

Three Paradigms for Selective Attention in Vision

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ABSTRACT

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The first study investigated the underlying mechanisms of selective attention and the extent of which an irrelevant stimulus is processed as well as the nature of this processing. A spatial filtering paradigm was used to quantify the effects of an irrelevant stimulus in a selective attention task (Chapter 1). The results have shown that if the task requires observers to constrain their attention to a small spatial area, a blocking mechanism is used for selection. In blocking, unattended stimuli are blocked from further processing. If the task requires observers to distribute their attention to a large spatial area, an attenuation mechanism is used for selection. In attenuation, the unattended stimuli are reduced in strength, but at high intensities (e.g., high contrast), they can still have access to further processing. In the second study, the same paradigm was used with the combination of many-to-one response mapping of the flanker paradigm to unravel the nature of the effects of irrelevant stimuli on the judgment of a relevant stimulus (Chapter 2). The results have shown that the effects of irrelevant stimuli are consistent with a failure of selection, which is an example of blocking mechanism.

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INTRODUCTION

Goal of dissertation

This dissertation describes the research that investigated which selection mechanisms are used for different visual selective attention tasks and the nature of the effect of irrelevant stimuli on the judgment of a relevant stimulus. Selective attention can be defined as using relevant sources of information while ignoring the irrelevant sources. Selection mechanisms are the systems that make selection possible. Understanding these mechanisms and the fate of an irrelevant stimulus is one of the main goals of selective attention research.

Overview of the dissertation

In the introduction, I describe the topics that I investigated and provide a brief explanation of the experiments. Chapter 1 and 2 describes the experiments I carried out in collaboration with John Palmer and Cathleen Moore and discusses the significance of the results. Chapter 3 summarizes the findings and discusses the future work. The first study has been published and the second is in preparation for publication.

Overview of the studies

Sensory and cognitive systems constantly deal with countless stimuli some of which are relevant and some are irrelevant. These systems have to select the stimuli that are relevant in order to carry out tasks in a goal directed manner and not be distracted by the countless irrelevant stimulation. The manner of which the selection is accomplished is controversial. There are two main mechanisms of selection: blocking (Broadbent, 1958) and attenuation (Treisman, 1960). Blocking refers to receiving

information from only the selected stimulus while blocking any other information.

Attenuation refers to getting full information from the selected stimulus and attenuated information from the other stimuli. Previous research has not reached a consensus on which selection mechanism is used (Boradbent, 1958; Sperling & Melchner, 1978; Mack & Rock, 1998). In Experiment 1.1, a new method allowed directly measuring response to irrelevant stimuli. In a spatial filtering paradigm (Palmer & Moore, 2009) one can display stimuli at relevant and irrelevant locations in the periphery while manipulating the distance between these locations and the intensity of the stimuli. This paradigm required observers to monitor a narrow relevant location and ignore the other locations. The design allowed measuring response for both the relevant and irrelevant stimuli. The response to the irrelevant stimulus reveals the selection mechanism. At the largest separation, response to the irrelevant stimulus was at chance. At the smallest separation, response to the irrelevant stimulus was the same as response to the target indicating that observers could not differentiate the relevant and irrelevant stimuli. At the medium separation, response to the irrelevant stimulus was somewhere between chance and perfect. For such separation at high contrasts, the response for the irrelevant stimulus did not reach near perfect. This result is consistent with blocking.

In Experiment 1.2, a spatial monitoring paradigm was used in which a single relevant stimulus was displayed at different locations. Only one of those locations was cued as the most likely location to have the target. This paradigm required observers to monitor a large area for detecting the target. The contrast of the stimulus was varied as well as the location of the stimulus. I measured proportion correct as a function of stimulus contrast. When the stimulus appeared at the cued location, the performance

was near perfect. As the location of the stimulus got further away from the cued location, the performance at medium contrasts declined, but at high contrasts, it reached near perfect. This result is consistent with attenuation.

There are cases in which an irrelevant stimulus affects the judgment of relevant stimulus. The nature of this effect has been a long debate. One line of research suggested that this effect was due to interactive processing of stimuli or interactive processing of response codes, or both (Estes, 1972; Eriksen & Eriksen, 1974; Botella, 1996). The other line of research suggested that this effect was due to less than ideal selection conditions in which selection inevitably fails (Yantis & Johnston, 1990; Lachter, Forster, & Ruthruff, 2004). The previous research failed to use a design that could test both hypotheses. Experiment 2.1 and 2.2 combined two paradigms to take advantage of their unique characteristics. As in the flanker paradigm (Eriksen & Eriksen, 1974), a set of stimuli were mapped to different response sets so that two of the stimuli required the same response while the other two required another response. As in the spatial filtering paradigm, these stimuli were presented in the periphery. Their separation and contrasts were varied. The stimulus-response mapping of flanker paradigm allows three congruency conditions: identical where both stimuli are identical, response congruent where the stimuli are from the same response set, and response incongruent where the stimuli are from the different response sets. The results have shown that there was an effect of the irrelevant stimulus only in the response incongruent condition and only when the separation of the stimuli was small. The performance was somewhere between near perfect and chance even when the stimulus contrast was high. This result is consistent with failure of selection, which is an example of blocking.

CHAPTER 1

Distinguishing blocking from attenuation in visual selective attention

Sensory systems provide an understanding of the world and guide behavior. To do so, they must process sensory information selectively. What information is selected depends on the task and the goals of the observer. In the case of reading, for example, many words are visible at once, yet the reader selects and processes only one or two at any given moment and ignores the rest. How such selection is accomplished is a controversial issue. One possible mechanism is *blocking* (Broadbent, 1958), and another is *attenuation* (Treisman, 1960). In the case of blocking, signals from unattended stimuli are eliminated at some point within the stream of processing, and therefore fail to gain access to later processes. In the case of attenuation, signals from unattended stimuli are reduced in strength but not completely eliminated. Thus, unlike blocked stimuli, attenuated stimuli—if strong enough—can gain access to downstream processes. This distinction between blocking and attenuation refers to how selection occurs, not to the level of processing at which it occurs (e.g., at “early,” sensory stages or “later,” semantic stages). This article presents a general experimental and theoretical approach that distinguishes blocking from attenuation.

Prior attempts to distinguish blocking from attenuation have led to little consensus. Unattended stimuli can sometimes go entirely unnoticed, which suggests that they were blocked from access to those processes that give rise to awareness. Such effects have been shown in paradigms such as selective listening (Broadbent, 1958), selective looking (Mack & Rock, 1998), and partial report (Sperling, 1960), as well as during performance of dual (concurrent) tasks (Bonnell, Stein, & Bertucci, 1992; Sperling & Melchner, 1978). However, sometimes an unattended stimulus that is semantically significant (e.g., one’s own name) reaches awareness, as if it has “broken

through” a selective filter (Cherry, 1953; but see Lachter, Forster, & Ruthruff, 2004). Findings such as these suggest that unattended stimuli are never completely blocked, but rather are merely attenuated. A related debate on the relative adequacy of blocking and attenuation accounts has unfolded in the neurophysiological literature on the effects of attention on single-cell responses (e.g., McAdams & Maunsell, 1999; Reynolds, Pasternak, & Desimone, 2000) and on the human hemodynamic response (e.g., Buracas & Boynton, 2007; Li, Lu, Tjan, Doshier, & Chu, 2008). We consider the neurophysiological literature further in the General Discussion.

Selection may occur through a variety of different mechanisms and at multiple points through the system. In the study reported here, we applied a psychophysical method that can be generalized to distinguish blocking from attenuation in a range of tasks and stimulus conditions (Palmer & Moore, 2009). This generality can help researchers develop a more complete picture of what mechanism is engaged under what circumstances.

The key to distinguishing blocking and attenuation is that increasing the strength of attenuated stimuli can result in those stimuli influencing performance, whereas increasing the strength of blocked stimuli can have no influence on performance. This distinction is implicit in the logic of early studies on the “fate of unattended stimuli,” which measured indirect effects of unattended stimuli, such as priming effects (e.g., Shaffer & LaBerge, 1979). The approach we used goes further, by systematically manipulating the strength of the stimuli. Specifically, we measured psychometric functions from near-chance to perfect performance for a stimulus at a to-be-attended location. The stimuli that yielded asymptotically perfect or near-perfect performance

establish what we consider to be strong stimuli. We then measured the effects of a stimulus at a to-be-ignored location over the same range of strength—a new approach (Palmer & Moore, 2009). Psychometric functions for a stimulus at a to-be-ignored location allow one to test both qualitative and quantitative predictions that derive from the general distinction that increasing the strength of blocked stimuli cannot influence performance, whereas increasing the strength of attenuated stimuli can. In short, we ask whether a strong stimulus overcomes the effect of not being attended.

We applied this approach to two different selective attention paradigms: spatial filtering and spatial monitoring with partially valid cues. Both paradigms have been used to investigate the spatial resolution of selective attention (Intriligator & Cavanagh, 2001). In the case of spatial filtering (Figure 1.1a), stimuli in some locations must be ignored in order to perform the assigned task (Palmer & Moore, 2009; see also the related tasks used by Eriksen & Eriksen, 1974; Gobell, Tseng, & Sperling, 2004). Such filtering tasks are a good model for reading, in which one must ignore some words on the page in order to read others. While one is reading a line of text, other lines of text are “foils” for the task at hand. In contrast, in the case of spatial monitoring with partially valid cues (Figure 1.1c), the relevant stimulus can appear in many locations, but it is most likely to appear in a cued location (Eckstein, Peterson, Pham & Droll, 2009; Posner, 1980; Shimozaki, Eckstein, & Abbey, 2003). Such monitoring tasks are a good model for driving, as relevant events typically occur on the road but can also occur elsewhere. In this case, the stimuli at uncued locations are not foils because they can be relevant to the task. In sum, both the filtering and the monitoring paradigms include cues that

indicate the relevance of different locations. The paradigms differ in that filtering includes irrelevant foils whereas monitoring does not.

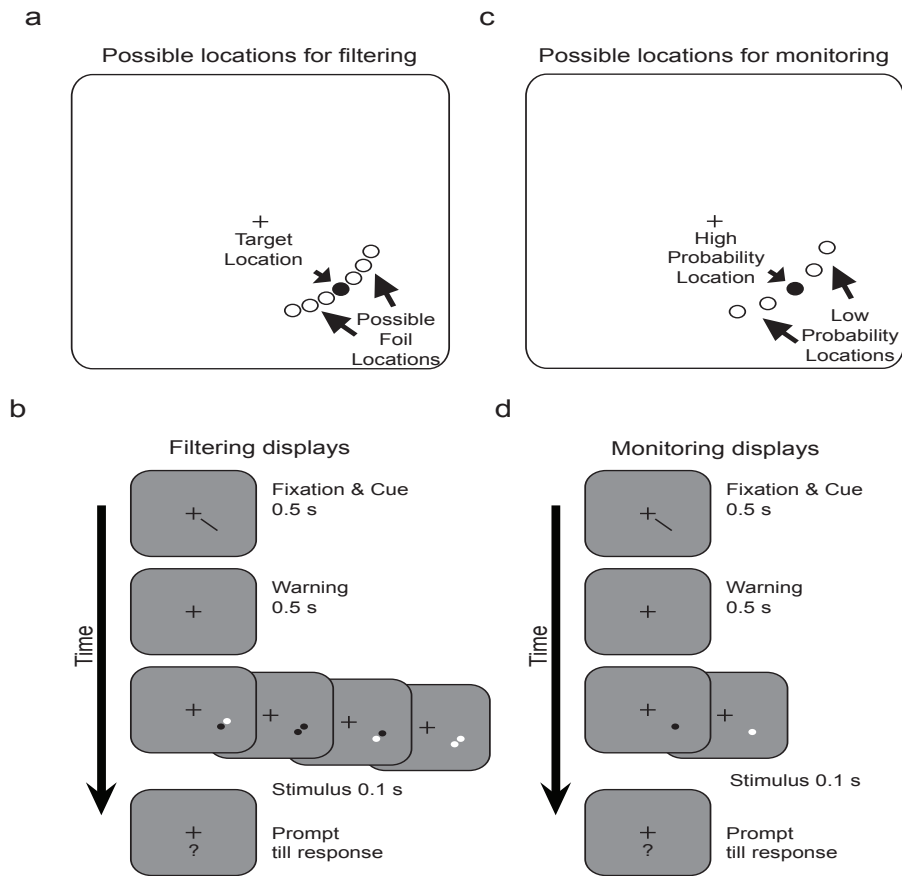


Figure 1.1. Illustrations of the stimuli and procedure of Experiment 1.1 (spatial filtering) and Experiment 1.2 (spatial monitoring). In Experiment 1, the critical display (a) included two discs, a target at a cued location and a foil that could be located at any of six other locations. In Experiment 1.2, the critical display (c) consisted of a single target disc that could appear at a high-probability location (i.e., the cued location) or one of four low-probability locations. In both experiments, the trial sequence (b, d) consisted of presentation of the cue (with a fixation point), a warning period, the critical stimulus display, and finally a response prompt. Observers' task was to report whether the target disc was darker or lighter than the surround. The sequence for Experiment 1.1 (b) shows multiple possible critical displays, illustrating all combinations of target and foil polarity, and the sequence for Experiment 1.2 (d) shows displays with both possible target polarities. However, only one critical display was presented on any single trial. Although both the target and foil stimuli are clearly visible in the illustrations in (b), the actual displays appeared to include only a single stimulus because one was at a near-threshold contrast. These diagrams are not to scale.

General method

In both experiments, stimuli were briefly presented in the periphery, and observers judged the contrast polarity of the target, that is, whether the target was lighter or darker than the surround. A low-frequency tone indicated that the response was incorrect; there was no tone to indicate that the response was correct.

Six observers participated in both of the experiments. They were consenting adults with normal or corrected-to-normal visual acuity (author S. Y.-E. was one of the observers). The stimuli were presented on a calibrated video monitor controlled by a Macintosh computer using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Eye movements were recorded using a video system (EyeLink, SR Research, Ottawa, Ontario, Canada). Eye position was recorded for all trials, and trials were included in the analysis only if good fixation was confirmed. Across observers in Experiment 1.1, a mean of $1.4 \pm 0.4\%$ of trials were excluded (range = 0.4%–3.3%). (Throughout this article, the plus-minus notation specifies the standard error of the mean for the value being described.) In Experiment 1.2, a mean of $1.4 \pm 0.7\%$ of trials were excluded (range = 0.3%–4.6%). Most of these exclusions were due to eye blinks or equipment problems, rather than to saccades to the peripheral stimulus locations. In summary, observers were successful at maintaining fixation, and the data set did not include any trials with saccades to peripheral locations. Further details of the method are the same as for our previous studies (Palmer, Huk, & Shadlen, 2005; Palmer & Moore, 2009).

Experiment 1.1: Spatial filtering

For the filtering task used in Experiment 1.1, targets were presented at a cued location, and irrelevant foils were presented at nearby locations. Target contrast, foil contrast, and the separation between the target and foil locations were manipulated to test the hypotheses.

Method. The task is illustrated in Figures 1.1a and 1.1b. In the critical stimulus display, two discs with a diameter of 0.3° were presented at an eccentricity of 8.0° . One disc (the *target*) was presented at the location cued by a bar marker at the beginning of the trial. The other disc (the *foil*) appeared at an uncued location, on either side of the cued location. Both targets and foils appeared with both possible polarities (lighter or darker than the surround). The polarities of the target and foil were independent of one another. Because targets and foils were sampled from the same set of stimuli, they were distinguished by location only. Observers had to ignore the foils to perform the task. The cue was always in the same location, corresponding to the clock position of 4:30. We also manipulated the separation between the target and foil. Three target-foil separations were used in Experiment 1.1: 0.6° , 1.2° , and 2.4° .

Contrast was varied for both of the stimuli as shown in Table 1.1. (The values of contrast were slightly different for each observer to roughly match performance across observers.) *Target psychometric functions* were determined from trials in which the foil had a constant, near-threshold contrast, and the contrast of the target was variable within the range from near threshold to well above threshold. *Foil psychometric functions* were determined from trials in which the target had a constant, near-threshold contrast, and the contrast of the foil was variable within the range from near threshold to well above threshold. The purpose of pairing a low-contrast target with foils to determine

the foil function was to minimize the effect of the target on that function. In this we were successful, as the polarity of the target had no reliable effect on the foil function (see the congruency analysis in Palmer & Moore, 2009).

Table 1.1. Target and foil contrast values that were paired in Experiment 1.1

Target contrast	Foil contrast					
	5%	7%	10%	14%	20%	100%
100%	X					
20%	X					
14%	X					
10%	X					
7%	X					
5%		X	X	X	X	X

Analysis and predictions. Results were analyzed using psychometric functions relating behavioral performance to stimulus contrast. All psychometric functions were cumulative normal functions raised to a power (Pelli, 1987) and fit using maximum likelihood methods. This method of analysis yields functions that are essentially indistinguishable from a fit to a Weibull function (Pelli, 1987). The psychometric functions were described by three parameters: upper asymptote, detection threshold, and exponent. The exponent was always fixed to 3, which is typical for contrast detection experiments. The detection threshold was defined as the contrast necessary to yield a performance level halfway between chance (.5) and the estimated asymptote. This definition is used when there are *lapses*, which are errors that occur independently of the stimulus value. It also captures a regularity predicted by attention-switching models (e.g., Shaw, 1980). Suppose the percentage of attended trials drops from 100% to 50%; in this case, such models predict that the upper asymptote drops from 100% to 75% while the threshold remains the same. The threshold is constant because the same stimulus yields the criterion performance halfway between chance and the upper asymptote.

Separate psychometric functions were derived for the target and the foil. The target psychometric function was the proportion of trials in which the response corresponded to the contrast polarity of the target (i.e., proportion correct), as a function of target contrast. The foil psychometric function, which is new to this approach, was the proportion of trials in which the response corresponded to the contrast polarity of the foil, as a function of foil contrast. (Note that a response corresponding to the contrast polarity of the foil was not equivalent to a correct response because it depended on the

foil rather than the target.) If selection were perfect, then the foil psychometric function would be constant at .5 because the polarity of the foil was independent of the polarity of the target. However, if selection failed, the foil psychometric function could differ from .5. If selection failed completely, the foil psychometric function would be identical to the target psychometric function. Thus, a feature of this method is that performance can vary from one extreme to the other. Selection must fail completely for small-enough separations and is likely to be perfect for large-enough separations. Thus, the attention effects are as large as possible with a binary response measure.

Blocking and attenuation have different implications for the foil psychometric function. Blocking predicts that in the case of intermediate target-foil separations and imperfect selection, the psychometric function will reach an asymptote at an intermediate value because strong stimuli cannot overcome the blocking. In contrast, attenuation predicts that the asymptote will remain high, because with sufficient stimulus strength, an attenuated stimulus can produce the same high level of performance that an unattenuated stimulus can. How selection affects the threshold and shape of the foil psychometric function depends on further assumptions about how selection is implemented.

