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Distinguishing Blocking From Attenuation in Visual Selective Attention

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Abstract

Sensory information must be processed selectively in order to represent the world and guide behavior. How does such selection occur? Here we consider two alternative classes of selection mechanisms: In *blocking*, unattended stimuli are blocked entirely from access to downstream processes, and in *attenuation*, unattended stimuli are reduced in strength but if strong enough can still access downstream processes. Existing evidence as to whether blocking or attenuation is a more accurate model of human performance is mixed. Capitalizing on a general distinction between blocking and attenuation—blocking cannot be overcome by strong stimuli, whereas attenuation can—we measured how attention interacted with the strength of stimuli in two spatial selection paradigms, spatial filtering and spatial monitoring. The evidence was consistent with blocking for the filtering paradigm and with attenuation for the monitoring paradigm. This approach provides a general measure of the fate of unattended stimuli.

Keywords

selective attention, blocking, attenuation, spatial filtering, spatial monitoring, attention sharing, attention switching

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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 (Bonnel, 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, Dosher, & 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,

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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 asked 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 (Fig. 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 (Fig. 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.

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, a mean of 1.4 ± 0.4% of trials was 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 2, a mean of 1.4 ± 0.7% of trials was 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: Spatial Filtering

For the filtering task used in Experiment 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 1a and 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: 0.6°, 1.2°, and 2.4°.

Contrast was varied for both of the stimuli as shown in Table 1. (The values of contrast were slightly different for each observer to roughly match performance across observers.)

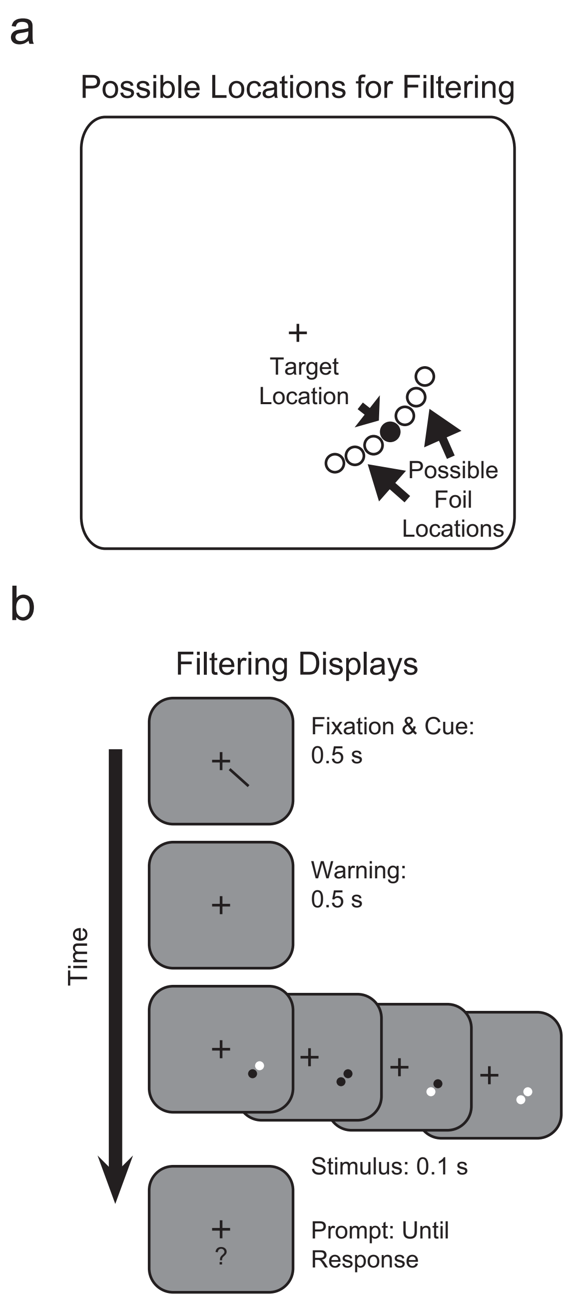

Fig. 1. Illustrations of the stimuli and procedure of Experiment 1 (spatial filtering) and Experiment 2 (spatial monitoring). In Experiment 1, the critical display (a) included two discs, a target at a cued location and a foil that could be located at any of six other locations. In Experiment 2, the 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 (b) shows multiple possible critical displays, illustrating all combinations of target and foil polarity, and the sequence for Experiment 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.

