Spatial Attention

KYLE R. CAVE

Abstract

Visual perception requires selective filtering. The process of selecting a portion of the visual input according to its location is described as spatial attention. Spatial attention has been measured with a wide variety of experimental techniques, including spatial cuing, spatial probes, distractor interference, ERP, and SSVEP. The results show that spatial attention sometimes takes the form of a gradient, with strong facilitation of processing within a central region and less facilitation and perhaps even inhibition in the surround. The positioning of the attentional gradient is controlled in part by a bottom-up system that directs attention to locations that differ from surrounding locations in basic features. There is also top-down direction of attention, which favors locations with features matching a defined target. A variety of different experiments have demonstrated that attention can be allocated to a particular location in the visual field, but another set of experiments show that attention can be allocated to a visual object, and that attention that is directed to one part of an object can spread to other parts of the same object. It is difficult to determine whether spatial attention and object-based attention are controlled by the same system or by separate systems. Determining the boundaries between different attentional systems should become easier with the use of ERP data to provide precise timing information about attentional processes, and fMRI to localize the brain regions controlling attention and to measure attentional modulation of perceptual processing activity.

INTRODUCTION

Visual perception requires a combination of different processes, from early processes that detect edges and infer surfaces, to later processes that match the incoming input to memory representations to achieve recognition. The earliest processes rely more on local comparisons that can be done with short neural connections, but the later stages require integration of information across large parts of the visual field, and thus require that information be transmitted over long distances within the brain. The earlier processing stages can produce more information than can be processed by the later stages, and thus outputs of the earlier states must be filtered to select just those parts with the highest potential for informativeness before they are

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routed to higher level mechanisms. This filtering process is often labeled as "attention."

Visual information arriving at the eye is spread across the two-dimensional array of the retina, and this spatial organization is, to a large extent, maintained through the early stages of processing. Although many important types of information are encoded in the early stages, location seems to play a unique role in the organization of this information, as can be seen in the spatial maps in the superior colliculus, the lateral geniculate nucleus, primary visual cortex, and other brain regions serving vision. Location also plays an important role in visual attention.

FOUNDATIONAL RESEARCH

Spatial Cuing

One obvious reason why location is important in visual attention is that visual information at the center of gaze is projected onto the fovea, which has the highest spatial resolution within the retina. Thus, an important part of selecting visual information is pointing the eyes toward the most informative location in the environment. However, spatial cuing experiments (Eriksen & Hoffman, 1974; Posner, Snyder, & Davidson, 1980) have shown that this overt attention is not the whole story. Even without moving the eyes, it is possible to select one part of the visual field for faster, more detailed processing. In these experiments, subjects are asked to keep their eyes fixed at one location, while a cue appears some distance away, signaling that an upcoming stimulus is most likely to appear at that location. This cue causes covert attention to be allocated to that location, so that when the stimulus does appear, subjects will respond to it more quickly if it is at the cued location, and more slowly if it appears elsewhere.

There are two different aspects to this spatial cuing effect on attention. If, throughout the course of the experiment, the stimulus appears more often at the cued location than somewhere else, then the cue is providing useful information that can improve performance. In many of these experiments, the cue is a symbol appearing at the center of gaze, and subjects must interpret the symbol to know which location should be attended. As long as the cue is informative, subjects have an incentive to interpret the symbol and move their spatial attention to the indicated location. This internally motivated cue use is called endogenous orienting. In other cases, a cue can move attention to a location even if the subject believes that it is uninformative. For this exogenous orienting, the cue must be a flash or other salient stimulus located at the location to be cued.