Figures 1.2a and 1.2b present predictions for two specific models. (Formal definitions and quantitative predictions are given in Palmer & Moore, 2009; in particular, see the appendix on the contrast gain model and the all-or-none mixture model.) In a *contrast gain model* (attenuation; Figure 1.2a), the effective contrast of stimuli at uncued locations is reduced, and the degree of reduction decreases with increasing separation between the cued location and the foil (Reynolds et al., 2000). The elegance of this

model is that attention affects only the effective contrast and not the further processing of the stimulus. In a switching model (blocking; Figure 1.2b), behavior is determined entirely by the target on some trials and by both the foil and the target on others. The probability that behavior is influenced by the foil decreases with increasing separation between the cued location and the foil (Shaw, 1980). One can interpret this decreasing probability with separation as reflecting the imprecision with which the observer directs attention; hence, this model is called the *imprecise-targeting model* (Bahcall & Kowler, 1999). The elegance of this model is that attention affects the mixture across trials of only two possible states: attended and ignored.

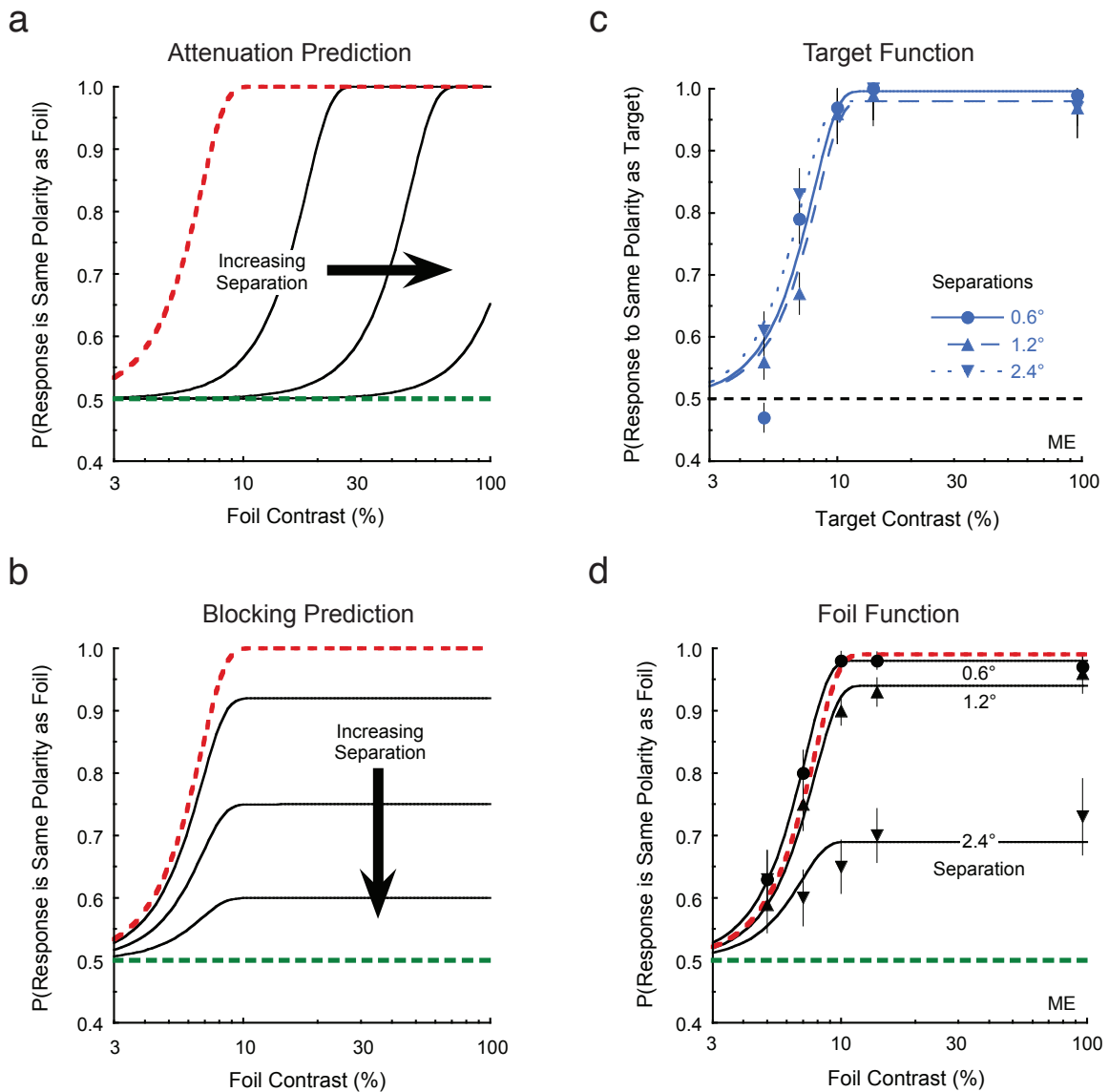


Figure 1.2. Predictions and example results for Experiment 1.1. The contrast gain model (attenuation; a) and the imprecise-targeting model (blocking; b) generate different predictions for the foil psychometric function. Results for observer M. E. are shown in (c) and (d), which present observed performance and the best-fit target and foil psychometric functions for the three tested target-foil separations. The error bars indicate the standard error of the proportions. In (a), (b), and (d), the dashed green lines show the predictions for the extreme of perfect selection, which is likely at large target-foil separations. The dashed red curves show the predictions for the extreme of no selection, which is likely at small target-foil separations.

These models make different predictions for the foil psychometric function. The critical test concerns how this function changes between the extremes of perfect and no selection, that is, at intermediate separations. The contrast gain model (Figure 1.2a) predicts a horizontal shift with increasing separation. Thus, there is a change in threshold but not asymptote. In contrast, the imprecise-targeting model (Figure 1.2b) predicts a vertical scaling with increasing separation. There is a change in asymptote but not threshold. In sum, the general predictions are that blocking affects the asymptote and attenuation does not; the specific predictions are that imprecise targeting affects only the asymptote, and contrast gain affects only the threshold.

Results. Figure 1.2c shows the observed performance and best-fit target psychometric functions for a single observer (M. E.). As expected, the amount of separation from a low-contrast foil had little effect on target detection. However, the critical predictions all involved the foil function. Figure 1.2d shows the observed performance and best-fit foil psychometric functions for the three separations in the same observer (results for all observers are shown in Figures S1 and S2 of the Supplemental Material available). The results are consistent with imprecise targeting (blocking). Separation affected the asymptote almost exclusively, having little or no effect on the threshold. This was true for all 6 observers; the mean asymptote dropped from $.96 \pm .01$ for the smallest separation to $.59 \pm .03$ for the largest separation. This is almost the maximum possible effect, ranging from near-perfect performance (1.0) at the smallest separation to near-chance performance (.5) at the largest separation. In contrast, across the 6 observers, the contrast threshold did not change with separation; the mean threshold was $6.6 \pm 0.4\%$ for foils at the smallest separation, $6.6 \pm 0.7\%$ for

foils at the largest separation, and $6.7 \pm 0.4\%$ for targets. In summary, performance on the spatial filtering task was consistent with selection by blocking and not attenuation.

Experiment 1.2: Spatial monitoring

Method. The method for Experiment 1.2 was the same as for Experiment 1.1 except that the target location was probabilistic and foils were eliminated. The locations used and the trial sequence are illustrated in Figures 1.1c and 1.1d. The task was to judge the contrast polarity of a single disc (target); the precue indicated its most likely location. The target appeared in the cued location on 50% of the trials (*valid*), and in each of four nearby locations on 12.5% of the trials (*invalid*). The invalid *near* and *far* locations were 3.6° and 7.2° to either side of the cued location, respectively. Thus, separation in this task refers to the distance between the target and the cued location. This was not a filtering task because it was not necessary to ignore information at uncued locations. Indeed, uncued locations had to be monitored because the target sometimes appeared in them.

Results. Figures 1.3a and 1.3b illustrate the psychometric functions predicted by the contrast gain and the imprecise-targeting models, respectively. As in the case of filtering, the contrast gain model predicts a horizontal shift in the psychometric function (threshold change) as separation increases, whereas the imprecise-targeting model predicts a vertical scaling (asymptote change). Figure 1.3c shows the observed performance and best-fit psychometric functions for observer M. E. (results for all observers are shown in Figures S3 of the Supplemental Material). Unlike the results for spatial filtering, the results for spatial monitoring were consistent with contrast gain

(attenuation). For all 6 observers, separation affected the threshold almost exclusively, having little or no effect on the asymptote. Across observers, the mean contrast threshold was $6.8 \pm 0.5\%$ for the valid condition, $8.1 \pm 0.6\%$ for the invalid-near condition, and $9.6 \pm 0.7\%$ for the invalid-far condition. The asymptotes were $.98 \pm .01$ for the valid condition, $.98 \pm .01$ for invalid-near condition, and $.97 \pm .01$ for the invalid-far condition. In summary, spatial monitoring yielded performance consistent with selection by attenuation and not blocking.

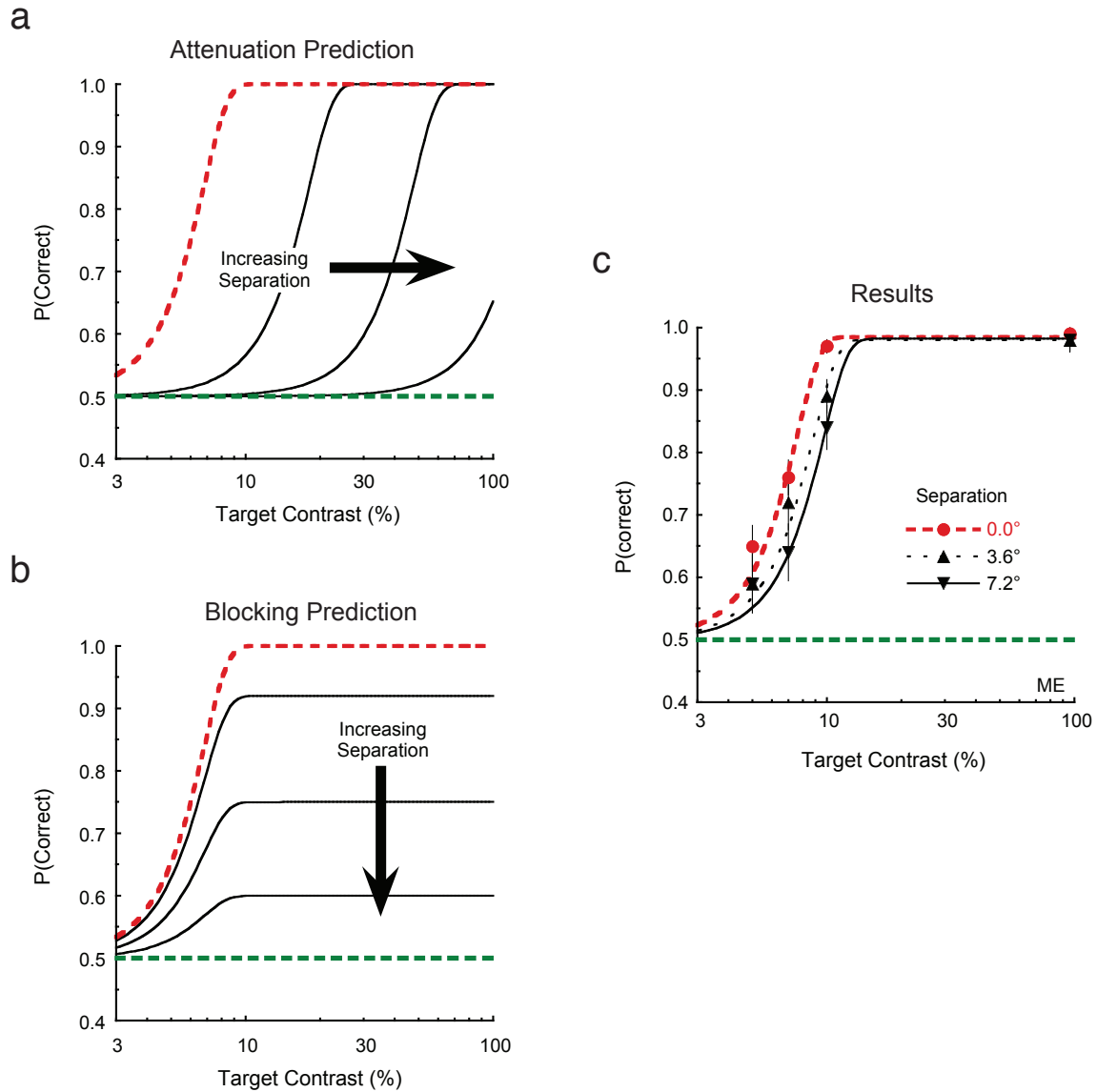


Figure 1.3. Predictions and example results for Experiment 1.2. The contrast gain model (attenuation; a) and the imprecise-targeting model (blocking; b) generate different predictions for proportion correct as a function of target contrast. The observed performance and best-fit psychometric functions for 1 observer (M. E.) are shown in (c). The error bars indicate the standard error of the proportions. In all three graphs, the dashed green lines show the prediction for the extreme of very narrow selection, with the stimulus at a large separation completely ignored. The dashed red curves show what is expected if there is no selection, which for this experiment is the same as when the stimulus is at the cued location.

Spatial extent of selective attention

Figure 1.4 characterizes the spatial extent of selection averaged across observers. In the case of spatial filtering (Experiment 1.1), separation affected the asymptote almost exclusively, whereas in the case of spatial monitoring (Experiment 1.2), separation affected sensitivity almost exclusively. Moreover, the asymptote for spatial filtering changed from near 1.0 at the smallest separation to near chance (.5) at the largest separation, whereas the threshold for spatial monitoring changed by a factor of less than 2. This figure also highlights the fact that the *critical separation*—a measure of the spatial extent of selection—must be estimated differently for the two tasks. This is because selection affects different aspects of performance for the two tasks. Previous work has estimated the spatial extent of selection in a variety of ways with a variety of results (Intriligator & Cavanagh, 2001; Sagi & Julesz, 1986). The current results provide insight into the heterogeneity of these results because the critical separation depends on the underlying mechanism of selection. The asymptote is relevant for spatial filtering, whereas the threshold is relevant for spatial monitoring. We fit Gaussian-shaped functions and estimated the critical separation with a single width parameter defined as the separation that yields half the response observed with zero separation (for details, see Palmer & Moore, 2009). The critical separation was $1.6^\circ \pm 0.1^\circ$ for spatial filtering and was greater than 10° for spatial monitoring. In summary, the spatial filtering and spatial monitoring paradigms yield evidence of different selection mechanisms and different estimates of the spatial extent of selection.

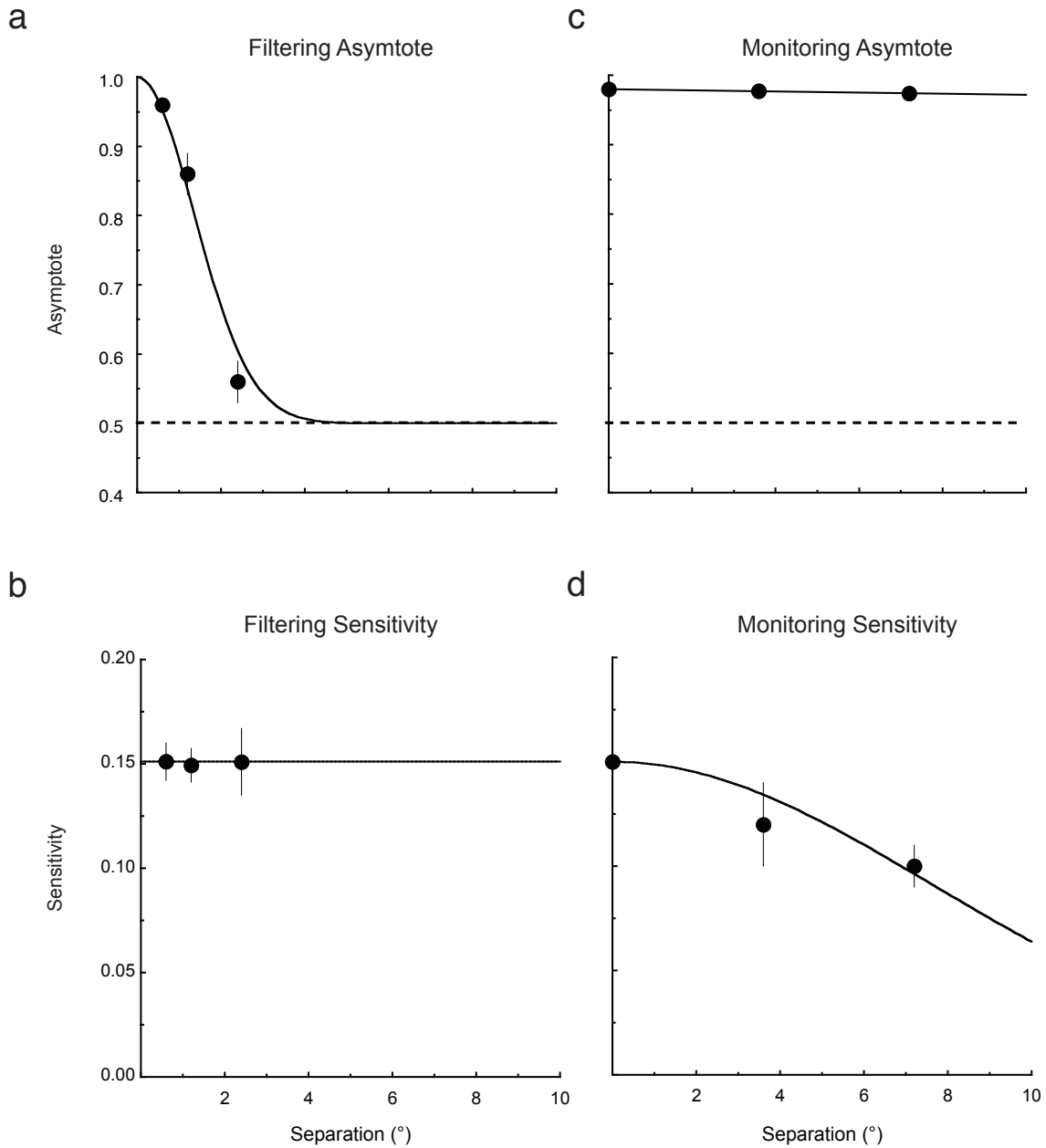


Figure 1.4. Mean asymptote and sensitivity (1/threshold) in Experiment 1.1. (spatial filtering) and Experiment 1.2 (spatial monitoring). For filtering, the asymptote (a) and sensitivity (b) are shown as a function of the separation between the foil and the cued location; for monitoring, the asymptote (c) and sensitivity (d) are shown as a function of the separation between the target and the cued location.