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

Table 1. Target and Foil Contrast Values That Were Paired in Experiment 1

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

Note: In this grid, the combinations of target contrast and foil contrast that were used are marked by an "X."

target had no reliable effect on the foil function (see the congruency analysis in Palmer & Moore, 2009).

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 2a and 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; Fig. 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; Fig. 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.

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 (Fig. 2a) predicts a horizontal shift with increasing separation. Thus, there is a change in threshold but not asymptote. In contrast, the imprecise-targeting model (Fig. 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.

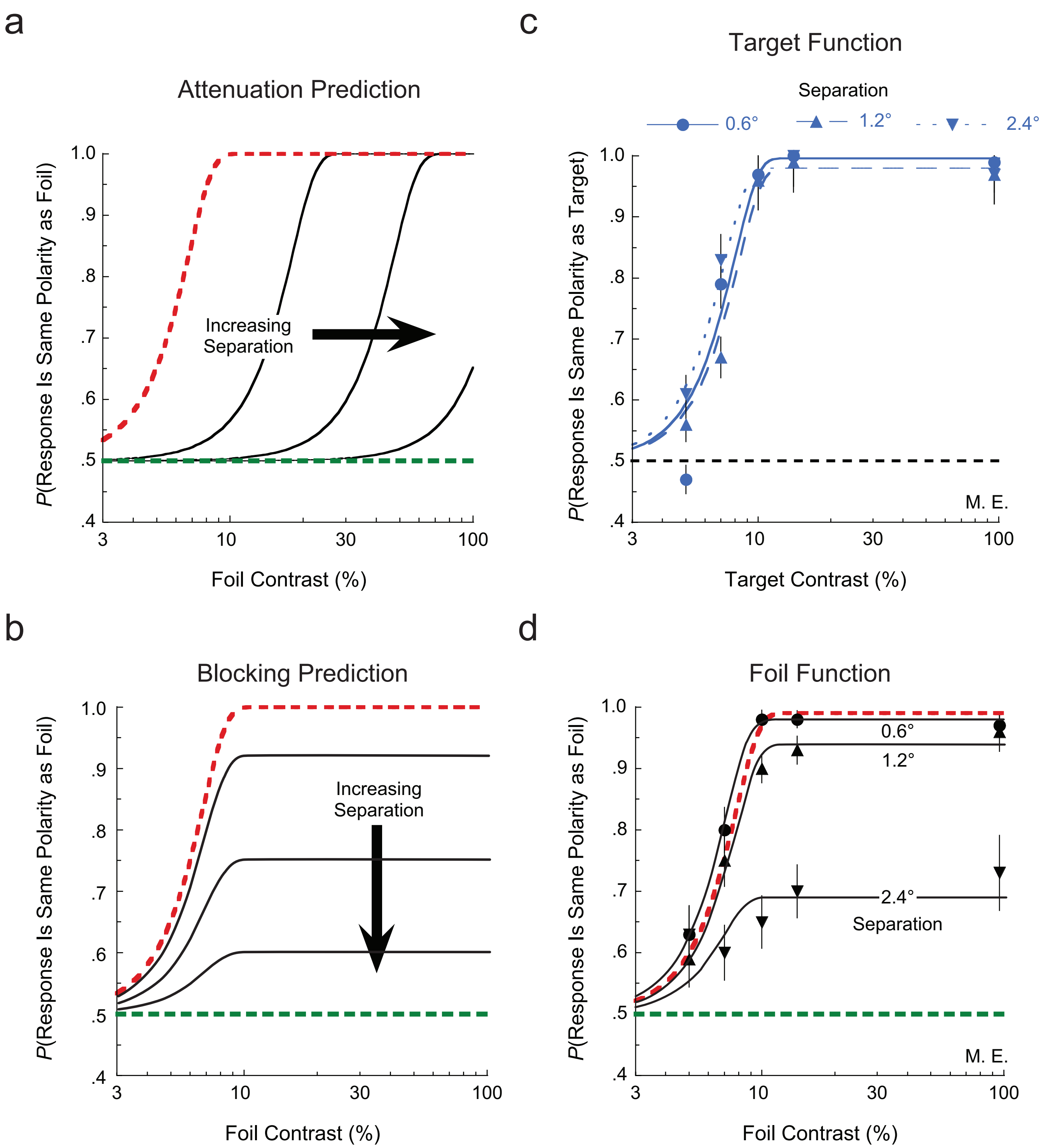

Fig. 2. Predictions and example results for Experiment 1. The contrast gain model (attenuation; a) and the imprecise-targeting model (blocking; b) generate different predictions for the foil psychometric function. Results for observer M. E. are shown in (c) and (d), which present observed performance 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.

