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Using a filtering task to measure the spatial extent of selective attention

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ABSTRACT

The spatial extent of attention was investigated by measuring sensitivity to stimuli at to-be-ignored locations. Observers detected a stimulus at a cued location (target), while ignoring otherwise identical stimuli at nearby locations (foils). Only an attentional cue distinguished target from foil. Several experiments varied the contrast and separation of targets and foils. Two theories of selection were compared: contrast gain and a version of attention switching called an all-or-none mixture model. Results included large effects of separation, rejection of the contrast gain model, and the measurement of the size and profile of the spatial extent of attention.

1. Introduction

The spatial extent of attention refers to the region of space in which perceptual tasks are affected by an attentional state. For example, one might cue a point in space as relevant to a task and then measure the extent to which nearby locations are also affected. If attention affects sensitivity, then one can refer to the effect of attention across space as a *spatial sensitivity function*, highlighting an analogy to spatial tuning functions of neurons in sensory areas of the cortex. Such spatial sensitivity functions, like tuning functions of neurons, can have different profiles for different conditions. For example, the spatial sensitivity function might be quite narrow under some conditions, with only a small region surrounding the cued location showing effects of attention, whereas under other conditions it may extend more broadly around the cued location. Also, like the spatial tuning function of neurons, the spatial sensitivity function may sometimes have relatively complex profiles such as an antagonistic center-surround structure. These issues have been investigated through a diverse range of paradigms.

In the present study, we develop a filtering paradigm to characterize the spatial extent of attention that is based on psychophysical theories. The theoretical basis of this paradigm allows a quantitative evaluation of alternative answers to multiple questions within a single theoretical framework. A goal in developing this framework is to provide a common theoretical context within which one can derive and test hypotheses about the effects of attention on human behavior and the effects of attention on the underlying neurophysiology.

Perhaps the best known approach to investigating the spatial extent of attention is to cue a location and observe how detection or discrimination performance changes with increasing separation between the cued location and the target. Sagi and Julesz (1986), for example, used a dual-task paradigm in which observers were to discriminate whether a stimulus presented at a cued location was a T or an L, while simultaneously monitoring the display for the presentation of probe dots at other locations. They found that for a cued location at an eccentricity of 4°, there was a region surrounding the cued location with a diameter of 3° that had improved detection performance relative to more distant locations. Several studies have used variations of this dual-task approach to further study the spatial extent of attention (e.g., Huang & Dobkins, 2005; LaBerge, 1983; Lee, Itti, Koch, & Braun, 1999; Zenger, Braun, & Koch, 2000).

An alternative to the dual-task approach is to use partially valid cues (e.g., response time: Shulman, Wilson, & Sheehy, 1985; Moore, Lanagan-Leitzel, & Fine, 2008; accuracy: Niebergall, Tzvetanov, & Treue, 2005). In this paradigm, detection or discrimination performance to stimuli presented at cued locations (*valid condition*) is compared to performance at uncued locations (*invalid condition*). Shulman et al. (1985) found, for example, that increasing the distance between the cued location and the uncued location increased the response time to the uncued location monotonically for distances of 0–20°.

The cueing paradigm has been modeled in different ways. Sperling and Weichselgartner (1995) did so using a theory that

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emphasizes gain mechanisms, which are natural specifications of the idea that the processing of stimuli at uncued locations is attenuated relative to that at cued locations (Treisman, 1960). Bahcall and Kowler modeled it as an all-or-none process whereby sometimes stimuli at the cued location are processed, but other times stimuli at an uncued location are processed instead. This is a specification of the idea that stimuli at uncued locations are filtered out from further processing (Broadbent, 1958) or as attention switching from the cued to uncued locations (Sperling & Melchner, 1978).

There are several interesting variations of the cueing paradigm. Some studies use cues that indicate the location of the target with 100% validity and study the effect of noise (e.g., Davis, Kramer, & Graham, 1983; Dosher, Liu, Blair, & Lu, 2004; Eckstein, Shimozaki, & Abbey, 2002; Eriksen & Hoffman, 1973). Other studies introduce an array of stimuli and require the maintenance and manipulation of the attended stimuli (Intriligator & Cavanagh, 2001; Moore, Lanagan-Leitzel, Chen, Halterman, & Fine, 2007). Studies of this sort (i.e., that included competing noise) have yielded estimates of the spatial extent of attention that tend to be narrower than estimates from dual-task and partially valid cueing studies. Such diversity of estimates regarding the spatial extent of attention has contributed to conclusions that the spatial extent of attention is under flexible control and that it depends on the stimulus and task (e.g., Cheal, Lyon, & Gottlob, 1994; Eriksen & St. James, 1986; LaBerge & Brown, 1989).