General discussion

Our central thesis essentially concerns the definition of blocking and attenuation. Rather than define them in specific terms that refer, for example, to different types of physiological gain mechanism (e.g., contrast gain vs. response gain; Huang & Dobkins, 2005; Pestilli, Ling, & Carrasco, 2009), we define them in terms of the consequences of selection. In particular, blocking is any process that affects the asymptotic behavioral response to a to-be-ignored stimulus, whereas attenuation is any process that affects sensitivity but not the asymptotic response to a to-be-ignored stimulus. These definitions reflect the idea that increasing the strength of a successfully blocked stimulus can have no effect on performance, whereas increasing the strength of a stimulus that is merely attenuated can influence performance in a way that reflects the strength of the stimulus. Across an extended range of stimulus strengths, we found effects of stimuli at an uncued location on asymptotic performance (blocking) in a spatial filtering task and on sensitivity (attenuation) in a spatial monitoring task.

This study differs from previous efforts to distinguish blocking and attenuation not only in the definitional difference, but also in exploiting a large range of stimuli. One needs to identify how strong a stimulus must be to overcome attenuation. To do so, we measured a wide range of strengths for the stimuli in both experiments. In Experiment 1.1, the target psychometric function revealed performance that varied from near chance to perfect for the set of contrast values used. We then used the same set of contrast values to determine if there was an asymptote for the foil function. The existence of such an asymptote for foils is our evidence that the effect of stimulus strength was as strong as it can be. In short, we compared the asymptotes of the target

and foil psychometric functions. For Experiment 1.2, a similar comparison can be made between the psychometric functions for stimuli at the cued location versus stimuli at the uncued location. In this case, the asymptote remained at perfect or near-perfect performance, and all of the effects were described by changes in threshold

In order to test particular models, we have emphasized the contrast gain model as an example of attenuation and the imprecise-targeting model as an example of blocking. These are only examples of the general classes of attenuation and blocking models. Alternative attenuation models include those that incorporate limited capacity or Bayesian weighting (Eckstein et al., 2009). There are also several alternative blocking models that are relevant to our results for filtering. One alternative is to extend a response gain model developed for neurons to behavior (Pestilli et al., 2009). Another alternative is to assume that the initial processing of the stimuli is parallel and unaffected by selection, and that selection instead has its effect at the level of the decision process (Egeth, Virzi, & Garbart, 1984). This last alternative highlights the point that our experiments do not distinguish between early and late selection (Miller, 1987; Yantis & Johnston, 1990), but are instead concerned with the mechanism of selection. Nevertheless, a hint as to the stage of processing at which selection occurs is provided by the introspection of the observers. Observers in Experiment 1.1 reported seeing a high-contrast foil even when it was a large distance from the target, and had no effect on performance (cf. Mack & Rock, 1998). Although such reports may be misleading, they are consistent with selection modulating task-specific decision processes rather than perceptual processes.

Why did selection occur through blocking in the spatial filtering task and through attenuation in the spatial monitoring task? Two recent theories can account for this overall pattern. One is a version of imprecise targeting that includes flexible pooling over space (Palmer & Moore, 2009). According to this theory, performance is limited by imprecise targeting (blocking) when the spatial extent of attention is narrow. This limitation reflects the resolution of selection (Hein & Moore, 2009, 2010; Intriligator & Cavanagh, 2001; Moore, Hein, Grosjean, & Rinkenaur, 2009; Moore, Lanagan-Leitzel, Chen, Halterman, & Fine, 2007; Moore, Lanagan-Leitzel, & Fine, 2008) and is also related to the idea of intrinsic spatial uncertainty (Pelli, 1985). As the spatial extent of selection increases, the resolution of attention no longer limits performance because the “jitter” is all within the range of selection. The effects of contrast gain (attenuation) are revealed because it now limits performance. This model fits the overall pattern of results across our two experiments because the spatial filtering task required a very narrow spatial extent of selection so that the foils would not influence responses, whereas the spatial monitoring task required a much larger spatial extent of selection so that stimuli at uncued locations could be detected.

The other theory that can account for the overall pattern of results is an extension of physiological theories developed for single neurons. The general idea of these theories is that attention effects are mediated by the gain of single neurons. If this gain modulates the effective contrast, it is known as contrast gain and is an example of attenuation (Reynolds et al., 2000). Alternatively, if the gain affects the neuron's output, it is known as response gain (McAdams & Maunsell, 1999). Furthermore, if the neural outputs relevant to behavior are saturating, then response gain can result in blocking

(Pestilli et al., 2009). A recent extension of these ideas combines the effect of attention with contrast normalization (Reynolds & Heeger, 2009). In this theory, narrowing attention results in response gain (blocking), whereas broadening attention results in contrast gain (attenuation). This theory is compatible with the current results and finds support in other recent studies (Herrmann, Montaser-Kouhsari, Carrasco, & Heeger, 2010).

In summary, a property that distinguishes between blocking and attenuation is the asymptotic behavior generated by strong stimuli. By measuring the effects of stimuli at uncued locations across a range of stimulus strengths, we demonstrated likely instances of both mechanisms. In the case of spatial filtering, when the spatial extent of selection was narrow, irrelevant information was blocked. In the case of spatial monitoring, when the spatial extent of selection was broad, information from uncued locations was attenuated.

CHAPTER 2

Failures of selection can account for color flanker effects

At any given time, people are bombarded with visual information that guides our behavior. The challenge for the cognitive system is to process the relevant information for a task related response and ignore the irrelevant ones. How the cognitive system manages this vast amount of information can be better understood by studying selective attention. In a selective attention task, there is an aspect of the stimulus that is relevant to the task and other aspects that are irrelevant. An observer's goal is to use the relevant information and ignore the irrelevant information. In selective attention, a basic question is to what extent are irrelevant stimuli processed. In the current study, we consider how an irrelevant stimulus can sometimes affect the response to the relevant stimulus. We will exploit two experimental paradigms that allow measuring the effects of irrelevant stimuli: *the flanker paradigm* and *the spatial filtering paradigm*.

Flanker paradigm

The flanker paradigm (Eriksen and Eriksen, 1974) is one of the frequently used methods to study the effect of irrelevant stimuli on behavioral performance. Figure 2.1 shows examples of the stimulus-response mapping and the display of the classic flanker paradigm with foveal targets. In this task, there is a set of stimuli (e.g., letters) mapped to two different responses. The stimuli are presented in an array. The center of the array is defined as target location and it is typically viewed foveally. A target is presented simultaneously with distractors called flankers, which are displayed at both sides of the target. Observers are instructed to attend only the target location and respond to the target while ignoring the flankers, as these are irrelevant to the task. The stimulus-response mapping allows three different target-flanker congruency conditions.

A target can be displayed with 1) flankers that are identical to the target, 2) flankers that are from the same response set as the target, or 3) flankers that are from the different response set from the target. The response time and the accuracy can be compared in different congruency conditions. In any given trial, the identity of the flanker is independent of the identity of the target.

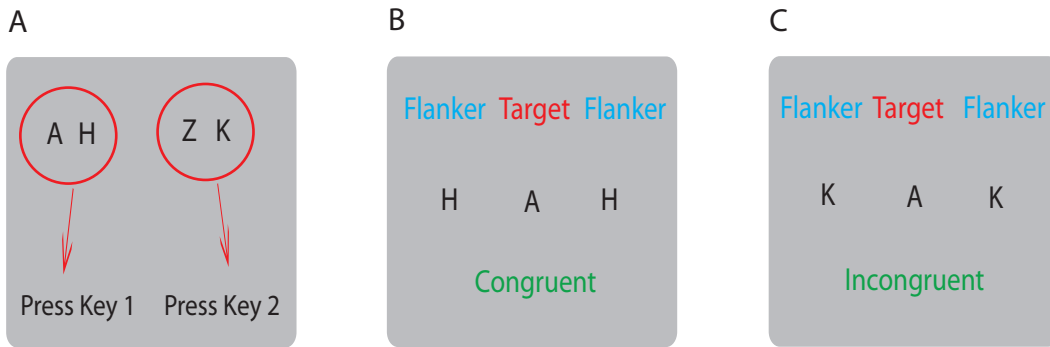


Figure 2.1. An example of stimulus-response mapping and congruent and incongruent trials in the flanker paradigm. Panel A shows grouping of four letters into two response sets. Panel B shows an example of a congruent trial in which the target and flanker are from the same response set. Panel C shows an example of an incongruent trial in which the target and flanker are from the different response sets. In the flanker task, the target is displayed in the center while two identical flankers are displayed at both sides of the target.

There is convincing evidence indicating that the identity of the flankers affects the response time and accuracy of target judgment (e.g., Eriksen and Eriksen, 1974; Miller, 1987; Mordkoff & Egeth, 1994; Cohen and Shoup, 1997; Wühr & Müesseler, 2001). For example, Eriksen and Eriksen (1974) reported that response time was slower in the incongruent condition in which the target and flankers were from different response sets in comparison to the congruent condition in which the target and flankers were from the same response set. This is called the *flanker congruency effect*. The flanker congruency effect was observed not only with letters but also with simple features like color and orientation (e.g., Cohen & Shoup, 1997; Cohen & Shoup, 2000). Wühr and Müesseler (2001) showed that flanker congruency effect can also be measured with accuracy. They found that the accuracy was higher in the congruent condition in comparison to the incongruent condition.

There are alternative explanations for the effects of irrelevant stimuli on the judgment of a relevant stimulus. Eriksen and Hoffman (1973) mapped four letters to two response sets as in the flanker experiments. They presented these letters in a circular array. One of the stimulus locations was indicated as the target location and observers were instructed to press the corresponding lever based on the identity of the letter in the cued location. The distractors were either from the same or different response sets as the target allowing response congruent and response incongruent trials. Response time in the response incongruent trials was slower than the response time in the response congruent trials in which the stimuli had different physical features (e.g., A and U). Response incongruency impaired response time more than feature incongruency. Eriksen and Eriksen (1974) interpreted these results as an indication that the flankers

affect performance at the response selection stage and not at sensory and perceptual stages in which the stimulus features are processed. More specifically, they suggested that the flanker congruency effect is due to *response competition*. For response competition to occur, both the target and flankers are processed to the level that the corresponding response codes of these stimuli are activated. In another words, semantic information of the target and flanker are extracted during the process prior to selection. This indicates that the observers identify both the target and the flankers, hence, they know which response category each these letters are from. In the congruent trials, the target and flankers activate the same response code. When the same code is activated, the correct response is primed and selected more accurately and faster. In the incongruent trials, however, different response codes are activated. Information from the flankers accumulates and competes with information from the target. This competition delays the response selection and sometimes causes an incorrect response.

Alternatively, the effects of irrelevant stimuli on the judgment of a relevant stimulus have been interpreted as being due to *feature competition* (Estes, 1972; Bjork & Estes, 1973), which occurs during perceptual processing. For example, Bjork and Estes employed a letter identification task in which observers were asked to look for a target letter. The target was either presented with a task-irrelevant symbol, which was the sign “#” or was embedded in a letter string. In this example, the distractors were the task-irrelevant symbol and the non-target letters in the letter string. The difference between this task and the flanker tasks is that the distractors were not assigned an overt response. They found that the target identification was more accurate when the

target was presented with the irrelevant symbol in comparison to the target identification when the target was embedded in a letter string. Furthermore, they found that the targets that had more features like curvatures and orientations (e.g., R) were identified better in comparison to the targets that had fewer features (e.g., L) when embedded in a letter string. According to Bjork and Estes, high number of features is easier to identify because the distinctiveness of the target features from the distractor features makes it easier to inhibit the distractors. If the target and distractor features are similar, there is a competition between the feature analyzers, which causes errors and increases the response time.

Another interpretation of the flanker congruency effect that combines these ideas is *multistage competition* (Botella, 1996). The multistage competition refers to the interactive processing that includes stimulus evaluation and response selection and execution. Some studies have shown that response competition cannot account for the entire flanker congruency effect (Coles et al., 1985; Gratton et al., 1988; Smid et al., 1990; Botella, 1996). For example, Botella designed an experiment in which he assigned stimuli an overt response (e.g., press "0") and a no-go response, which required observers to refrain from making an overt response. There were also stimuli that were not associated with any response. This stimulus-response assignment allowed him to test hypotheses of response competition and multistage competition. Botella defines stimulus evaluation as a stage where it is determined whether or not stimuli are assigned a response. This is a stage in the perceptual and cognitive processes, which is prior to response selection. According to Botella, if response competition alone accounts for the flanker compatibility affect, the conditions in which

flankers were assigned a no-go response should have response time similar to the response time in the conditions in which the flankers are not assigned any kind of response. Response time should be impaired only in the conditions in which the target and flankers are from different response sets. He found that response time was slower when the flanker was assigned a no-go response when the observers actively refrained from making a response in comparison to when the flanker was not associated with any response. He also found that response time was slower when the target and flankers were from the different response sets in comparison to when the target and flankers were from the same response set. The fact that flankers slowed response time even when they were not assigned a motor response, but a no-go response, indicates that there is interference between the target and flanker prior to response code activation. Botella concluded that there is a competition at the level of stimulus evaluation as well as at the level of response selection and execution.

In summary, there are several different explanations for the flanker congruency effect. The response competition, feature competition, and multistage competition accounts, however, all consider interactive processing of the target and flanker at some stage of the perceptual and cognitive processes. Hence, we will refer to all these accounts as examples of interactive processing.

Spatial filtering paradigm

An alternative paradigm to study the effect of irrelevant stimuli is spatial filtering (Palmer & Moore, 2009; Yiğit-Elliott, Palmer, & Moore, 2011). Figure 2.2 shows examples of stimulus display in the spatial filtering paradigm. In this paradigm, one

location in the periphery is cued as the target location and a target is displayed at that cued location. In addition, another stimulus, which is called the *foil*, is displayed at either side of the target. The target and foil are drawn from the same set of stimuli. What makes them different is their location. The main experimental manipulation in this paradigm is the distance between the target and foil. This manipulation allows one to measure whether or not the distance affects the selection of the target. In this paradigm, the contrast of the stimuli is also varied to provide information about interaction between stimulus processing and the effect of distance.

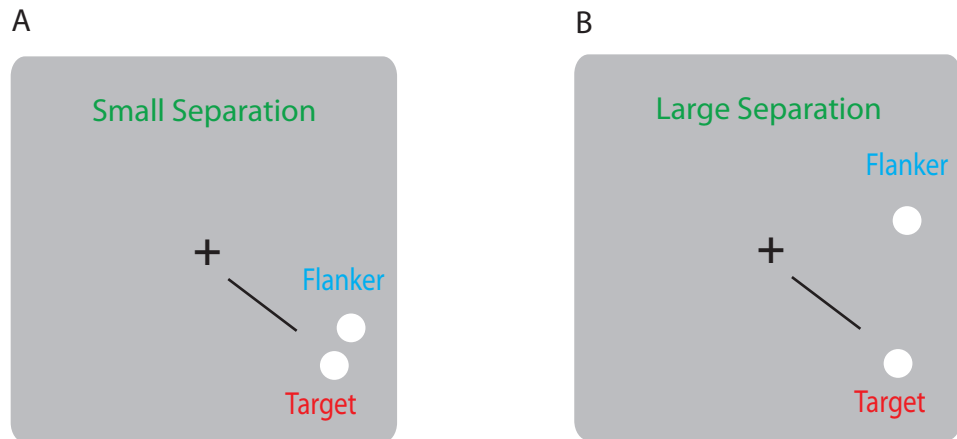


Figure 2.2. An example of stimulus display in the spatial filtering paradigm. Panel A shows an example of small target-flanker separation. Panel B shows an example of large target-flanker separation. In both separation conditions, the target location is cued and both target and flanker are displayed in the periphery.

Yiğit-Elliott, Palmer, & Moore (2011) used spatial filtering to distinguish between two possible mechanisms of selection: blocking and attenuation. Blocking refers to receiving information from only the selected stimulus and no information from the other stimuli (Broadbent, 1958). If the correct stimulus is selected, an observer responds to the stimulus as if no other stimuli were present. Attenuation, on the other hand, refers to getting the maximum information from the selected stimulus and attenuated information from the unselected stimulus (Treisman, 1960). According to the attenuation model, if the irrelevant stimulus is strong enough (e.g. high contrast), this would overcome the attenuation and an observer can be affected by the irrelevant stimulus.

Yiğit-Elliott et al. (2011) used flashes of light as stimuli. The target always appeared at the cued location. Observers were instructed to respond to the target and ignore the foil. The task was to indicate whether or not the target luminance was lighter or darker than the background. They varied the separation between the target and foil. They also varied the contrast of the stimuli in a fashion that the target and foil never had the same contrast. There were trials in which the target contrast was always near threshold while the foil contrast was varied between near threshold and maximum contrast. There were also trials in which the foil contrast was always near threshold while the target contrast was varied between near threshold and maximum contrast. This contrast manipulation allowed them to measure psychometric functions for the target and foil separately. The purpose of the study was to reveal whether or not increased contrast of the foil made observers respond to it as if it was the target. In other words, they tested whether increased contrast of the foil overcame attenuation.

The results of this study showed that increasing the foil contrast, even when the target contrast was low, did not overcome attenuation. When the target-foil separation was small, observers sometimes selected the foil to respond and sometimes the target and the contrast of the unselected stimulus did not affect the performance. Yiğit-Elliott et al. (2011) concluded that increasing the contrast of an irrelevant stimulus cannot overcome attenuation; therefore it does not affect performance. If the irrelevant stimulus is presented at a small distance from the relevant one, observers sometimes fail to select the right stimulus. When one stimulus is selected, the other one does not affect the performance no matter how high its contrast is.

In summary, the spatial filtering paradigm provides means to investigate the effect of distance between a relevant and irrelevant stimulus on performance. The results of the spatial filtering studies showed when the distance between a relevant and irrelevant stimulus is large, one can select the relevant stimulus successfully and the irrelevant stimulus does not affect performance. When the distance between these stimuli is small, observers sometimes fail to select the relevant stimulus and when one of the stimuli is selected, the other does not affect the performance.

Failure of selection in flanker experiments

Is it possible that the failure of selection contributes to the flanker congruency effect? In the original flanker paradigm, the target is viewed foveally while the flankers are displayed in the periphery. This design with foveal targets provides a well-defined target location that minimizes spatial uncertainty of the target. In addition, acuity and the

processing speed of visual stimuli are the best at the fovea. Thus, many have assumed that the foveal targets are always selected.

It remains possible that on some trials, observers attend the irrelevant stimulus instead or in addition to the relevant stimulus. In other words, there is failure of selection in some trials that causes the flanker congruency effect. According to this account, the stimuli are processed separately instead of interactively. If selection fails and the observer selects the flanker, the response would be incorrect in a condition in which the target and flanker are from different response sets. The selection is more likely to fail when the target and flanker are presented at a small separation (Eriksen & Eriksen, 1974; Yantis & Johnston, 1990; Yiğit-Elliott, Palmer, & Moore, 2011). In this case, it is possible that the observers identify both stimuli but have to make a decision about which one of the two stimuli was at the cued location.

