed) deteriorates noticeably with age. More investigation would be of great practical importance, and could provide new perspectives on underlying mechanisms.

Cultural/Visual Environment. Recent work suggests that observers from Western countries (e.g., the United States) generally attend to individual objects in a scene, whereas observers from East Asian countries (e.g., Japan) generally attend to the scene as a whole. Western observers show a *search asymmetry*: They can detect a long line among short lines more quickly than vice versa. Meanwhile, East Asian observers are equally slow for both. Preliminary work suggests that some of these differences disappear when significant time is spent in the other culture. If these results hold, they would indicate a strong effect of culture—or at least, visual environment—on the way attention is used. Interesting issues would then arise as to which (visual) characteristics are relevant, and why.

Mental Set. Attentional control—including the speed of visual search—can be influenced by explicit instruction to the observer. Such results suggest that an observer may have available several processing *modes*, each corresponding to a particular "mental set." (Some of these may account for the cultural differences mentioned above.) If so, interesting questions arise as to the nature of these modes, and the conditions that trigger them.

KINDS OF ATTENTION

Another important issue is whether there exists one kind of attention or several. Occasional conflicts have occurred in claims regarding the speed, sensitivity, and even function of attention; it is not even clear as to what extent it travels along perceptual structures or "raw space." The existence of multiple kinds of attention could help resolve some of these issues. It would also create new ones, such as determining the taxonomy that would best describe these kinds, and establishing the various ways in which a process could be "preattentive" or "nonattentional."

On the basis of function, speed, and structures operated upon, several groupings of attentional processes can be delineated. An important question is the extent to which these groupings correspond to distinct aspects—or even kinds—of attention (or, perhaps, more precisely, attentional processing):

Attentional Sampling. This is the selective pickup of information by the eye. The eye has high acuity and color perception only in the few degrees around the point of fixation. It must therefore—together with the head and body—move around to pick up the right information from the environment. Sampling has traditionally been referred to as *overt attention*. It has long been known to differ from operations carried out internally, which are often collectively referred to as *covert attention*.

Attentional Filtering (Gating). Irrelevant information can degrade performance, and must be removed as soon as possible. Ways of doing so include *spatial filtering* (selection only from a particular region of space) and *feature filtering* (selection of items containing a particular feature); these are largely the focus of classical approaches. Selection can be *diffuse* (over a wide range) or *focused* (over a restricted range). It appears that the mechanisms involved can be switched quickly (typically, within 50 ms) and operate on the basis of simple properties, such as color, motion, or spatial position.

Attentional Binding. This is the selective linking of properties so as to capture the structure of the world at any given moment. This can be done in various ways, such as *feature binding* (e.g., linking the color and orientation of an item) and *position binding* (e.g., linking an item to a precise position in space). Binding differs from filtering, being concerned not with *access*, but *construction*. The mechanisms involved also appear to differ, being slower (completing within about 150 ms) and involving organized structures rather than simple properties.

Attentional Holding. When a physical object changes over time (e.g., a bird takes flight), it is useful to perceive an underlying structure that remains the same. The associated representation must be "held" across time, likely via vSTM; such "holding" therefore differs from binding. The mechanisms involved also appear to differ, being even slower (completing within about 300 ms) and operating on no more than three to four items at a time.

Attentional Individuating. It is often useful to perceive not just *an* object, but a *particular* object (e.g., when determining if one item is to the left of another). Such "individuating" (or "indexing") may also be the basis of tracking. The mechanisms involved can act quickly (about 50 ms per item) and involve up to seven to eight structures at a time.

KINDS OF VISUAL EXPERIENCE

A parallel set of concerns involves conscious visual experience. As in the case of attention, it has been widely assumed that there exists only one kind of visual experience. But just as color and motion are distinct aspects—or even kinds—of experience concerned with distinct *physical* properties of the world, so might there be other kinds of experience concerned with distinct *structural* properties:

Fragmented Experience. This is the experience of simple features with little structure and poor localization; in some ways, it is what is experienced when viewing an Impressionist painting. It can be encountered in brief displays, where the experience is one of a fleeting array of simple colors and shapes with relatively little structure. This has sometimes been termed *background consciousness*—the experience of the background when attention (binding) is focused on foreground objects.

Assembled Experience. This is the experience of unstructured properties (fragmented experience) along with a degree of superimposed static structure. It can be encountered in displays presented for at least 150 ms, the time needed for binding; it is essentially what is experienced under stroboscopic conditions. Although no new sensory (physical) properties are present, more complex kinds of structure are. Among other things, this distinction allows two kinds of inattentional blindness to be distinguished: *Type 1*, the absence of *fragmented* experience (i.e., the absence of sensory qualities, perhaps caused by an absence of attentional gating), and *Type 2*, the absence of *assembled* experience, with simple sensory qualities still present but no higher level structure (perhaps caused by an absence of attentional binding).

Coherent Experience. This is the "standard" experience encountered when giving complete attention to a physical object: Not only is the static structure of assembled experience present but also movement—or more generally, change—along with the impression of an underlying substrate that persists over time. The absence of coherent experience (change blindness) might be regarded as *Type 3 inattentional blindness*, caused by an absence of attentional holding.

Sensing. Observers in change detection experiments occasionally report that they "sense" or "feel" a change without having any visual experience of it. The status of this "sensing" is controversial. It has been suggested that it is simply a "weakened" form of seeing (i.e., coherent experience). However, it differs qualitatively from the other kinds of visual experience, and appears to involve different mechanisms as well.

An important challenge for future work is to determine the extent to which these really are distinct kinds of visual experience, and how they may relate to various kinds of attention. There are also important issues concerning what might be called *dark structure*—structure is never experienced at all, yet still affects visual perception.

CONCLUSION

The nature of attention and its relation to perception have long been issues cloaked in mystery, involving matters that are highly subjective and poorly defined. But a great deal of progress has been made, particularly over the past century. A considerable amount of understanding now exists as to how attention operates, and the role it plays in our conscious experience. And, importantly, this understanding has suggested new questions, concerning issues that researchers of earlier times had not even imagined. Investigating these issues will no doubt require much time and effort. But the results are likely to shed interesting new light on the way we experience our world.

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