Spatial Probes

The simple spatial cuing paradigm has been a foundation on which other more complex experimental procedures have been built. The stimulus that triggers the response can be thought of as a probe that measures attention at a location. Across trials, it can be applied to many different locations to produce a full picture of attentional allocation. The simple cue can be replaced with other more complex stimuli coupled with tasks requiring spatial attention. The first example of this came from Hoffman and Nelson (1981), who combined a probe task with a letter search task. Reports of the probe stimulus were more likely to be correct if it appeared near a correctly reported target of the letter search. Spatial attention allocated to the letter target apparently also improved discrimination of the probe stimulus if it was in the same vicinity. This experiment, and the many probe experiments that followed, demonstrated the general nature of spatial attention, enhancing the processing of any stimulus appearing within the selected region. This spatial aspect of attention led Posner, Snyder, and Davidson (1980) to compare attention to a spotlight that illuminates just one selected part of the visual field.

Flankers and Distractor Interference

The importance of location in attention is made apparent by a technique used by Eriksen and Eriksen (1974). They simply required subjects to identify a letter appearing in the middle of the visual field. Other letters appeared along with the target letter, and although the locations of these letters made it clear that they were not the target, these letters could affect the response if they were close enough to the target location. If these flanker letters were associated with the same response as the target, then the response was faster, and if the flankers were associated with a different response, then the response was slower. If the flankers were close to the target (within 1° of visual angle), they were able to activate responses to the point that they either facilitated or competed with the response being activated by the target letter. This flanker effect shows that spatial selection is not perfect, and that distractors are not always fully excluded.

Gradient Versus Moving Spotlight

Experiments by Downing (1988) and by Laberge and Brown (1989) showed that attentional facilitation could take the form of a gradient, with stronger perceptual sensitivity for locations nearer the cue, and a fall-off in sensitivity with distance. Sperling and Weichselgartner (1995) argued that this area of attentional facilitation can be deallocated from one location and reallocated to a new location without selecting locations in between. For a detailed review of the relevant findings on shape and movement of the attentional gradient, see Cave and Bichot (1999).

ATTENTIONAL CAPTURE AND BOTTOM-UP ATTENTIONAL CONTROL

One big challenge for the visual system is deciding where in the visual field to allocate the gradient of spatial attention in order to be most effective. Given that this decision must be made before visual processing is completed and before objects have been identified, it has to be done with only partial information. This control of attention requires a balance between different factors, but one important factor is the presence of featural variation in the visual field. Spatial attention is often allocated to a location that differs from its surrounding locations in the basic visual features present there. Attention is often captured by a location with a red stimulus that is surrounded by green, or a horizontal contour that is surrounded by vertical, or a moving object that is surrounded by stationary objects. Experiments by Theeuwes (1992) demonstrate that attention can be captured by unique features (singletons) even if they are irrelevant to the current task.

This attentional capture shows the importance of stimulus-driven or bottom-up factors in controlling attention. However, Folk, Remington, and Johnston (1992) have shown that attentional capture can be prevented in some circumstances. To reconcile these results, Bacon and Egeth (1994) proposed that the attentional system can shift modes depending on the needs of the task. When a target object differs from the distractors in some basic feature, searchers may simply use “singleton detection mode,” in which attention is captured by any item that has a unique feature that differs from its surroundings. Thus, when Theeuwes’ subjects search for a shape singleton (diamond target among circle distractors), their attention will be captured by a color singleton (red among green). However, if the task makes it difficult to find the target by singleton search, searchers may instead switch to “feature search mode,” in which attention is allocated to those locations that have a specific feature value known to belong to the target.

TOP-DOWN ATTENTIONAL GUIDANCE AND THE TARGET TEMPLATE

The ability to search for a specific feature is another important factor in the control of spatial attention: Many visual tasks require that attention be directed to locations that have a specific color, size, or other feature, even though that feature may not be a unique singleton. This top-down guidance toward known targets must be balanced against the bottom-up capture by unique objects. The top-down guidance requires that some sort of internal target definition be maintained in order to guide attention. This target representation has sometimes been called the "target template," although some tasks require that it be more general than implied by the term "template."