Results

Figure 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 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 Figs. S1 and S2 of the Supplemental Material available online). 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 ± .01 for the smallest separation to .59 ± .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 ± 0.4% for foils at the smallest separation, 6.6 ± 0.7% for foils at the largest separation, and 6.7 ± 0.4% for targets. In summary, performance on the spatial filtering task was consistent with selection by blocking and not attenuation.

Experiment 2: Spatial Monitoring

Method

The method for Experiment 2 was the same as for Experiment 1 except that the target location was probabilistic and foils were eliminated. The locations used and the trial sequence are illustrated in Figures 1c and 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 3a and 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 3c shows the observed performance and best-fit psychometric functions for observer M. E. (results for all observers are shown in Fig. 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 ± 0.5% for the valid condition, 8.1 ± 0.6% for the invalid-near condition, and 9.6 ± 0.7% for the invalid-far condition. The asymptotes were .98 ± .01 for the valid condition, .98 ± .01 for the invalid-near condition, and .97 ± .01 for the invalid-far condition. In summary, spatial monitoring yielded performance consistent with selection by attenuation and not blocking.

Spatial Extent of Selective Attention

Figure 4 characterizes the spatial extent of selection averaged across observers. In the case of spatial filtering (Experiment 1), separation affected the asymptote almost exclusively, whereas in the case of spatial monitoring (Experiment 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° ± 0.1° 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.

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 mechanisms (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.