Eriksen and Eriksen (1974) observed that when the distance between the target and flankers is more than 1° in visual angle, the flanker congruency effect was reduced and eventually disappeared. There is other evidence showing that when a target and flanker are separated enough, the identity of flankers do not affect performance (Yantis and Johnston, 1991; Paquet, 2001; Lachter, Forster, & Ruthruff, 2004). For example, Yantis and Johnston argued that in the original flanker experiments, the stimulus display caused what they call “attentional leakage” due to imperfect selection conditions. They found that when these imperfections are fixed by displaying the stimuli in the periphery and increasing the distance between the stimuli, the irrelevant stimuli do not have effect on performance. In a different study with more complex stimuli like words, Lachter et al. (2004) used a priming task to test whether or not an irrelevant prime could effect word

identification. When they controlled for the locus of selection and ensured that the irrelevant stimulus was not attended, they did not observe priming effects. The dependence of the flanker congruency effect on the target-flanker separation indicates that interactive processes cannot account for the effect without some modification.

The current task

In the current study, we combined the aspects of the flanker and spatial filtering paradigms. As in the flanker paradigm, we used a set of stimuli, colored disks, and assigned the stimuli to two groups of response so that we can have different congruency conditions. As in the spatial filtering paradigm, we displayed the stimuli in the periphery and we varied the contrast of the stimuli and the separation between them. We measured correct response as a function of stimulus contrast as done in the previous spatial filtering studies.

We aimed to investigate the nature of the flanker congruency effect. We considered three alternative explanations for this effect. First, we considered attenuation. Attenuation might occur as a result of interactive processing of stimuli. In this study, we specifically focused on multiplicative attenuation as an example of attenuation in general. Second, we considered a combination of failure of selection as an example of blocking. Finally, we considered attenuation and blocking. We explained both specific and general versions of these models and specify the predictions of each model (see Appendix for more details).

Alternative models and predictions

Attenuation. According to this model, the target and flanker are both processed interactively either at one or more stages of the perceptual and response processes. Depending on the congruency of the flanker, this interaction results in attenuation of the information one receives from the target. Attenuation is a general model that can predict different performance levels and different shapes for the psychometric function. In the current study, we consider *multiplicative attenuation*.

According to multiplicative attenuation, an irrelevant flanker attenuates the information from the target in a multiplicative fashion. More specifically, displaying a target with an incongruent flanker is similar to reducing the target contrast and affecting the detection threshold. For example, assume that the target and flanker contrast in a congruent trial was at 10%. The target contrast in this trial would be perceived as 10% and the performance, for example, would be at 70% on average. If the same target were presented with an incongruent flanker, due to multiplicative attenuation, the incongruent flanker would make the target contrast perceived as 7% and the performance, for example, would be at 60% on average. In other words, the same contrast would result in different performance levels based on the target-flanker congruency. At high contrasts, the target overcomes this attenuation. Therefore, we see the attenuating effects of an incongruent flanker only at the low contrasts. Therefore, this performance difference between the congruency conditions is seen as a horizontal shift of the psychometric function, which plots performance as a function of log-scaled stimulus contrast. If the flanker congruency effect is due to multiplicative attenuation, the model predicts that the detection threshold in the incongruent condition will be higher than the detection threshold in the congruent condition. Panel A of Figure 2.3 shows the

predicted psychometric functions of three conditions for the multiplicative attenuation model.

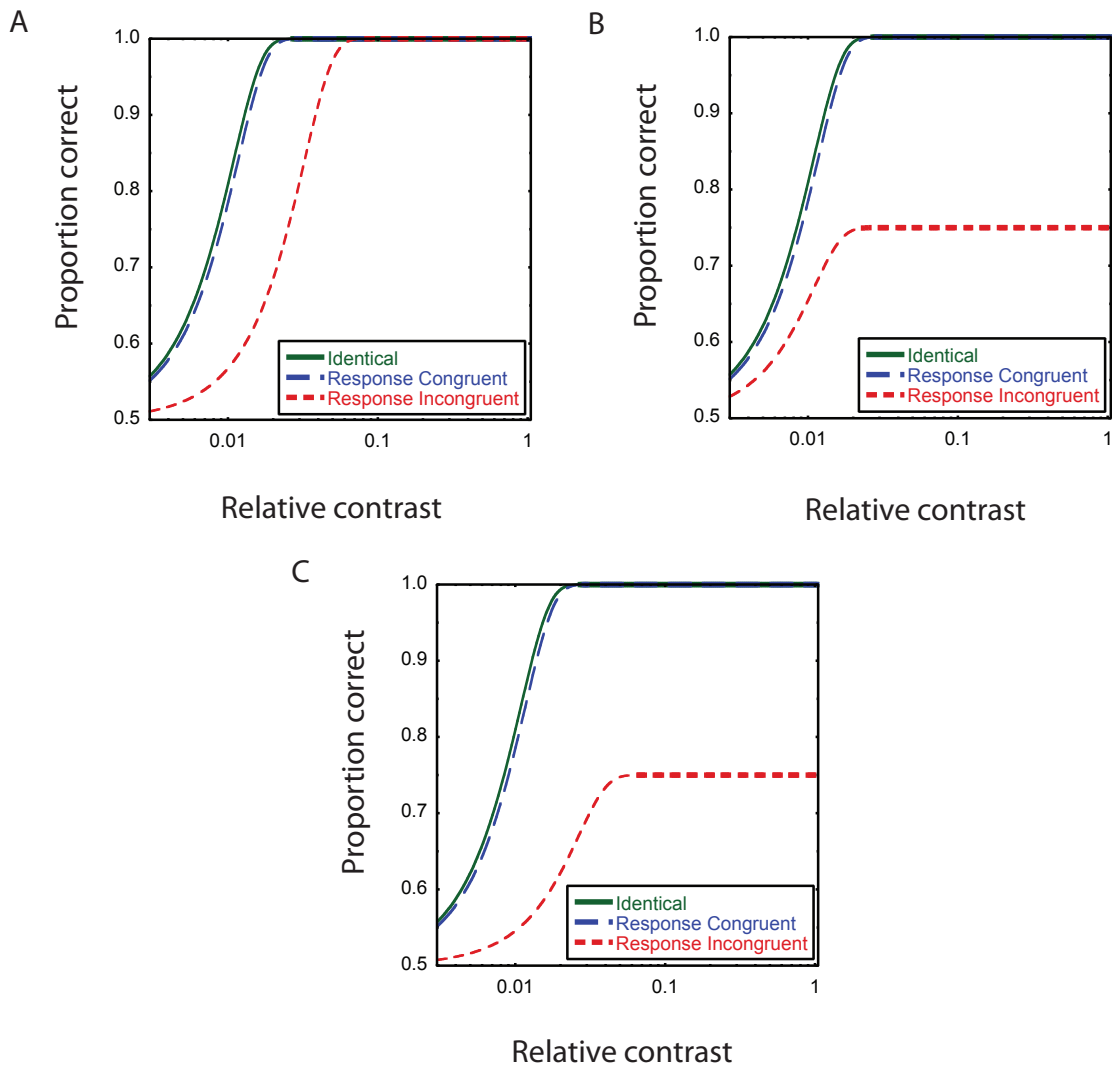


Figure 2.3. Predictions of the multiplicative attenuation, failure of selection, and both failure of selection and multiplicative attenuation models. The graphs plot the stimulus contrast (0 to 1) on the x-axis and the proportion of correct response on the y-axis. Panel A shows the prediction of the multiplicative attenuation model. The performance in the congruent trials is the same while the detection threshold in the incongruent condition is lower than the congruent conditions. Panel B shows the predictions of the failure of selection model. The performance in the congruent trials is the same while the asymptote of the incongruent condition is lower than the congruent conditions. Panel C shows the predictions of both the multiplicative attenuation and the failure of selection model. The performance in the congruent trials is the same while the detection threshold and the asymptote of the incongruent condition is lower than the congruent conditions.

Why assume multiplicative attenuation? Multiplicative processes are common in the analysis of attention (e.g., Reynolds, Pasternak, & Desimone, 2000; Huang & Dobkins, 2004; Williford & Mounsell, 2006) and adaptation (Pestilli, Viera, & Carrasco, 2007). Of relevance to the current case, they have also been suggested to account for changes in sensitivity due to priming (Morton, 1969).

More general theories of attenuation will typically share the property of affecting the threshold of the psychometric function along with effects on the shape of the psychometric function such as the slope of the function. Regardless of the type of effect the attenuation has on stimulus signal, all attenuation models predict that the high contrast stimulus overcomes such attenuation. Therefore, any effect of attenuation can be anywhere on the psychometric function but the asymptote. In summary, a multiplicative interaction is a good starting point for the development of theory and the signature effect on the threshold is common to most, if not all, plausible theories of interactive processing.

Blocking. According to this model, information from the unselected stimulus is blocked at least on some trials; therefore it does not affect performance on these trials. In this study, we consider *failure of selection* as an example of blocking. According to failure of selection, observers fail to select the target in some fraction of the trials. Selecting the flanker or the target in the congruent trials does not impair performance, because the response to the flanker is the same as the target. In contrast, selecting the flanker in the incongruent trials would result in error, because the response to the flanker is different than the response to the target. For example, assume that an observer always selects the target successfully. At the low contrasts, the performance

would be low. As the contrast increases, the performance would get better. At the high contrasts, it is likely that the observer would respond correctly 100% of the time. Now, assume that the observer randomly selects a stimulus: half the time selects the target and half the time selects the flanker. At low and high contrasts, the performance would be at chance. What happens if the observer selects the target successfully 75% of the time? At low contrasts, the performance would be low. At high contrasts, the performance would be at 75%. This performance difference between the different levels of failure of selection is seen as scaling of the asymptote of the psychometric function, which plots performance as a function of stimulus contrast. Furthermore, because the stimuli are not processed interactively, the contrast of the stimulus that is selected in a given trial would be perceived the same in both the congruent and incongruent conditions not allowing a horizontal shift of the psychometric function. If the flanker congruency effect is due to failure of selection, the model predicts that the asymptote of the psychometric function in the incongruent condition will be lower than the asymptote in the congruent condition. It is also hypothesized that the detection threshold will be the same in the congruent and incongruent conditions. In the models that predict scaling of the asymptote, the threshold is defined as half way between the asymptote and the chance. For example, if the function reaches the asymptote at 100%, the threshold is the contrast value that produces the 75% performance. If the function reaches the asymptote at 75%, then the threshold is the contrast that produces the 62.5% performance. Panel B of Figure 2.3 shows the predicted psychometric functions of three conditions for the failure of selection model.

The problematic case for current purposes is whether there are plausible interactive processes that mimic blocking in affecting only the asymptote and not the threshold. In other words, might an interactive process primarily affect strong stimuli and have only modest effects on weak stimuli? This seems unlikely to us but we consider this case further in the discussion by considering a blocking by interaction model in which the high contrast target cannot overcome the effect of an incongruent flanker.

Both mechanisms: Blocking and attenuation. According to this model, the target and flanker are processed interactively, and on some trials, the flanker is selected for response. For example, an observer selects the target to respond 75% of the time and in the incongruent trials, the observers perceive the contrast of the selected stimulus as lower than it actually is. In this case, the performance would be at 75% and there would be a horizontal shift of the psychometric function due to perceiving the contrast as lower than it actually is. If the flanker congruency effect is due to both blocking and attenuation, this theory predicts that the detection threshold will be higher and the asymptote will be lower in the incongruent condition in comparison to the detection threshold and the asymptote in the congruent condition. Panel C of Figure 2.3 shows the predicted psychometric functions of three conditions for the blocking and attenuation model.

In order to test these hypotheses, we designed a color flanker paradigm with peripheral targets where we used disks with the colors of red, blue, green, and yellow. We mapped colors to two response sets. In order to measure psychometric functions, we varied the contrast of stimuli. In Experiment 2.1, we presented the target and flanker at a small separation. The close proximity made it difficult to select the right stimulus. In

Experiment 2.2, we presented the target and flanker at a large separation. The large separation made it easy to ignore the flanker. Next, in Experiment 2.3 and 2.4, we tested whether or not our task can detect any benefit of viewing both stimuli where viewing both stimuli can only help the observer. Finally, in Experiment 2.5, we measured the spatial extent of the flanker congruency effect. In summary, these experiments estimate the relative contributions of attenuation and blocking using measures of the threshold and asymptote of the psychometric function.

General methods

Observers. Five consenting adults, with normal or corrected to normal vision, participated in these experiments. Author SYE was one of the observers. All observers, except SYE, were paid \$15 per hour for their participation. Three of the five observers (ER, JW, and SYE) were experienced in psychophysical judgments.

Apparatus. The stimuli were presented on a calibrated flat-screen CRT video monitor (19" View Sonic PF790) with a refresh rate of 75 Hz controlled by a Macintosh G4 computer (Mac OS 9.2.2). The display resolution was 832 x 624 pixels, which was 32° x 24° in visual angle at a viewing distance of 60 cm. There were 25.5 pixels per degree at the center of the display. The room lights were on to reduce the pupil size for recording the eye movements. The stimuli were created using the Psychophysics Toolbox version 2.44 (Brainard, 1997; Pelli, 1997) for MATLAB (version 5.2.1, Mathworks, MA). The peak display luminance was 108-cd/m² and the black level was 3.7 cd/m². The maximum luminance for red, green, and blue were 28, 76, and 10.9

cd/m² respectively. An adjustable height chair was used for seating. Observers used a chin rest to stabilize their head position to level their eyes with the middle of the monitor.

Eye movements were recorded using a video system (EyeLink II, Version 2.11, SR Research, Ottawa, Ontario, Canada) controlled by a DOS computer. The EyeLink II is a head-mounted binocular infrared video system with 250 Hz sampling. It was controlled by the EyeLink Toolbox extensions of MATLAB Version 1.2 (Cornelissen, Peters, & Palmer, 2002). We recorded and analyzed only the right eye position. Eye position was recorded for all trials, and trials were included in the analysis only if good fixation was confirmed. Five consecutive high frequency tones indicated the aborted trials due to bad fixation. The resolution of this system was about 0.1° for detecting saccades and better than 1.0° for sustained eye position over many trials.

Eye position data was not recorded for SYE in any of the experiments. Eye position data was not recorded for JW in Experiment 2.2. Table 2.1 shows the summary of the eye-position statistics for each observer in each experiment. The first column of the table specifies the percentage of aborted trials. They ranged from 0.9% to 12.9% with a mean of $4.2 \pm 0.8\%$. The aborts were mostly due to blinks or equipment malfunction rather than eye movements towards the stimuli. The third and fourth columns of the table specify the mean eye position relative to the fixation point at the beginning of the stimulus display. Across experiments, the mean horizontal position was $0.3 \pm 0.1^\circ$ and the mean vertical position was $-2.1 \pm 0.2^\circ$. The last two columns of the table specify the standard deviation of the eye position at the beginning of the stimulus display. Across experiments, the mean horizontal deviation was $0.8 \pm 0.1^\circ$ and the mean vertical deviation was $1.5 \pm 0.1^\circ$. These measures confirm that the observers

maintained fixation throughout all experiments and for the trials analyzed here did not make saccades to the peripheral stimulus locations.

Table 2.1. The summary statistics of the eye positions for each observer in all experiments.

Experiment and Observer	Percent aborted trials (%)	Mean horizontal position	Mean vertical position	SD horizontal position	SD vertical position
Experiment 1					
AK	3.1	0.5°	-1.2°	1.0°	1.5°
ER	1.2	0.4°	-1.8°	0.8°	1.6°
JW	10.5	0.3°	-2.2°	1.3°	1.4°
MS	4.5	0.4°	-3.2°	0.4°	1.1°
SY	0.9	-	-	-	-
Experiment 2					
AK	2.6	0.4°	-1.1°	0.8°	1.5°
ER	1.3	0.2°	-1.5°	0.7°	1.7°
JW	7.3	-	-	-	-
MS	3.4	0.4°	-3.2°	0.5°	1.1°
SY	1.1	-	-	-	-
Experiment 3					
AK	2.4	0.3°	-1.8°	0.5°	1.4°
ER	0.6	0.1°	-1.8°	0.6°	1.2°
JW	9.9	-0.0°	-1.7°	1.0°	1.8°
MS	3.7	0.4°	-2.8°	0.4°	1.3°
SY	1.8	-	-	-	-
Experiment 4					
AK	2.9	0.5°	-1.8°	0.8°	1.5°
ER	1.6	0.4°	-1.6°	0.7°	1.5°
JW	12.9	0.3°	-1.9°	1.3°	1.8°
MS	3.9	0.5°	-2.7°	0.4°	1.3°
SY	1.0	-	-	-	-
Experiment 5					
JW	11.7	-1.1°	-1.8°	1.6°	2.0°
MS	3.7	0.6°	-3.0°	0.3°	1.2°
Mean	4.2 ± 0.8	0.3 ± 0.1°	-2.1 ± 0.2°	0.8 ± 0.1°	1.5 ± 0.1°

Note. SD denotes standard deviation

Stimulus. The targets and flankers were drawn from the same set of stimuli. Location was the only distinction between a target and flanker. The colors of the target and flanker were independent from each other. Based on the color-response mapping, there were three congruency conditions: a) in the identical condition, the target and flanker had the same color, b) in the response congruent condition, the target and flanker required the same response, and c) in the response incongruent condition, the target and flanker required different responses.

In all experiments, the stimuli were four colored disks (red, green, blue, and yellow) that were mapped to different responses (e.g., press “0” for red and green; press “.” for blue and yellow). Color-response mapping was counterbalanced among observers. For example, if one observer was instructed to press one key for red and blue and press another key for yellow and green, another observer was instructed to press one key for blue and green and press another key for red and yellow. Table 2.2 shows the color-response mapping for each observer. Two colored disks with a diameter of 0.7° in visual angle were presented simultaneously at an eccentricity of 8° in visual angle. Disks were presented on a dark background (3.7 cd/m^2). One of four locations was indicated with a bar marker as the target location. An irrelevant stimulus, flanker, was presented simultaneously to either side of the target at a distance of either 11.3° or 1° in visual angle.

Table 2.2. The color-response mapping for each observer.

Observers	Press “.”	Press “0”
AK	Green-Yellow	Red-Blue
ER	Green-Blue	Red-Yellow
JW	Blue-Yellow	Red-Green
MS	Red-Yellow	Green-Blue
SY	Red-Green	Blue-Yellow

The color of the four primaries was chosen on the basis of a pilot study. The observers carried out a task in which we used the method of constant stimuli to measure the detection threshold for each color. In this experiment, one colored disk that had a diameter of 0.7° in visual angle was presented at an 8° visual angle eccentricity. The location of the colored disk was cued prior to the stimulus display. A high frequency tone indicated two temporal intervals in which the stimulus could appear. Observers indicated the interval the stimulus appeared by pressing a key. The stimulus appeared in both intervals in equal number of trials in random order. In addition, we collected pilot data for Experiment 2.2 itself. Color primaries for each observer were chosen based on the detection thresholds and color discrimination in order to assure equal performance at a given contrast for each color. Table 2.3 shows linearized relative RGB values that were used for each observer.