In addition to differences in the estimates of the size of the spatial extent of attention, qualitative differences have also been observed across studies and paradigms. In particular, whereas the studies cited so far all found monotonic effects of the separation between cued and uncued locations, other studies have reported non-monotonic effects (e.g., Cutzu & Tsotsos, 2003; Steinman, Steinman, & Lehmkuhle, 1995). In these studies, the observed performance is consistent with a center-surround profile analogous to the spatially antagonistic processing of visual information that is commonly observed in early visual neurons. Performance is better for stimuli presented at the cued location than for stimuli presented at a distant baseline location. Performance is worse, however, for stimuli presented at locations nearby the cued location than for stimuli presented at the distant baseline location. Such a profile is predicted by a computational theory developed by Tsotsos and colleagues (Tsotsos et al., 1995; see also Trappenberg, Dorris, Munoz, & Klein, 2001) in which top-down cue information is systematically combined with bottom-up stimulus processing. The center-surround profile has also received support from studies in which two items are cued and observers must process (e.g., identify) both. These studies often find reduced performance with reduced separations between the targets (Bahcall & Kowler, 1999; Becker, 2001; Cutzu & Tsotsos, 2003; Mounts, 2000; but see Sagi & Julesz, 1986).

An alternative to the cueing paradigms just reviewed is the filtering paradigm. In filtering paradigms, one must attend to some stimuli while ignoring others. For example, shadow the message in one ear while ignoring the message in the other ear (e.g., Cherry, 1953). Or, classify the size of a stimulus while ignoring the color (e.g., Gottwald & Garner, 1975). For a definition of a filtering task see Kahneman and Treisman (1984) and for a more recent discussion see the first chapter of Pashler (1998). This paradigm is also known as a gating task (Posner, 1964) or a focused attention task (Yantis & Johnston, 1990). More generally, one can find aspects of spatial filtering in masking (e.g., Baldassi & Verghese, 2005), crowding (e.g., Parkes, Lund, Angelucci, Solomon, & Morgan, 2001) and surround suppression paradigms (e.g., Petrov & McKee, 2006). To make clear what distinguishes a filtering paradigm, note that a partially valid cueing task is not an example of filtering because both valid and invalid stimuli are relevant to the response. Similarly, dual-task situations (e.g., Sagi & Julesz, 1986) are not examples of filtering because both tasks are relevant to a response. The filtering task that is probably most similar to the cueing studies reviewed above and that has been used to study the spatial extent of attention is the flanker paradigm (Eriksen & Hoffman, 1973; Eriksen & Eriksen, 1974). We focus our review on this task.

In the flanker task, performance to stimuli that are presented at a single relevant location is compared across conditions in which irrelevant but potentially distracting stimuli (flankers) are presented at variable distances from the relevant location. Thus, this is a filtering task. The special feature emphasized in the flanker task is the use of a many-to-one categorization task in which multiple stimuli (typically letters) are mapped onto a single response. This mapping allows one to compare the effect of flankers that are compatible with the category of the target to those that are incompatible with the target. Such a *flanker compatibility effect* must be mediated by post-categorical processing because the stimuli are arbitrarily assigned to categories. Eriksen and Hoffman (1973), for example, applied this task to the question of the spatial extent of attention. They found that the identification of target stimuli presented at fixation was influenced by compatible flanking letters when those letters appeared within 1° in either direction of the target, but not when they appeared farther away. These results have been replicated in several studies (e.g., Miller, 1991; Pan & Eriksen, 1993; Yantis & Johnston, 1990) and a recent study has reported evidence for a center-surround profile (Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005). More recently, this flankers task has been used with non-letter stimuli (e.g., Cohen & Shoup, 1997; Mordkoff, 1998). In general, the flanker task has several distinguishing features that make it useful for studying the spatial extent of attention. It measures manipulations of the irrelevant flankers rather than manipulations of the targets. Importantly, these targets and flankers are identical except for one being at a cued location and the others being at uncued location.

To summarize this brief review of prior approaches to studying the spatial extent of attention, the large range of prior approaches has lead to a large range of results regarding at least three aspects of the spatial extent of selection: the size of the spatial extent, the profile of the spatial extent, and the mechanism from which the spatial extent derives. In particular, some found large extents of spatial attention; others much smaller extents. Some found the spatial extent of attention to have a monotonic profile; others found it to have a center-surround profile. Some found results consistent with a form of gain; others found hints of an all-or-none filter.

In this article, we develop a theoretical framework within which these aspects of the spatial extent of attention—size, profile and mechanism—as well as others, can be addressed systematically within a common context. The framework is grounded in existing psychophysical theories of sensory phenomena. The idea is that by using explicit psychophysical theory, diverse behavioral effects of attention can be related to each other. Moreover, behavioral effects of attention can be related to the underlying neurophysiological effects of attention. The theory provides a framework within which to develop explicit linking propositions between behavioral and neurophysiological mechanisms (Teller, 1984).

1.1. Overview of the spatial filtering paradigm

The basis of our approach is a particular cueing paradigm, which we refer to as *spatial filtering in a visual detection task* or *spatial filtering* for short. The central idea is to present stimuli at both a relevant and an irrelevant location and to measure detection performance as a function of the separation between these locations. We refer to the stimulus at the relevant location as the *target* and the stimulus at the irrelevant location as the *foil*. Nothing other than location—relevant versus irrelevant—distinguishes the target