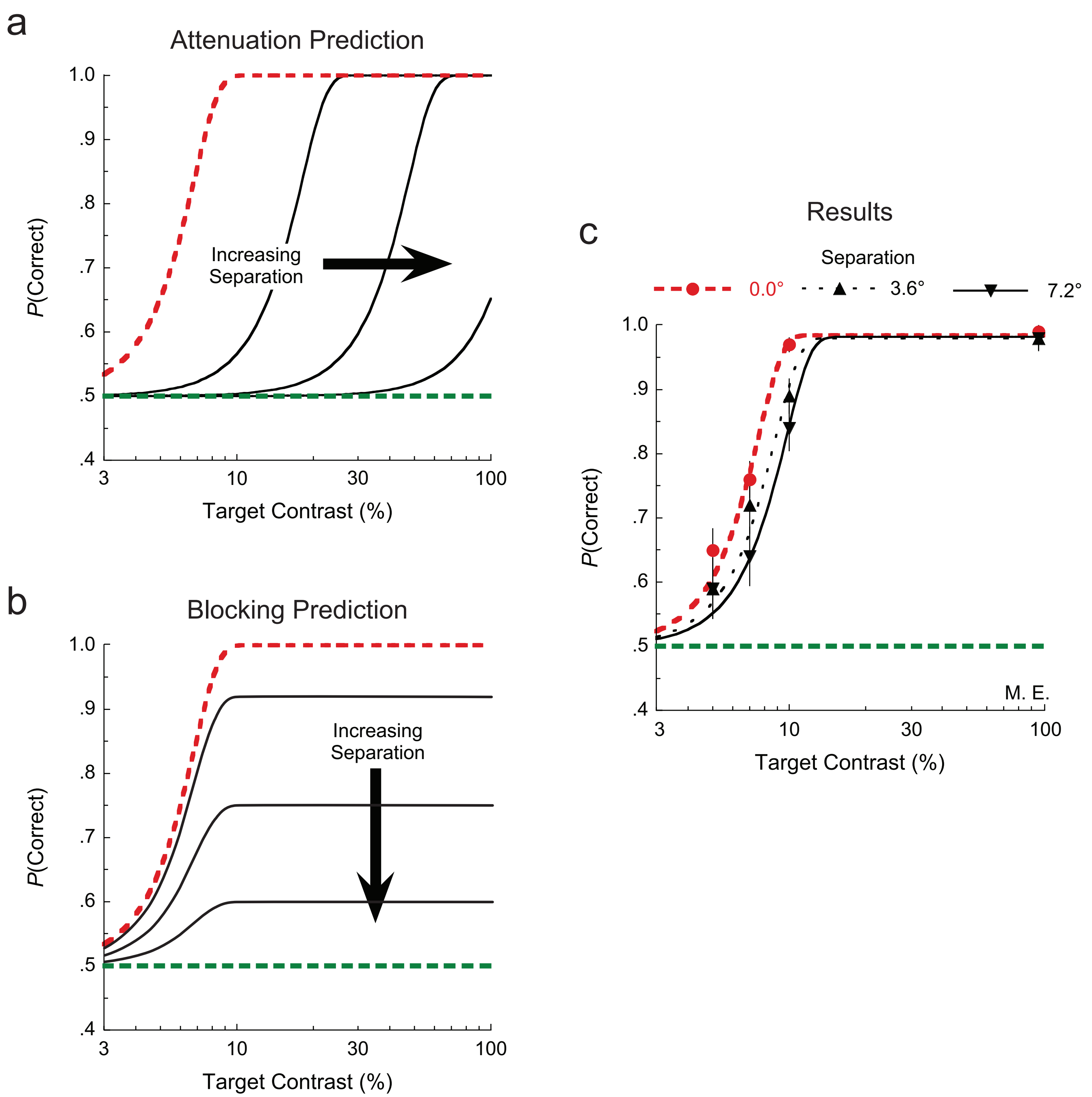

Fig. 3. Predictions and example results for Experiment 2. The contrast gain model (attenuation; a) and the imprecise-targeting model (blocking; b) generate different predictions for proportion correct as a function of target contrast. The observed performance and best-fit psychometric functions for 1 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 what is observed if the stimulus is at the cued location.

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, 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

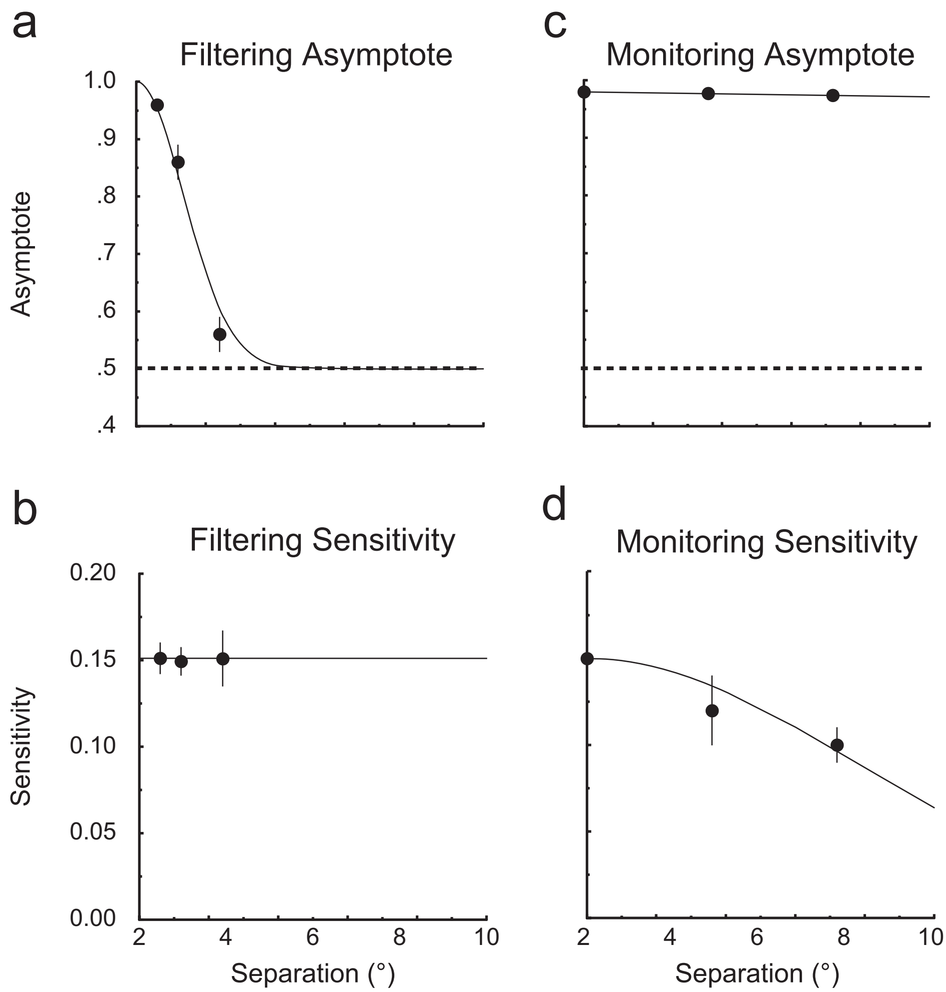

Fig. 4. Mean asymptote and sensitivity (1/threshold) in Experiment 1 (spatial filtering) and Experiment 2 (spatial monitoring). For filtering, the asymptote (a) and sensitivity (b) are shown as a function of the separation between the foil and the cued location; for monitoring, the asymptote (c) and sensitivity (d) are shown as a function of the separation between the target and the cued location. The error bars indicate the standard error of the mean asymptote or sensitivity, averaged from the values estimated for the 6 observers.