Because the target representation is active only for the course of a particular visual task and will change from on task to another, it is natural to compare it to visual working memory, the temporary storage proposed by Baddeley (2007) to hold visual information that is actively being used in cognitive tasks. Perhaps the target information that guides attention top-down is stored in the same visual working memory that is used for other visual tasks that require temporary storage. If the search target representation and visual working memory are one and the same, then whenever something is stored in visual working memory for a nonattentional task, we might expect attention to be captured by stimuli that match the stored information. This idea has been tested with various different search and memory tasks. In some circumstances, holding an item in visual working memory does redirect search, while in other circumstances it does not (Olivers, Peters, Houtkamp, & Roelfsema, 2011; Woodman, Carlisle, & Reinhart, 2013). There is some type of link between visual working memory and the attention target representation, because one can interfere with the other under the right conditions, but they are probably not one and the same thing.

Object-Based Attention

Although location is very important in allocating attention, there is also abundant evidence that attention can be shaped by object boundaries. When two objects are superimposed, one can be selected over the other (Duncan, 1984), and when an attended object moves, attention can move with it (Kahneman, Treisman, & Gibbs, 1992). These demonstrations have led to a distinction between spatial attention, which is allocated to a location, and object-based attention, which is allocated to an object representation.

Many of the experiments in object-based attention have focused on how attention that is initially cued to one part of an object can spread to other parts of the same object. Egly, Driver, and Rafal (1994) provided a useful experimental paradigm for studying this aspect of object-based attention by extending Posner's cuing procedure. Posner originally placed two boxes in the stimulus display (one on each side of fixation), and cued one of them as the expected target location. Egly, Driver, and Rafal extended these boxes to make them long narrow rectangles, and then cued just one end of one rectangle. The test stimulus, to which subjects responded as quickly as possible, appeared in one end of one of the two rectangles. Responses were fastest when it appeared at the cued end, as expected from Posner's original experiments. However, responses were faster for a stimulus at the uncued end of the cued rectangle than for a stimulus on the uncued rectangle, even though distance from the cue was the same for both stimuli. Attention at the cued location spread to facilitate visual detection of other locations within the same object. See Chen (2012) for a review of object-based attention.

Although this type of object-based attention is easy to demonstrate experimentally, it does seem to require that attention be spread broadly across a large area (Goldsmith & Yeari, 2003), and that the objects be visible long enough for them to be interpreted as separate objects (Chen & Cave, 2008). Object-based attention also varies according to whether the stimulus configuration is described as one object or two (Chen, 1998). Thus, even though the object organization of a scene can affect attention when the objects are irrelevant to the task, encoding the object organization is apparently not a necessary step in allocating attention.

The relationship between location-based attention and object-based attention is not clear. They could arise from separate attentional mechanisms working at different processing stages within the visual system. Selection that occurs within the early processing mechanisms of the lateral geniculate nucleus and primary visual cortex could be responsible for location-based attention, while selection among more abstract object representations in temporal regions could be producing object-based attention. On the other hand, there might be a single spatial selection mechanism, with the locations that are selected being shaped by the perceived object organization. This idea of a unified spatial/object selection is consistent with theories in which attention is driven by an interaction between low level visual processing and higher level object representations (Heinke, Mavritsaki, Backhaus, & Kreyling, 2009).

VISUAL SEARCH

Cuing experiments, in which the target location is known or at least expected in advance, have demonstrated both location selection and object selection. As important as attention is in these relatively simple tasks, it is probably even more important in search tasks, in which the target location is unknown and the allocation of attention is probably much more complex in search. Most search experiments do not address the role of spatial location in selection, but instead test the capacity limits of attention by adding more and more objects to the search array. These search experiments have been important in exploring the perceptual limitations that make attentional selection necessary (Treisman & Gelade, 1980; Wolfe 2007). Search experiments have been the primary tool for determining which visual properties are identified early in processing and can effectively guide attention (Wolfe & Horowitz, 2004).