Table 2.3. Color primaries used for each observer.

Observers	R-G-B values for red	R-G-B values for green	R-G-B values for blue	R-G-B values for yellow
AK	1, 0, 0	0, 0.6, 0	0, 0, 0.6	0.8, 0.5, 0
ER	1, 0, 0	0, 0.3, 0.05	0, 0, 0.65	1, 0.4, 0
JW	1, 0, 0	0, 0.3, 0.05	0, 0, 0.72	1, 0.4, 0
MS	1, 0, 0	0, 0.3, 0.05	0, 0, 0.8	0.75, 0.3, 0
SY	1, 0, 0	0, 0.3, 0.05	0, 0, 0.72	1, 0.4, 0

In the main experiment, the contrast of the stimuli was varied. In a given trial, the target and flanker contrast was identical. For example, if the target contrast was 0.5%, the flanker contrast was also 0.5% in that trial. Table 4 shows the contrast values for each observer in Experiments 2.1, 2.2, 2.3, and 2.4. The contrast values were slightly different for each observer to match their performances.

Table 2.4. Contrast values (0-1) for each observer in Experiments 1, 2, 3, and 4.

Observers	Experiment 1				
	Contrast Values				
AK	0.0025	0.0035	0.0050	0.1000	1.0000
ER	0.0035	0.0050	0.0070	0.1000	1.0000
JW	0.0050	0.0070	0.0100	0.1000	1.0000
MS	0.0070	0.0100	0.0140	0.1000	1.0000
SY	0.0070	0.0100	0.0140	0.1000	1.0000
	Experiment 2				
	Contrast Values				
AK	0.0025	0.0035	0.0050	0.1000	1.0000
ER	0.0035	0.0050	0.0070	0.1000	1.0000
JW	0.0070	0.0100	0.0140	0.1000	1.0000
MS	0.0070	0.0100	0.0140	0.1000	1.0000
SY	0.0070	0.0100	0.0140	0.1000	1.0000
	Experiment 3 & Experiment 4				
	Contrast Values				
AK	0.0025	0.0035	0.0050	0.1000	1.0000
ER	0.0035	0.0050	0.0070	0.1000	1.0000
JW	0.0050	0.0070	0.0100	0.1000	1.0000
MS	0.0050	0.0070	0.0100	0.1000	1.0000
SY	0.0050	0.0070	0.0100	0.1000	1.0000

Procedure. Observers were instructed to attend the cued location in all trials and ignore the stimulus at the uncued locations. Panel A of Figure 2.4 shows the sequence of a trial in Experiment 2.1 and Experiment 2.2. A fixation cross appeared and stayed at the center of the display throughout the trial. Two seconds after observers began fixating; a spatial cue that indicated the location of the target appeared for 0.5 second. The cue was followed by a 0.5 second warning interval. After the warning interval, the target and flanker appeared simultaneously for 0.2 second followed by an answer prompt until response. The task was to press the response key that corresponded the color of the target stimulus. A low frequency tone was presented when the response was incorrect. There was no tone for correct responses. A two-second interval separated the trials.

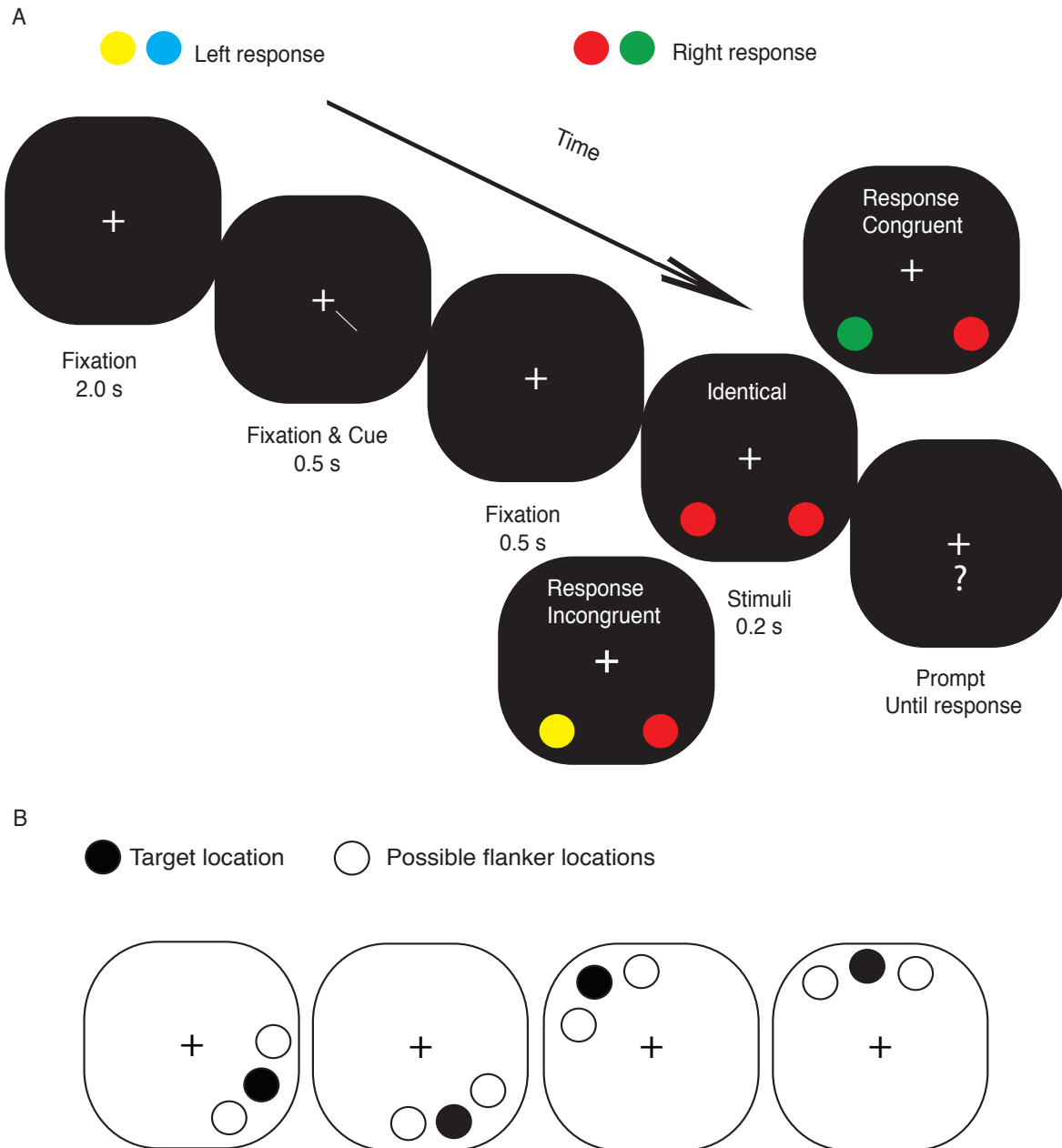


Figure 2.4. Trial sequence and possible target and flanker locations for flanker congruency experiments. The illustration of the trial sequence in panel A shows three critical congruency conditions in Experiments 2.1 and 2.2: Identical, response congruent, and response incongruent. In a given trial, only one of these three conditions was displayed. Panel B shows the possible flanker and target locations for Experiment 2.1. There were four possible target locations. For each target location, there were two possible foil locations. The separation between the target locations was the same as the separation between the target and flanker. Therefore, the flanker appeared at one of the possible target locations half the time. In each trial, only one flanker was presented simultaneously with the target.

Analysis. All psychometric functions were cumulative normal functions raised to a power (Pelli, 1987) and were plotted as a function of log-scaled stimulus contrast. They had three parameters: Upper asymptote, detection threshold, and exponent. In a preliminary analysis, we fit the functions allowing exponent to vary for each condition and each observer. The average value was about 1.5; thereafter, we fixed the exponent to that value. The detection threshold was defined as the value that is halfway between the upper asymptote and the chance level (0.5). Defining the threshold this way allows us to compare the thresholds of psychometric functions with different asymptotes.

Experiment 2.1: Flanker congruency with a small separation

In Experiment 2.1, we used a spatial filtering task with a small separation. A target was presented at a cued location and a flanker was presented at a nearby location. There were three main conditions. The relative contrast (luminance and chromaticity) of the target and flanker were varied.

Method. Two colored disks with a diameter of 0.7° in visual angle were presented at 8.0° in visual angle of eccentricity. One of four locations corresponding to polar angles of 131.5° , 138.5° , 228.5° , and 323.5° was indicated with a bar marker as the target location. A flanker was presented simultaneously to either side of the target with a distance of 1° in visual angle for four observers and at 1.4° in visual angle for the observer JW. Panel B of Figure 2.4 indicates the possible target and flanker locations. The size of the separation between the two possible target locations was the same as the separation between the target and flanker. Therefore, in a given trial, one of the possible target locations was a flanker location in that trial half of the time. For example,

if the target location was 131.5° in polar angle, the flanker location was either 138.5° , which is another possible target location, or 124.5° .

In each session, there were 160 trials. There were 40 trials in the identical and 40 trials in the response congruent conditions and there were 80 trials in the response incongruent condition. Each observer ran 20 sessions for a total of 3200 trials.

Results. Figure 2.5 shows the performance of all observers and the fitted psychometric functions for the three critical conditions. We analyzed the asymptotic performance and the detection threshold for each condition. The detection threshold was the same across all conditions. We compared three conditions separately and we also collapsed the identical and response congruent conditions together and compared it to the incongruent condition. Collapsed conditions are referred as congruent conditions throughout this article.

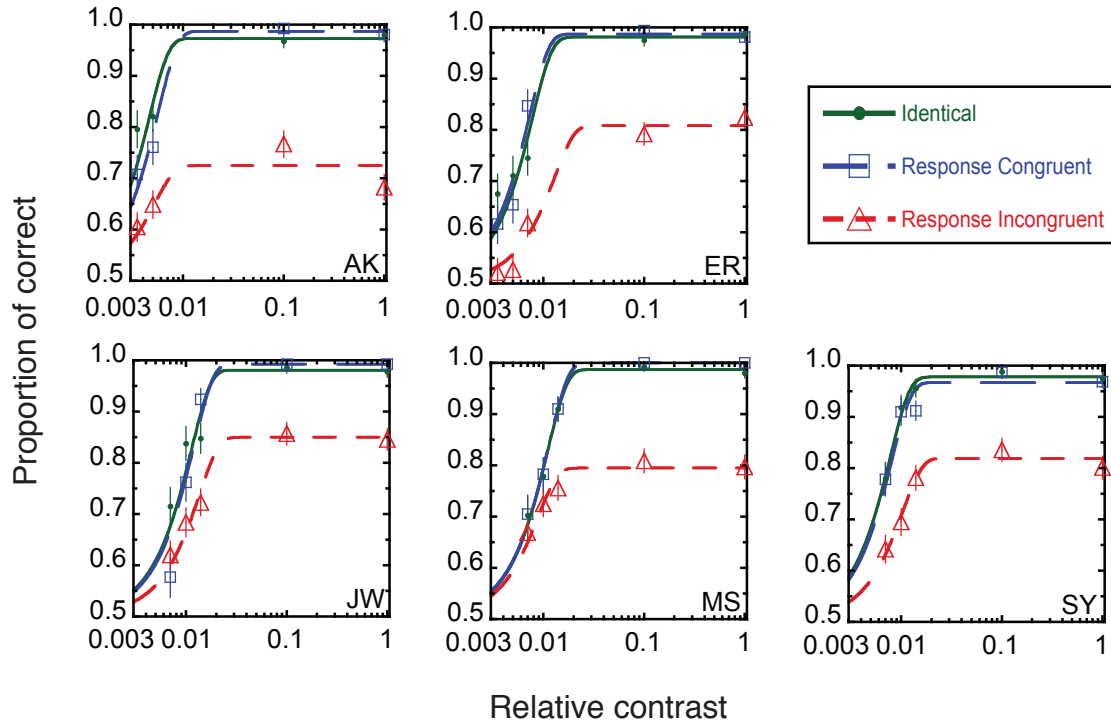


Figure 2.5. Results for small separation flanker congruency experiment. The graphs plot the contrast (0 to 1) of the stimuli on the x-axis and the proportion of correct response on the y-axis. Each panel plots the data from a single observer. The graphs show observed performance and the best-fit psychometric functions for three conditions. The error bars indicate the standard error of the proportions.

There was an effect on the asymptote. The average asymptote was 0.980 ± 0.002 in the identical condition and it was 0.987 ± 0.005 in the response congruent condition. In contrast, the average asymptote was 0.799 ± 0.021 in the incongruent condition. The reduction in the asymptotic performance between the congruent and incongruent conditions was 0.184 ± 0.021 and it was reliable ($t(4) = 8.97, p < 0.001$).

There was no effect on the thresholds. The average detection thresholds were 0.0066 ± 0.0010 , 0.0069 ± 0.0010 , and 0.0080 ± 0.0010 in the identical, response congruent, and response incongruent conditions, respectively. The difference between the detection thresholds of the congruent and the incongruent conditions was 0.0010 ± 0.0010 and it was not reliable ($t(4) = 1.68, p > 0.05$).

In summary, there is a significant flanker congruency effect in the incongruent condition causing asymptotic performance to drop. The flanker congruency effect is seen on only the asymptote and not on the detection threshold. These results also show that there is no performance difference between the identical and the response congruent conditions when the separation between the target and flanker is small.

Experiment 2.2: Flanker congruency with a large separation

Method. The stimuli, procedure, conditions, and the experiment length were similar to Experiment 2.1. The possible stimulus locations were different. One of four locations corresponding to polar angles of 45° , 135° , 225° , and 320° was indicated with a bar marker as the target location. A flanker was presented simultaneously to either side of the target with a distance of 11.3° in visual angle. Figure 2.6 indicates the possible target and foil locations. The size of the separation between the two possible

target locations was the same as the separation between the target and flanker.

Therefore, the four possible target locations were also possible flanker locations. For example, if the target location was 45° in polar angle in a given trial, the flanker location was either 135° or 320° in that trial, which are also possible target locations.

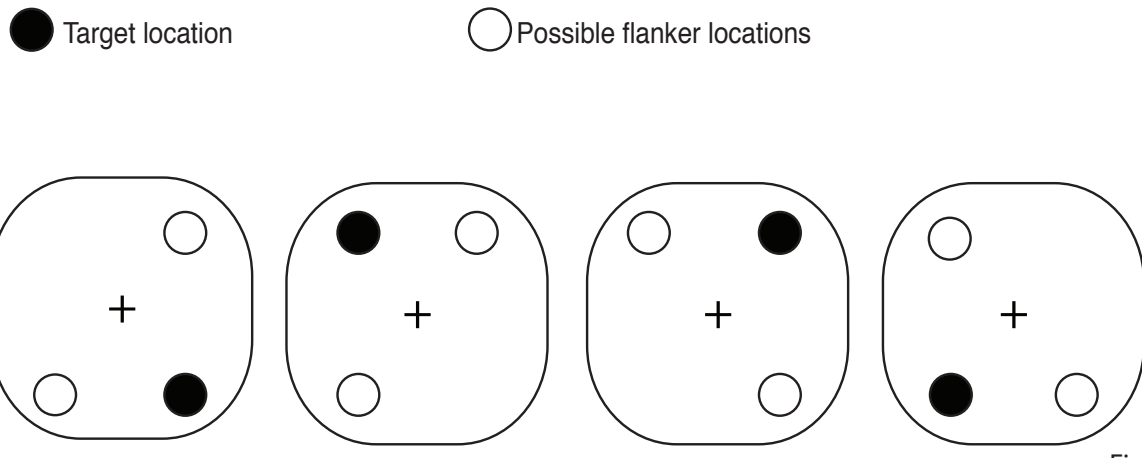


Figure 2.6. Possible target and flanker locations in Experiment 2.2. The target appeared in one of the four quadrants of the screen: lower right, upper left, upper right, and lower left. Distance between the possible target locations was same as the distance between the target and flanker. Therefore, the flanker always appeared at one of the possible target locations. In each trial, only one flanker was presented simultaneously with the target.

Results. Figure 2.7 shows the performance of all observers and the fitted psychometric functions for the three critical conditions. The results of the identical and response congruent conditions are averaged. The average asymptotic performance was slightly better in the congruent conditions than in the incongruent conditions.

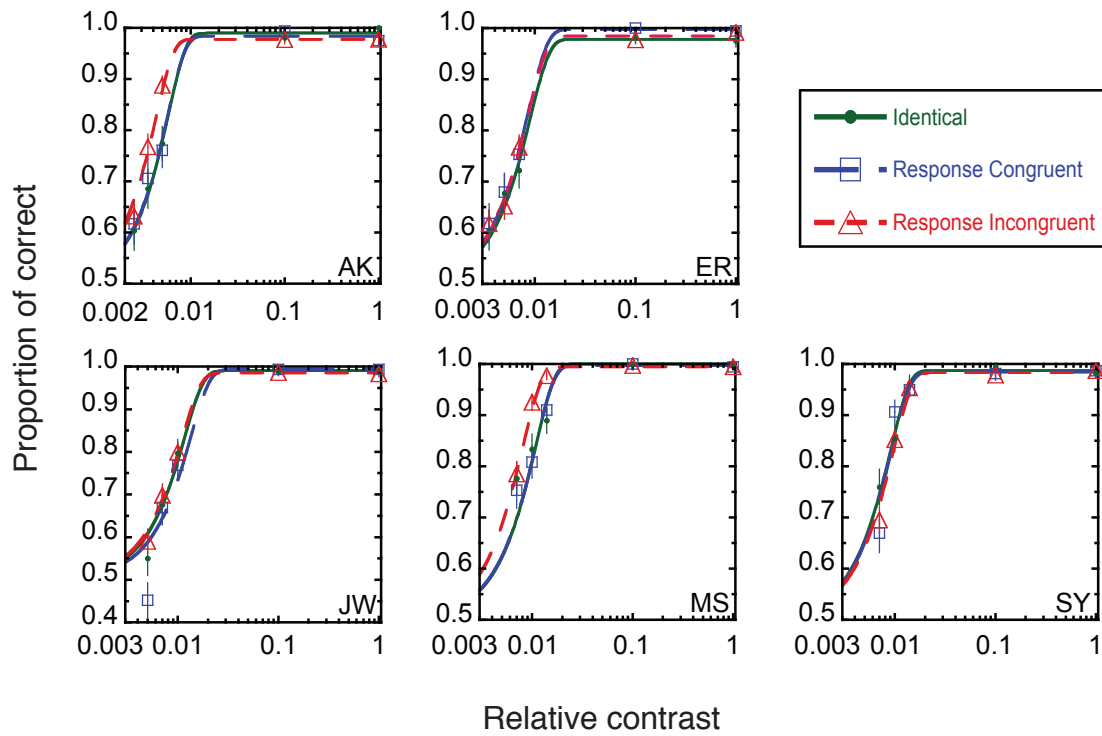


Figure 2.7. Results for large separation flanker congruency experiment. The graphs plot the relative contrast (0 to 1) of the stimuli on the x-axis and the proportion of correct response on the y-axis. Each panel plots the data from a single observer. The graphs show observed performance and the best-fit psychometric functions for three conditions. The error bars indicate the standard error of the proportions.