the asymptotes of the target and foil psychometric functions. For Experiment 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 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.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

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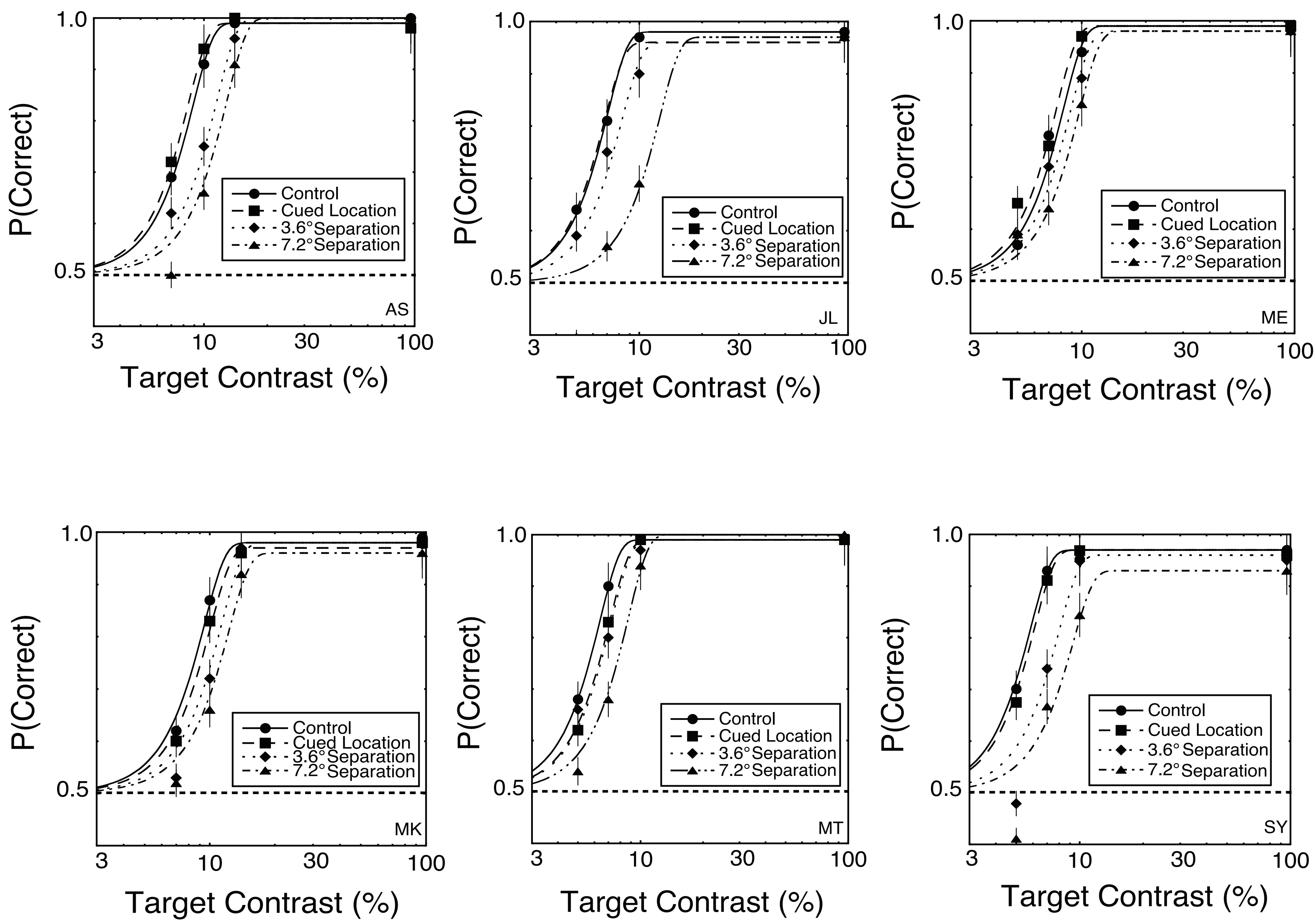

Figure S3. The results for spatial monitoring are shown for six observers. Each panel illustrates a different observer. The functions for larger separations show an increased threshold consistent with contrast gain.