Although search has not been used as much to demonstrate the spatial nature of visual selection, it is pretty clear that spatial selection plays a role in search. Many visual search experiments elicit a combination of eye movements and covert attention. The eye movements are clearly an instance of spatial selection, given that the goal of the eye movements is to direct the fovea toward the selected location. The role of covert attention in search can be studied by eliminating the eye movements, either by using an eyetracker or by presenting the search array so briefly that an eye movement cannot be programmed and executed before it disappears. Spatial selection can be demonstrated in these covert search tasks with spatial probes: Probes at target locations or at locations that share target features show attentional facilitation, even though the probes do not share the target features, and are only linked to those features by location (Kim & Cave, 1995).

CUTTING-EDGE RESEARCH

ERP, MEG, AND SSVEP

The history of research in spatial attention illustrates that much can be learned with behavioral experiments measuring response times and accuracy. However, event-related potential (ERP) methods based on measuring changes in electrical potential with scalp electrodes have provided a powerful tool for measuring how neural processing of visual signals changes with attention (Luck, Woodman, & Vogel, 2000; Mangun & Hillyard, 1995). The attentional enhancement of visual signals can be measured in ERPs within 100 ms or so after a stimulus appears. ERP methods also provide a way to measure attention at visual field locations that the subject is trying to ignore, which cannot be done with spatial probes that require a response. Also, experiments by Hopf *et al*. (2006) using a related method based on magnetoencephelography (MEG) have provided key demonstrations of the inhibitory attentional surround around attended locations, which corresponds to behavioral findings by Cave and Zimmerman (1997) and by Mounts (2000).

The electroencephalographic measurements used in ERP experiments can also be used to record steady-state visual electric potentials (SSVEPs), which can also reflect changes in neural activation caused by attention (Muller, Malinowski, Gruber, & Hillyard, 2003). In this paradigm, each stimulus in a visual display flickers at a different rate, and those stimulus oscillations are carried by the neural signals encoding those stimuli. When a particular stimulus is attended, the EEG signal will show a stronger oscillation at that stimulus' frequency. Thus, this method provides another way to measure spatial attention without a response from the subject.

SPLIT ATTENTION

Many of the experiments described here have started with the assumption that spatial attention selects a single unified region within the visual field. In fact, that assumption is built into the spotlight metaphor that drove early attentional research. However, many visual tasks require comparing or conjoining stimuli at two or more separate visual field locations, and the question arises whether those multiple locations can be selected without selecting distractor locations between them. A number of experiments have been presented over the years to demonstrate split attention, but it has been difficult to determine whether attention is simultaneously selecting to locations, or is moving quickly between them. Jans, Peters, and De Weerd (2010) have thoroughly reviewed these experiments and have tried to interpret them as the product of a single focus of attention. The theoretical assumptions that are necessary to defend the single attentional spotlight hypothesis require such complex operations that the split attention alternative begins to sound more plausible (Cave, Bush, & Taylor, 2010).

PERCEPTUAL LOAD VERSUS DILUTION

One of the more controversial general theories of attention comes from Nilli Lavie (2005), who suggests that there is a fixed amount of attentional capacity that can be allocated to different visual tasks, and that at any one moment, all of it will be used. This means that if the current visual task is relatively easy and uses only some of the available capacity (in other words, it has a low perceptual load), the rest will be applied to processing distractor items in the visual field, even though they are irrelevant to the current task. Lavie provides supporting evidence for this perceptual load theory from a number of experiments. She shows that the interference from a salient distractor decreases as the task requires processing of more items.

Perceptual load theory has faced a number of challenges. One of the more notable comes from Tsal and Benoni (2010) and Wilson, Muroi, and MacLeod (2011), who reject Lavie's claim that it is the extra perceptual load from additional relevant display items that absorbs attentional capacity and limits distractor interference. Instead, they propose that whenever items are added to the display, even if they are irrelevant to the task, they interfere with the processing of other items. This alternative account is referred to as *dilution*.

Comparing the evidence for perceptual load theory against the evidence for dilution is complicated by another factor, as pointed out by Chen and Cave (2013). In these studies, the search array generally appears suddenly, and these abrupt onsets have the effect of broadening the attentional zoom to encompass the full display. When the display is presented in a way that avoids the abrupt onsets, the results no longer show the general pattern of dilution. That does not mean that perceptual load theory prevails, as a number of other studies have challenged it, including one by Kyllingsbaek, Sy, and Giesbrecht (2011) showing that adding distractor letters can take processing resources away from targets. There may be validity in Lavie's general claim that processing of distractors varies according to the demands of processing targets, but the whole story is probably more complicated.