The average asymptotes were 0.989 ± 0.004 , 0.991 ± 0.003 , and 0.985 ± 0.003 in the identical, response congruent, and the response incongruent conditions respectively. The small asymptote difference between the congruent and incongruent conditions was 0.005 ± 0.001 and it was reliable ($t(4) = 5.20$, $p < 0.05$).

There was no effect on the thresholds. The average detection thresholds were 0.0072 ± 0.0010 , 0.0074 ± 0.0010 , and 0.0064 ± 0.0010 in the identical, response congruent, and response incongruent conditions, respectively. The detection threshold difference between the congruent and incongruent conditions was, 0.0009 ± 0.0004 and it was not reliable ($t(4) = 2.05$, $p > 0.05$).

In summary, the asymptotic performance was slightly better in the congruent conditions in comparison to the performance in the response incongruent condition. This is a miniature version of the effect seen with a large separation. Furthermore, the detection threshold is very similar between the congruent and incongruent conditions. Even though, it is not reliable, the detection threshold is lower in the incongruent condition in comparison to the congruent condition, which is the opposite of one might expect.

Experiment 2.3 and Experiment 2.4: Redundant targets

In the previous experiments, we did not find a flanker effect on the detection threshold. One possible explanation for the lack of flanker effect on the detection threshold is that our experiments were not sensitive enough to detect the change in threshold. In order to address this issue, we designed a redundant target experiment to test our ability to measure small effects on threshold.

In Experiments 2.3 and 2.4, either one or two stimuli were presented at cued locations. The second stimulus was presented either at a nearby (Experiment 2.3) or far (Experiment 2.4) location. When two stimuli were presented, they were both targets and they were always identical. Unlike previous experiments, the observers were instructed to attend both stimuli.

Method. The stimuli in Experiments 2.3 and 2.4 were similar to the stimuli in the previous experiments. The key difference is that there were no flankers in Experiments 2.3 and 2.4. Panel A of Figure 2.8 shows the sequence of a trial. The stimulus locations were chosen to match the corresponding filtering experiment. In Experiment 2.3, either one location corresponding to polar angles of 135° or 320° , or two locations corresponding to 131.5° and 138.5° or 316.5° and 323.5° were indicated as target locations by bar markers. In Experiment 2.4, either one location corresponding to the polar angles of 135° or 320° , or two locations corresponding to 45° and 320° or 135° and 225° were indicated as target locations by bar markers. Panel B of Figure 2.8 shows possible target locations. In both experiments, the number of cues indicated if the trial had a single target or two targets. Two targets were always identical in contrast and color. There were two critical conditions: 1) single target and 2) redundant targets. In each session, there were 160 trials. There were 80 trials in each condition. Each observer ran 10 sessions for a total of 1600 trials.

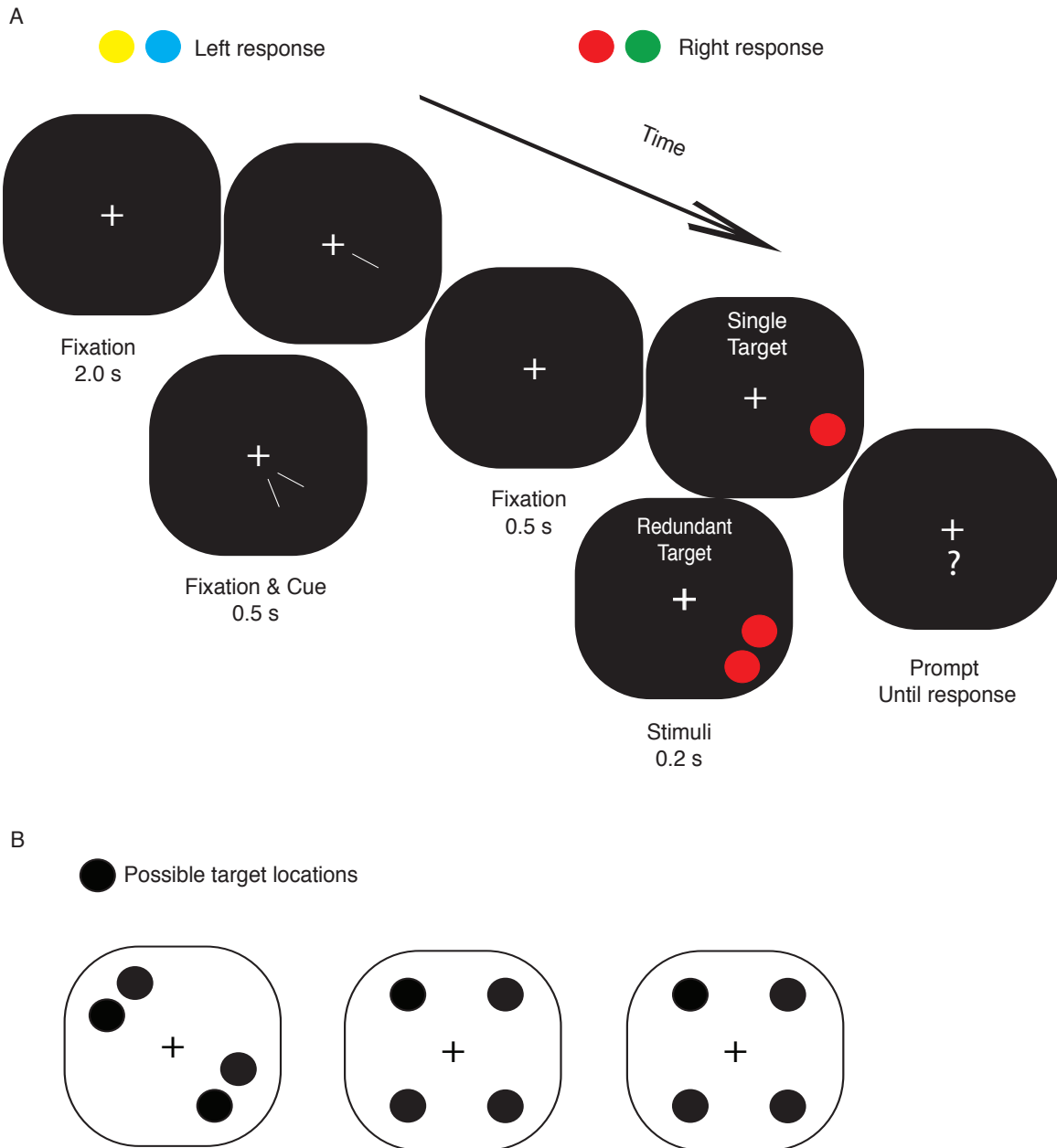


Figure 2.8. Trial sequence and possible target locations for redundant targets experiments. The illustration of the trial sequence in panel A shows two critical conditions in Experiments 2.3 and 2.4: single target and redundant targets. In a given trial, either one or two targets were displayed. Panel B shows the possible target locations for Experiment 2.3 and 2.4. The panel on the left shows the possible target locations when two targets were displayed at small separation. The panel in the middle shows the possible target locations when two targets were displayed at large separation. The panel on the right shows the possible target locations when only one target was displayed.

Results. Figure 2.9 and 2.10 shows the performance of all observers and the fitted psychometric functions for two critical conditions for Experiment 2.3 and Experiment 2.4 respectively. In both experiments, there was an advantage of viewing both targets in comparison to viewing single target.

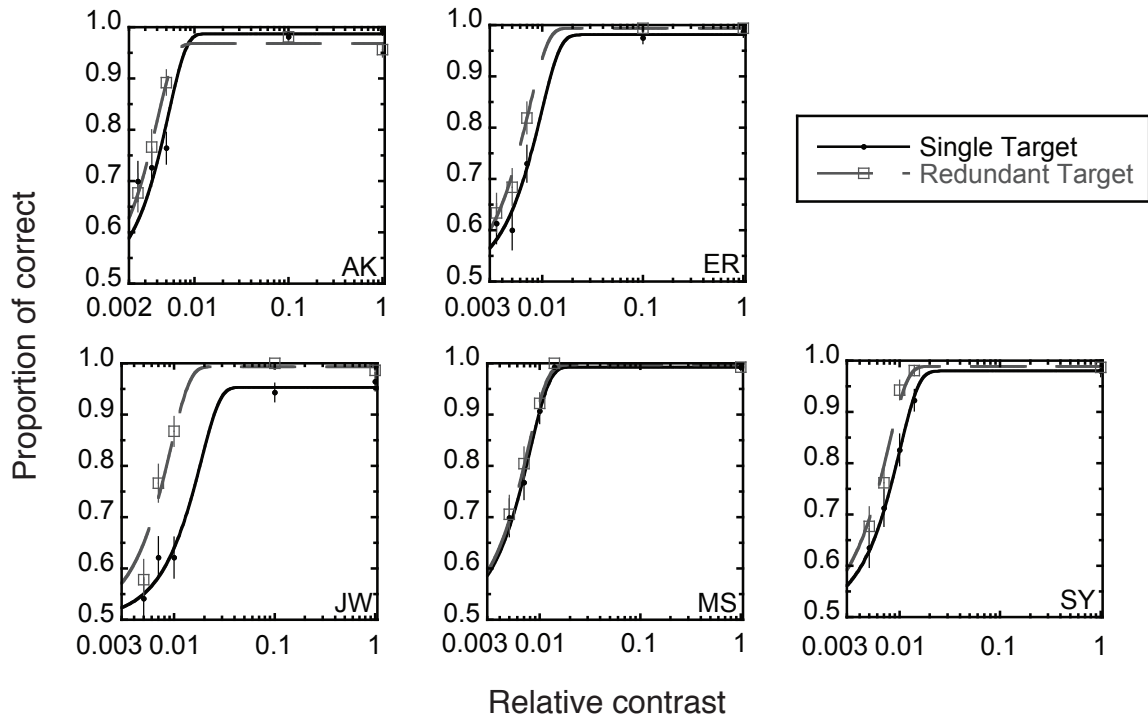


Figure 2.9. Results for the small separation redundant target experiment. The graphs plot the relative contrast (0 to 1) of the stimuli on the x-axis and the proportion of correct response on the y-axis. Each panel plots the data from a single observer. The graphs show observed performance and the best-fit psychometric functions for the two conditions. The error bars indicate the standard error of the proportions.

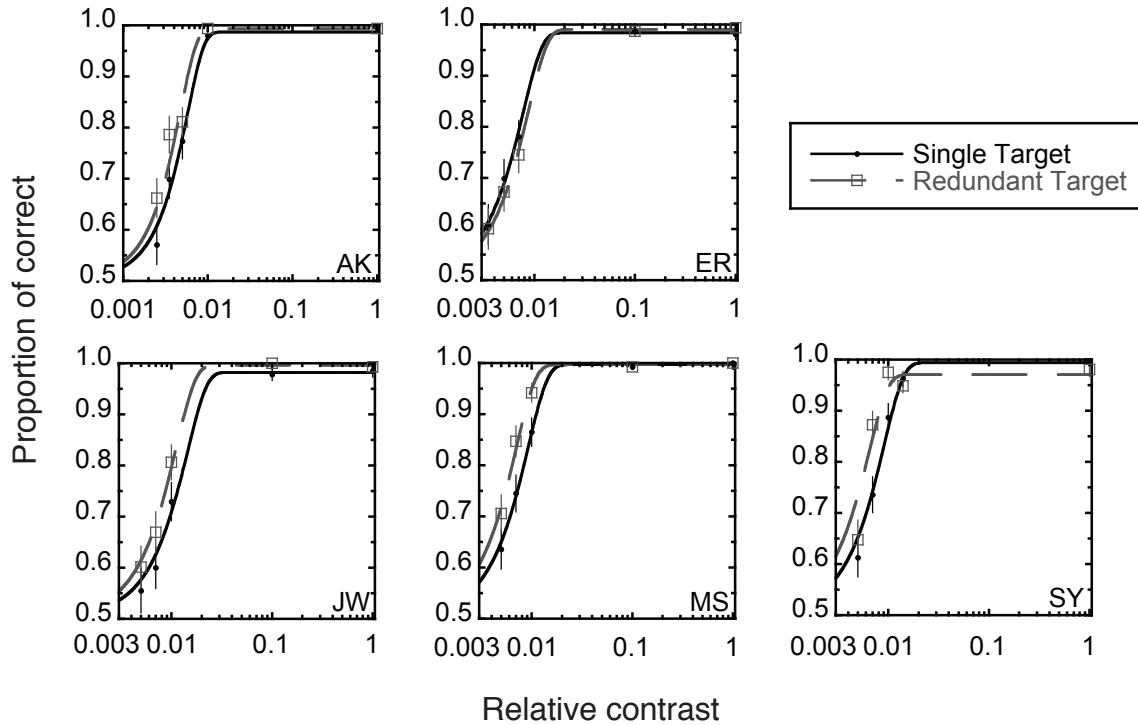


Figure 2.10. Results for the large separation redundant target experiment. The graphs plot the relative contrast (0 to 1) of the stimuli on the x-axis and the proportion of correct response on the y-axis. Each panel plots the data from a single observer. The graphs show observed performance and the best-fit psychometric functions for the two conditions. The error bars indicate the standard error of the proportions.

There were effects on the thresholds. The average detection threshold in the single target condition was 0.0081 ± 0.0020 in Experiment 3 and 0.0080 ± 0.0010 in Experiment 2.4. The average detection threshold in the redundant target conditions was 0.0058 ± 0.0010 in Experiment 2.3 and 0.0058 ± 0.0010 in Experiment 2.4. Across these two experiments, the detection threshold of the single target condition was 0.0080 ± 0.0014 and it was reliably higher than the detection threshold, 0.0058 ± 0.0010 , in the redundant targets condition ($t(4) = 3.30, p < 0.05$).

There were no effects on asymptotes. The average asymptote in the single target condition was 0.980 ± 0.007 in Experiment 2.3 and 0.991 ± 0.003 in Experiment 2.4. The average asymptote in the redundant targets condition was 0.987 ± 0.005 in Experiment 2.3 and 0.989 ± 0.005 in Experiment 2.4. Across these two experiments, the asymptotes of the single target and redundant targets conditions were not reliably different ($t(4) = 0.43, p > 0.10$).

In summary, the asymptotic performance between the single target and redundant targets conditions was the same. There was, however, an advantage of getting information from two sources rather than from a single source: The detection threshold in the redundant targets condition was lower than the detection threshold in the single target condition. These results confirm that the measure we used in the previous experiments is indeed sensitive enough to detect a threshold change due to combining information from two stimuli when they are both attended.

Discussion. Our results showed that when information was received from both stimuli, the detection threshold decreased in comparison to receiving information from a single stimulus.

Attending both stimuli can improve performance by probability summation (Graham, Robson, & Nachmias, 1977). Each stimulus provides a separate information channel. For one channel, denote the probability of detecting the stimulus by P_{stim} . Therefore, the probability of not detecting the stimulus is $1-P_{stim}$. Assume that there are two information channels that are probabilistically independent. Not detecting a stimulus in one of these channels is $1-P_{stim1}$ and detecting a stimulus in the other channel is $1-P_{stim2}$. The probability of not detecting the stimulus in either of the channels is now the product of $1-P_{stim1}$ and $1-P_{stim2}$. The probability of not detecting a stimulus is lower when there are two independent information channels in comparison to when there is one information channel. This applies to our redundant target experiments. The probability of an incorrect response was higher in the single target condition in comparison to the redundant target condition.

The size of the redundant target effect we found is consistent with the previous studies (e.g., Eriksen and Eriksen, 1974; Eriksen & Schultz, 1979; Miller, 1987; Flowers and Wilcox, 1982). For example, suppose, the probability of detecting a target is 0.5. The probability of not detecting a target at a single channel is $1-0.5 = 0.5$. The probability of not detecting a target at two channels is lower, $(1-0.5) \times (1-0.5) = .25$. This indicates that monitoring two channels increases the probability of detecting a stimulus by 0.25. For example, in our study for a representative observer, the proportion of correct was 0.74 when there was a single target. If the probability of detecting a target were 0.74, then not detecting it would be $1-0.74 = 0.26$ when there is a single target. The probability of not detecting a target when there are redundant targets would be $(1-0.74) \times (1-0.74) = 0.08$. According to the probability summation theory, the probability of

detecting the target when there are redundant targets should increase by $0.26 - 0.08 = 0.18$. For our conditions, we found that the redundant target increased the proportion of correct by 0.11, which is close to what the theory predicts. Our results showed that our experiment was sensitive to measure the effects on threshold of a magnitude relevant to probability summation effect.

Experiment 2.5: Spatial extent of selection

In Experiments 2.1 and 2.2, we showed that there is a flanker congruency effect only when the separation between a target and flanker is small. In Experiment 2.5, we investigated the spatial extent of this effect. In order to do that, we used the same spatial filtering paradigm that was used as in Experiments 2.1 and 2.2 and we presented the flanker at varying distances from the target.

Method. The stimuli were the same as in Experiments 2.1 and 2.2. Unlike the previous experiments, only high contrast stimuli were presented. One of 16 possible locations was indicated with a bar marker as the target location. A flanker was presented simultaneously to either side of the target with a distance of 0.7° , 1° , 1.4° , or 2.8° in visual angle. We chose 0.7° for the smallest separation, due to the size of the stimuli. Any separation smaller than 0.7° would cause the stimuli to overlap. For each separation between the target and flanker, there were four possible target locations. Table 5 shows the possible target and flanker locations in polar angle for a given target-flanker separation. The experimental conditions were the same as in Experiments 2.1 and 2.2.

Table 2.5. Possible target and flanker locations in polar angle in Experiment 2.5.

Separation in degrees of visual angle (°)	Upper left quadrant of screen		Lower right quadrant of screen	
	Target location in degrees of polar angle (°)	Flanker location in degrees of polar angle (°)	Target location in degrees of polar angle (°)	Flanker location in degrees of polar angle (°)
0.7	137.5	132.5 or 142.5	322.5	317.5 or 327.5
	132.5	127.5 or 137.5	317.5	312.5 or 322.5
1.0	138.5	131.5 or 145.5	323.5	316.5 or 330.5
	131.5	124.5 or 138.5	316.6	309.5 or 323.5
1.4	140	130 or 150	325	315 or 335
	130	120 or 140	315	305 or 325
2.8	145	125 or 165	330	310 or 350
	125	105 or 145	310	290 or 330

In each session, there were 128 trials. There were 32 trials in identical and response congruent conditions. There were 64 trials in response incongruent condition. Each observer ran 10 sessions for a total of 1280 trials.

Results . Figure 2.11 shows results for two observers. In the identical and response congruent trials, the performance is near perfect (1.0) at all separations. In the response incongruent condition, the performance was near perfect only at the largest separation. In this condition, as the separation decreased, the performance also decreased.

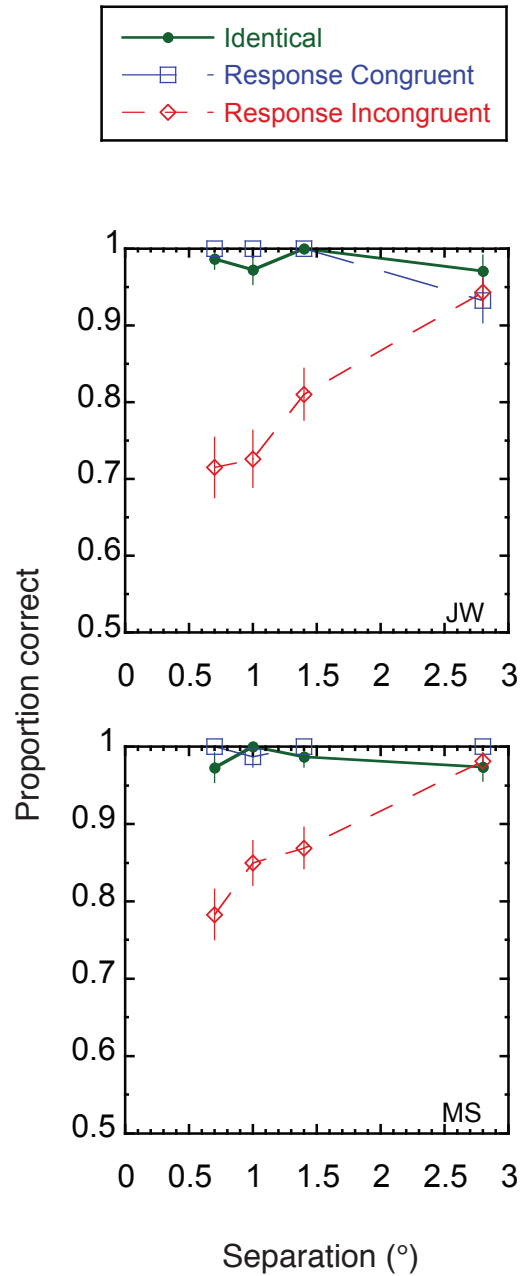


Figure 2.11. Results for the spatial extent of selection experiment. The graphs plot the separation between the target and flanker in degrees of visual angle on the x-axis and the proportion of correct response on the y-axis. Each panel plots the data from a single observer. The graphs show observed performance for three critical conditions. The error bars indicate the standard error of the proportions.

The performance collapsed across observers in the response incongruent condition varied from 0.75 ± 0.03 for the smallest separation to 0.96 ± 0.02 for the largest separation.

In summary, the performance in the response congruent condition declined drastically from near perfect at the largest separation to half way to chance at the smallest separation. If we could make the separation smaller than 0.7° , the performance would have approached chance.

Discussion

Summary of Results. Figures 2.12 and 2.13 show the summary of the results. Panel A of Figure 2.12 shows the asymptotic performance of all observers as a function of separation between the target and flanker. Asymptotic performance was the same at both separations in the identical, response congruent, single target, and redundant targets conditions as well as in large separation in the response incongruent condition. Asymptotic performance decreases drastically at small separation in the response incongruent condition.

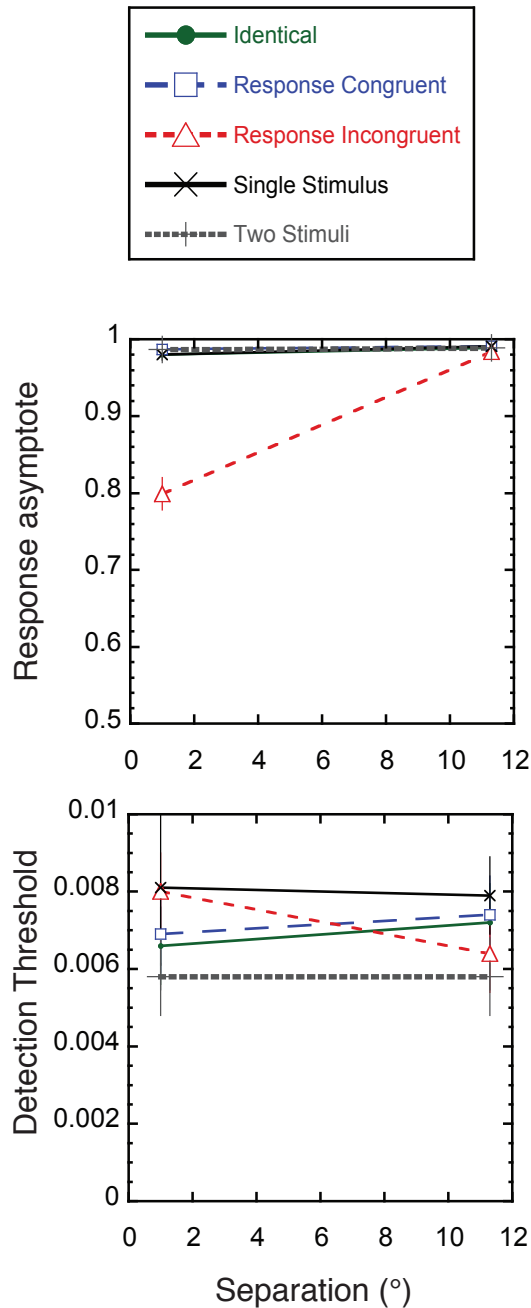


Figure 2.12. The summary of the results of Experiments 2.1, 2.2, 2.3, and 4. Panel A shows the mean asymptotic performance across all observers as a function of separation between two stimuli. Each line indicates the asymptotes from a single condition from each experiment. Panel B shows the mean detection threshold across all observers as a function of separation between two stimuli. Each line indicates the detection thresholds from a single condition from each experiment. In both panels, the error bars show the standard error of the mean estimate over observers.

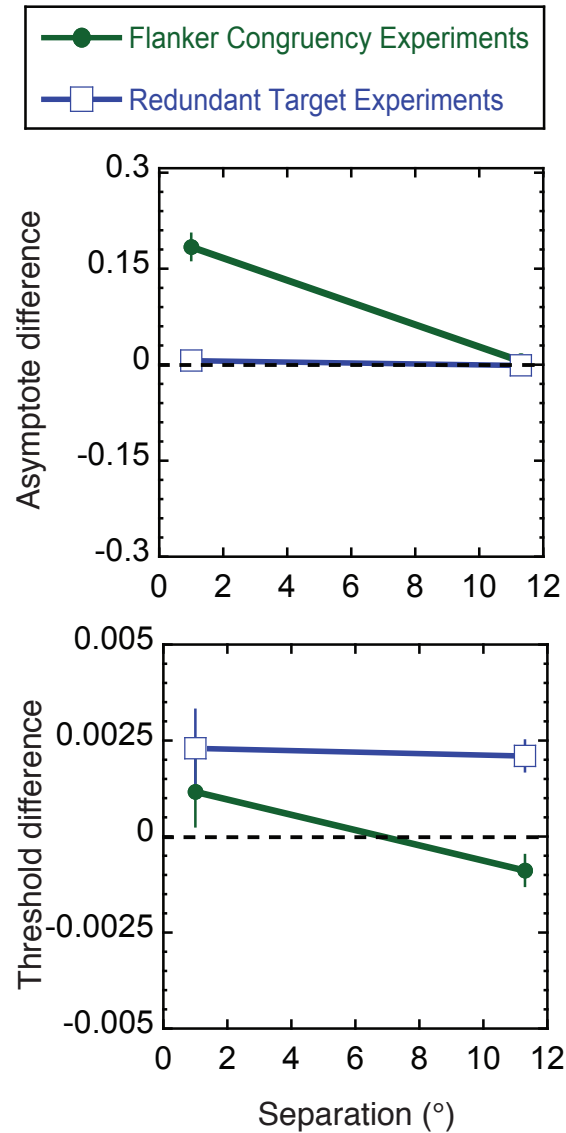


Figure 2.13. Summary of the differences of performance between two different conditions in Experiments 2.1, 2.2, 2.3, and 2.4. Panel A shows the difference between the asymptotes in the congruent and incongruent conditions, and the difference between the asymptote for the redundant targets conditions. Separation in degrees of visual angle between two stimuli is plotted on the x-axis and the asymptote difference is plotted on the y-axis. Panel B shows two different detection thresholds between the congruent and incongruent conditions, and the different thresholds for the redundant targets conditions. Separation between two stimuli is plotted on the x-axis and the detection threshold difference is plotted on the y-axis. The error bars indicate the standard error of the mean estimate over observers.

Panel A of Figure 2.13 shows the difference between asymptotic performance in the congruent and incongruent conditions as well as the difference between the single target and redundant target conditions as a function of separation. In the redundant target experiment, there is no asymptote difference between the single and redundant target conditions. In summary, there was a large effect of separation on the asymptote at small separation.

Panel B of Figure 2.12 shows the detection threshold as a function of separation. The detection threshold is similar in all conditions except in the redundant target experiments. Panel B of Figure 2.13 shows that the detection difference between the threshold for the congruent and incongruent conditions is close to zero at both separations. However, in the redundant target experiments, there is a difference between the single and redundant targets conditions at both separations. In summary, there is an effect of redundant targets on threshold, but no similar magnitude effect for the filtering task.

We investigated the nature of the flanker congruency effect and considered three alternative explanations: multiplicative attenuation, failure of selection, multiplicative attenuation and failure of selection. Figure 2.14 shows the alternative models we considered in detail. This study aims to differentiate between the blocking and attenuation models. Differentiating the alternative explanations for blocking and attenuation is beyond the scope of this study. Our results indicated that when a relevant and an irrelevant stimulus are presented in the periphery, the flanker congruency effect is due to failure of selection and not multiplicative attenuation. We also found that there is failure of selection when two stimuli are displayed at a small separation and not when

they are displayed at a large separation. Further, we tested whether or not an effect on detection threshold could be measured with our design and found that when two identical stimuli are presented as targets, attending both stimuli enhanced detection threshold in comparison to attending a single stimulus. Finally, we began to characterize how the congruency effect varied with separation.

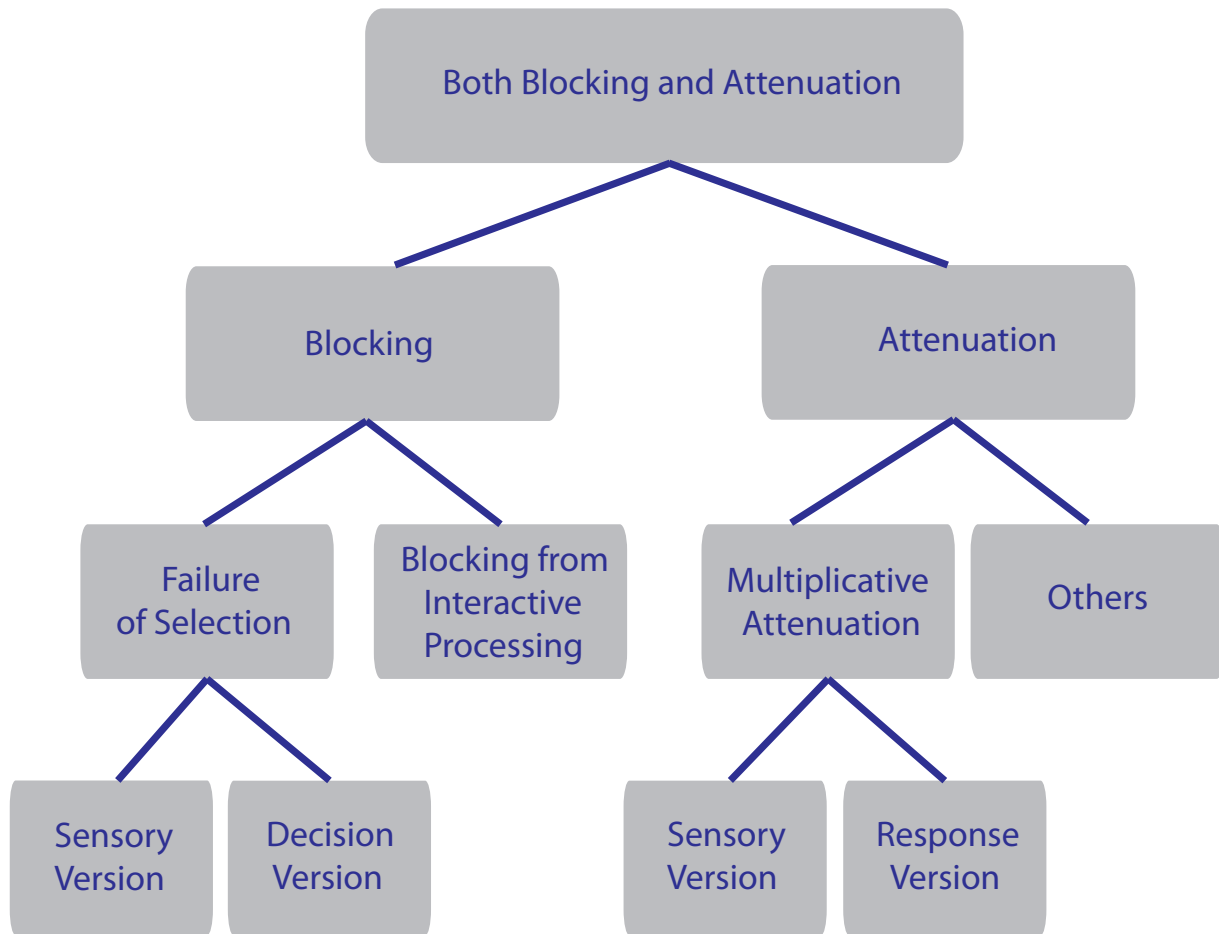


Figure 2.14. Alternative models for explaining the flanker congruency effect. Our experiments differentiate between the general blocking and attenuation from interactive processing models.

Models for blocking

Imprecise targeting. The results indicate that the flanker congruency effect is consistent with a failure of selection version of blocking. Blocking assumes that information from an unselected stimulus does not affect performance. In a fraction of the trials, the irrelevant stimulus is selected and the identity of the relevant stimulus does not matter for the response being made. Selection might fail due to number of reasons. One possible reason is spatial uncertainty. In this experiment at small separation, we presented stimuli in the periphery and cued the target location prior to stimulus display. Due to small separation between the stimuli, it was difficult to maintain focus on exactly the cued location. The spatial uncertainty can be thought as a small jitter in where to attend resulting in imprecise targeting (Bahcall & Kowler, 1999; Palmer & Moore, 2009). Imprecise targeting assumes that at a given trial, only one location is monitored for information. On some trials, a non-target location is monitored. If there is a stimulus at the monitored location, that stimulus drives the response. Imprecise targeting predicts that the effect of monitoring the wrong location is on the asymptote; as the separation between the stimuli decreases, observers monitor the wrong location more often. This causes high number of incorrect response; therefore decreasing the asymptote of the psychometric function.

Selection by decision. Another possible explanation for the failure of selection is that selection is made by decision after both stimuli were processed and a response was prepared for each stimulus as opposed to preparing a response for only the stimulus at the cued location. According to this view, the observers process both stimuli regardless of their location. Stimuli are processed to the level of color identification and

each stimulus activates a response code and the observers prepare a response for each stimulus. If the response codes agree, the response is made immediately. If they disagree, a further decision is made to determine which of the two stimuli is more likely to be at the cued location. By this hypothesis, the root of the flanker congruency effect is the localization of the relevant stimulus.

Blocking by interaction. Blocking is not necessarily result of a selection that is all or none. Interactive processing can result in the modulation of the peak response instead of the effective contrast as in the response gain models of physiology (Huang & Dubkins, 2005; Ling & Carrasco, 2006). According to the blocking by interaction model, in the incongruent trials, the flanker is assumed to attenuate the effective peak response for the target at high contrasts. Because the high contrast target cannot overcome this response attenuation, this model predicts that modulated effective response peak changes the upper asymptote resulting in a horizontal shift (Pestilli, Ling, & Carrasco, 2009). The predictions of this model and the failure of selection model are similar in that both predict the effect of the modulated response to be on the upper asymptote. It is difficult to differentiate between these two models with our design.

In summary, we considered three alternative blocking models. Our results are consistent with imprecise targeting, selection by decision, and blocking by interaction. Blocking by interaction makes predictions similar to the predictions of failure of selection and these cannot be differentiated with our design.

Models for attenuation

Multiplicative attenuation. The interactive processing causes the modulation of the effective contrast. In the congruent trials, the flanker is assumed to increase the effective contrast of the target while in the incongruent trials, the flanker is assumed to attenuate the effective contrast in a multiplicative fashion (Reynolds et al., 2000). At the high contrasts, the target overcomes the attenuating effects of the incongruent flanker. This model predicts that the modulated effective contrast changes detection threshold causing a horizontal shift of the psychometric function.

It is possible that the attenuation affects the stimulus signal in a different way rather than multiplicatively. Such an effect can cause psychometric function to change in any different way. However, the key feature of attenuation predicts that regardless of the type of effect the attenuation has on stimulus signal, a high intensity stimulus overcomes this attenuation allowing asymptote to reach near perfect.

Attenuation can be caused by the sensory processing of stimuli in which the simple features of stimuli interact with each other causing the incompatible features to attenuate the effective intensity of the relevant stimulus. Attenuation can also be caused by response competition, which occurs after each stimulus activates a corresponding response code. If these codes are compatible, they prime each other. If they are incompatible, they compete with each other allowing the irrelevant response code to attenuate the strength of the relevant response. In either case, the high contrast stimulus overcomes the attenuation.

Multiplicative attenuation predicts that the effect of the flanker is on threshold. We did not find any threshold effect in our flanker congruency experiments. Therefore, we did not find evidence for any version of multiplicative attenuation.

The locus of selection

The flanker congruency effect has been used to distinguish the locus of selective attention. The locus of selective attention refers to where in the processing of stimuli the selection occurs: early or late relative to stimulus identification and response selection.

Late selection

The flanker congruency effect itself has been often accepted as an evidence for the late selection. Late selection theories assume that visual stimuli are processed unselectively in parallel (e.g., Duncan, 1980b; Miller, 1987). Selection occurs after all stimuli are processed to identity. During the parallel processing of all stimuli, the semantic information is extracted. However, this information only reaches awareness after selection. It is further assumed that the semantic information that is extracted prior to selection is processed interactively; hence the identity of the flankers affects performance.