Localizing Brain Mechanisms for Spatial Attention

The focus here has been mainly on behavioral studies of attention, and on ERP studies that provide timing information about the neural processing underlying attention. These results can now be combined with a large number of functional MRI studies showing which brain regions are involved in attentional selection. The relevant brain regions are often organized into two categories. The "sites of attention" are those brain regions within the visual system that are responsible for identifying objects, including primary visual cortex (V1) and the ventral, or "what" pathway. The activity within these regions is modulated according to attentional goals (Kastner & Pinsk, 2004). That modulation seems to be controlled by another set of cortical regions often described as "sources of attention," which include frontal and parietal regions that are linked together in such a way that they are often referred to as the frontal-parietal network (Corbetta, Patel, & Shulman, 2008).

Interpretation of these studies of large-scale brain activation can be guided by measurement of attentional effects on individual neurons (Moran & Desimone, 1985). When these neuroscience findings are combined with the decades of research on attentional performance described earlier, we have a rich environment within which to construct detailed theories of attentional selection.

KEY ISSUES FOR FUTURE RESEARCH

Attentional Zoom

Over the years, a number of detailed computational models have been proposed to explain how the attended location is chosen, but these models have had less to say about how the size of the attended area can be adjusted according to the task. Nonetheless, there are clear demonstrations that attention can zoom in to a small region for difficult tasks, and can pan out to select a wide area for easier tasks (Eriksen & St. James, 1986; Laberge, 1983; Larsen & Bundesen, 1978). More recently, Rijpkema, van Aalderen, Schwarzbach, and Verstraten (2008) have used brain imaging to show that cortical regions with different receptive field sizes can be activated to match the attentional zoom settings required for different visual tasks. Models of attention need to be expanded to capture this adjustment of attentional zoom more fully.

DIFFERENTIATING ATTENTIONAL MECHANISMS

As noted earlier, it is usually difficult to determine the extent to which the task of visual selection is divided across separate mechanisms. For instance, are spatial attention and object attention performed by a single system or two separate systems? Are there different selection mechanisms working at different levels of the hierarchy within the visual system? Or does attentional selection require coordination between lower and higher levels of visual processing? The behavioral methods that have been used to explore these questions for some time can now be augmented with localization information from fMRI and timing information from ERP studies in order to find the boundaries between the different parts of the attentional system. This line of enquiry may also provide a better understanding of the computational limitations within the visual system that make attentional selection necessary in the first place.

ATTENTION AND CONSCIOUSNESS

Spatial attention seems to be necessary to prevent the visual system from being overwhelmed by the amount of incoming retinal input to be processed. However, it has been natural to assume that this selection mechanism also serves as the gateway to visual consciousness. Perhaps everything that is selected makes its way into our awareness, while everything not selected remains outside of conscious. That assumption, however, is contradicted by evidence showing that visual stimuli can be selected without making it into awareness. One unusual example comes from Jiang, Costello, Huang, and He (2006), in which nude images draw attention to their location without the observer's awareness. Thus, visual selection and consciousness must be separate, and even when a stimulus is selected within the visual system, it may still not be able to pass through the higher level gateway into awareness.

Koch and Tsuchiya (2007) suggested that there might be a pathway for stimuli to enter consciousness without being selected by spatial attention, based on the finding by Li, VanRullen, Koch, and Perona (2002) that animals and vehicles could be detected in scenes while attention was occupied in a different part of the visual field. While it is clear that performance on the detection tasks can be surprisingly good, it is not clear that it is done without any contribution from spatial attention (Cohen, Alvarez, & Nakayama, 2011). Thus, the full relationship between spatial attention and conscious experience remains to be fully worked out.

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