Late selection theories typically assume interactive processing, but it is also possible that each stimulus is processed in parallel but independently. In this case, there would be no effect of the flanker on behavioral performance. Thus, the absence of a flanker effect is not evidence against late selection.

Early selection

Early selection theories assume that visual stimuli are processed in parallel only to the point of simple features (Broadbent, 1958). The rest of the perceptual and response processes include only the selected stimulus due to capacity limitations. Thus, selection occurs before semantic information is extracted. Filtering of the irrelevant stimuli provides the advantage of reducing the possible interactive processes to the

simple features. According to these theories, the identity of the irrelevant stimuli cannot affect behavior at the later stages of processing. However, these theories do not rule out interactive processing of simple features, because they assume that the simple features are processed before selection. In summary, early selection predicts no interactive processing for stimulus identification, but does allow the possibility for interactive feature processing.

In the current study, we used colored disks as stimuli. For our selective attention task, the response was based on the stimulus colors; color is a physical property of stimuli, hence, considered as simple feature. Simple features are assumed to be processed prior to selection by both early and late selection theories. Thus, the current study has little to say about early versus late selection. Instead, the focus is on the nature of selection: is it by blocking or attenuation? In the future, we intend to extend these study to tasks that depend on semantic processing that will have more to say about early versus late selection.

Accuracy versus response time

In the flanker experiments, response time has been frequently used as the dependent variable. There are conflicting views on whether or not response time and accuracy measure the same aspects of perceptual and cognitive processing. One of the early studies indicated that response time measures the limitations of cognitive processes while accuracy measures limitations of sensory processes (Santee & Egeth, 1982). Santee and Egeth suggested that when the stimulus input is limited, the accuracy measures interference between two or more stimuli that is based on feature

competition. This feature competition occurs early in the processing. They also suggested that the response time measures processes related to response preparation and execution, which occurs later in the processing. Moreover, they argued that when the stimulus display is long or unlimited (display stays until response), both measures are sensitive to “late” processes such as response selection and execution.

Alternatively, there is evidence that the tasks that require voluntary attention to stimuli can measure attentional effects both with accuracy and response time (Prinzmetal, McCool, & Park, 2005). Other studies also have shown that accuracy and response time are affected by the same aspects of the perceptual and cognitive processing (e.g., Wühr and Müessler, 2001; Palmer, Huk, and Shadlen, 2005). Wühr and Müessler presented two objects as stimuli where one was defined as target. Target was presented with another identical target or with a flanker. Consistent with the flanker experiments carried out with response time, the proportion of correct responses were higher when the flanker was identical to the target rather than when it was different from the target. Palmer, Huk, and Shadlen (2005) required subjects to indicate the direction of motion in a noisy display. They showed that in this motion discrimination task, accuracy and response time improved as motion strength was increased.

In the current study, the task required voluntary attention and we varied the difficulty of detection by varying the contrast. While it might be argued that the response time is a more sensitive measure of interactive processing we, nevertheless, found a flanker congruency effect with accuracy. In summary, we suspect accuracy and response time have a lot in common.

Differences between the original and the new paradigm

There were three main differences between the original flanker paradigm and our design. First, in the original flanker paradigm, targets were displayed at the fovea while the flankers were in the periphery. When the target location is very well defined, selection is less likely to fail. Our design is different than the original flanker paradigm in the sense that we introduced a spatial uncertainty by presenting the target and flanker in the periphery and introducing different locations as possible target locations. This spatial uncertainty accentuates the effect of failure of selection by showing how it depends on the separation between a relevant and an irrelevant stimulus. Second, in the original flanker experiments letters are most often used instead of stimulus that is judged by its simple features such as color. We wanted to keep our design as simple as possible by using a design that required response that was driven by simple features rather than more complex stimulus judgment such as letter identification. Third, flanker experiments most often uses the measure of response time and tests stimuli that have high stimulus strength such as high contrast. In our study, we measured accuracy as a function of relative contrast. This design allowed us to measure the effects of irrelevant stimuli for a full range of stimulus difficulties.

These differences between the original flanker experiments and ours are essential in interpreting our results. We introduced a well-controlled design that tests very specific predictions regarding the effects of contrast and effects of separation on performance. It, however, remains to be seen how our results will generalize to original flanker experiments.

Conclusion

Our experiments provide a detailed analysis of the effect of the irrelevant stimuli on accuracy in the flanker paradigm. Unlike previous flanker experiments, we presented targets in the periphery to match the sensory processes for the relevant and irrelevant stimuli and used a range of contrasts and separations to characterize the effect of the irrelevant stimulus. Our results are consistent with the failure of selection version of blocking. The results are not consistent with several models of attenuation that might arise from either sensory or response code interaction.

CHAPTER 3

Conclusions

Summary of results

First, consider the spatial filtering paradigm; irrelevant information was blocked for the spatial filtering paradigm in which a narrow location was monitored for detecting a target (Experiment 1.1). In contrast, irrelevant information was attenuated for spatial monitoring in which a wide range of locations was monitored for detecting a target (Experiment 1.2). Next, consider the flanker paradigm; there was an effect of an irrelevant stimulus on the judgment of a relevant stimulus only when the irrelevant stimulus was incongruent with the relevant one and when the separation between the two stimuli was small (Experiment 2.1). This effect disappeared when the separation between the stimuli was large (Experiment 2.2). The congruency effect was consistent with blocking and not attenuation. In conclusion, in order to distinguish blocking from attenuation, one needs to observe asymptotic behavior at high stimulus intensities. Different selection mechanisms are used in different selective attention tasks. In a flanker paradigm with peripheral stimuli, the effect of the flanker is consistent with failure of selection, not attenuation.

Future directions

In a current flanker study that I am conducting, I use the measure of response time in addition to accuracy. Response time can be more sensitive to changes in the congruency conditions and it might reveal effects of interactive processing that are too small to detect with the accuracy measure.

In these studies, the stimuli were most likely processed in parallel even though irrelevant stimulus was supposed to be ignored. This is due to simple stimuli that were

used in these studies. A future study with more complex stimuli such as words is likely to be processed serially, because there is a limit of the number of words that can be processed in parallel (e.g., Scharff, Palmer, and Moore, 2011a). Such an experiment gets to the heart of the original interest in using the flanker paradigm to determine if selection occurs before or after processing of stimuli.

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Appendix

Mixture model for the flanker congruency effect

In the mixture model, one location is monitored and because of location uncertainty, the stimulus at this location can be either the target or the flanker. Mean response in the flanker congruency experiment is a mixture of the trials in which an observer monitors the target versus the flanker. In the congruent trials, regardless of which stimulus is monitored, the response is the same, because the target and flanker require the same response. In the incongruent trials, however, the response is different depending on which stimulus is being monitored. We can formulate the mean response separately in the congruent and incongruent trials. We denote the contrast as x . The mixture parameter is denoted as h . We assume a psychometric function, ψ , which is monotonically increasing. The domain of the function is the contrast values of the stimuli and the range is the proportion of correct responses. In other words, ψ measures proportion correct as a function of varying contrast. Response for the congruent and incongruent conditions are defined, respectively, as

$$p_c = \psi(x) \text{ and}$$

$$p_i = h \psi(x) + [1 - h] (1 - \psi(x)).$$

Let's walk through these equations. On some trials, the performance is determined by the target and on other trials, it is determined by the flanker. In the congruent trials, the target and flanker require the same response. Therefore, monitoring either the target or the flanker does not change the performance, $\psi(x)$. In the incongruent condition, the target and flanker require opposite response. If one correctly selects the target, which leads to a correct response, the performance is defined by $\psi(x)$. If one selects the

flanker, which leads to an incorrect response, the performance is $1 - \psi(x)$. Therefore, monitoring the flanker changes the performance in the incongruent trials.

Multiplicative attenuation model

In the multiplicative attenuation model, a flanker changes the effective stimulus contrast. In the incongruent trials, the flanker attenuates the effective contrast of the target. At high contrasts, the target overcomes this attenuation; therefore, the effect of the attenuation is only on the detection threshold and not the asymptote.

We can formulate the attenuation in the incongruent trials. We denote the contrast as x . The attenuation parameter is denoted as a . We assume a psychometric function, ψ , which is monotonically increasing. The domain of the function is the contrast values of the stimuli and the range is the proportion of correct responses. In other words, ψ measures proportion correct as a function of varying contrast. Response for the congruent and incongruent conditions are defined, respectively, as

$$p_c = \psi(x) \text{ and}$$

$$p_i = \psi(ax).$$

Let's walk through these equations. In the congruent trials, there is no attenuation from the flanker. Therefore, the performance does not change due to flanker and is defined as $\psi(x)$. In the incongruent trials, the flanker attenuates the effective contrast in a multiplicative fashion. Therefore, the performance is performance is defined by $\psi(ax)$.

Supplemental Material

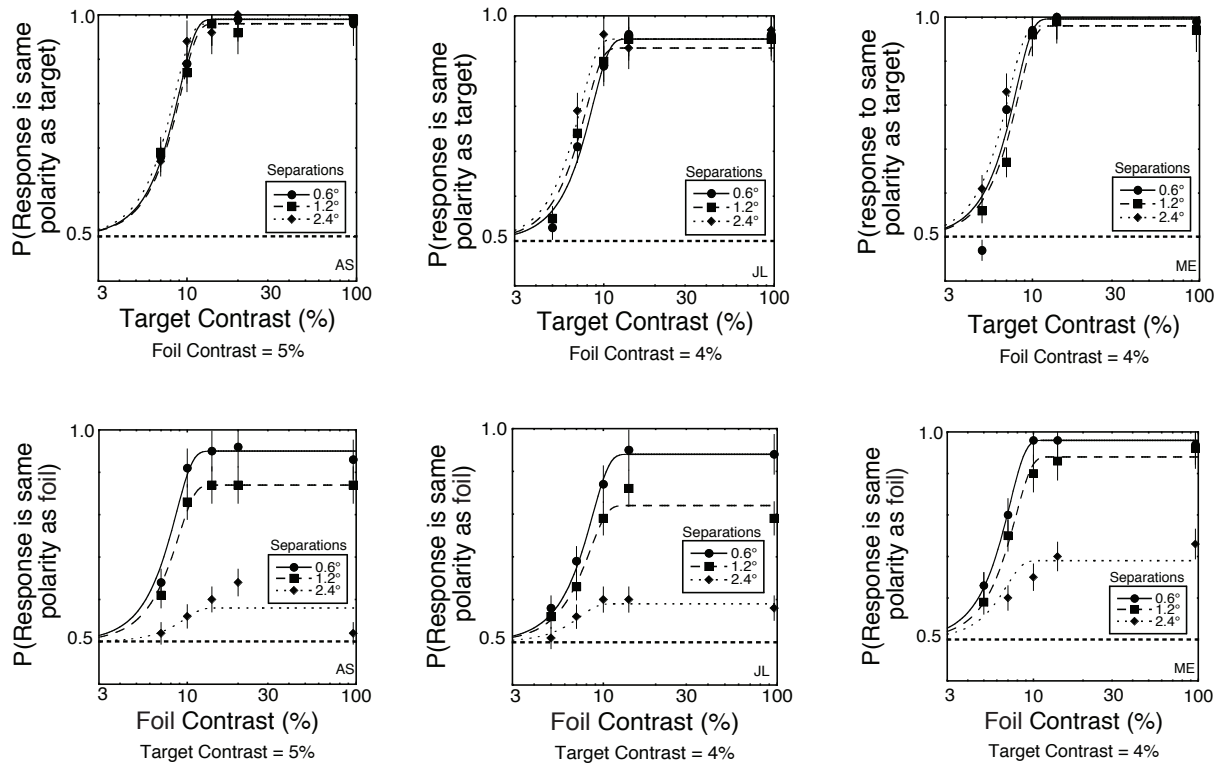


Figure S1. The results for spatial filtering are shown for 3 observers. Each column shows a different observer. The top panels show a target psychometric function and the bottom panels show a foil psychometric function. There is little or no effect of separation for the target functions. In contrast, there is a large effect of separation for the foil functions. The functions for larger separations show a reduced asymptote consistent with imprecise targeting.

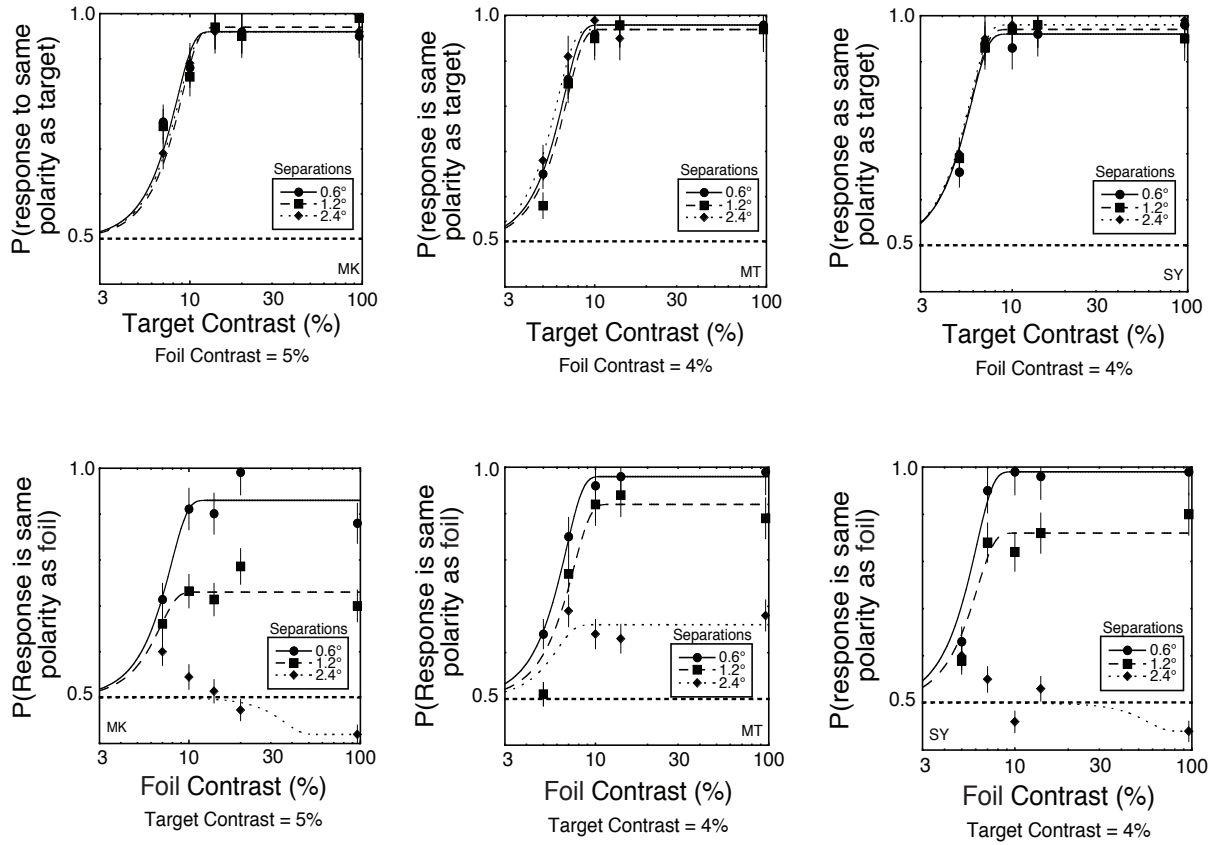


Figure S2. The results for three more observers from spatial filtering with the identical format as Figure S1.

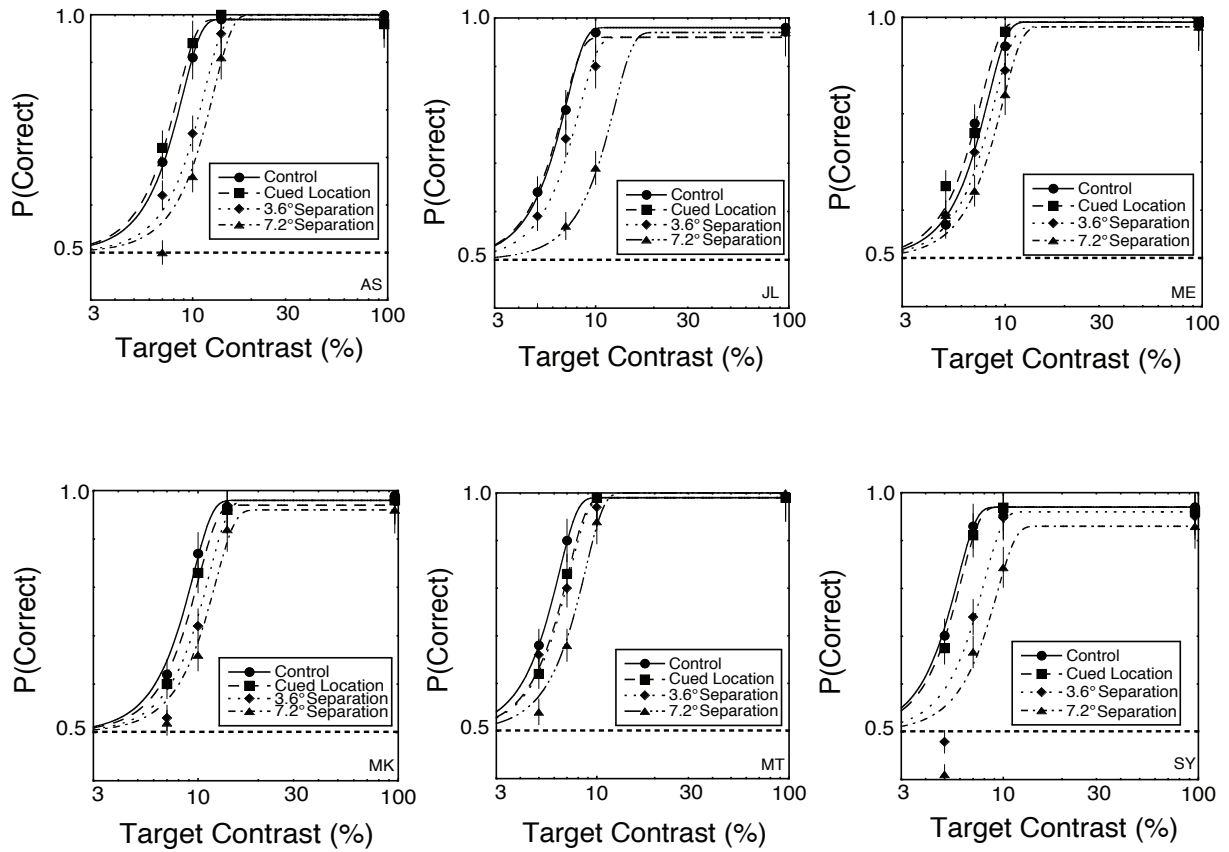


Figure S3. The results for spatial monitoring are shown for six observers. Each panel illustrates a different observer. The functions for larger separations show an increased threshold consistent with contrast gain.

VITA

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