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Research Article

A Mixture Distribution of Spatial Attention

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Abstract. Although it may seem paradoxical, the unified-focus and multiple-foci theories of spatial selective attention are both well supported by experimental evidence. However, the apparent contradiction is illusory and the two competing views may be reconciled by a closer examination of the spatial mechanisms involved. We propose that the deployment of attention may be modeled as a mixture of individual distributions of attention and we tested this hypothesis in two experiments. Participants had to identify targets among distractors, with the targets presented at various distances from the cued locations. Experiment 1 confirmed that the distribution of attention may be described by a mixture of individual distributions, each centered at a cued location. Experiment 2 showed that cue separation is an important determinant of whether spatial attention is divided or not.

Keywords: spatial selective attention, divided attention, distributed attention

In many real-life activities (e.g., while walking or driving), we must simultaneously direct attention to multiple spatial locations in order to acquire information that is critical to the successful performance of the task at hand. Understanding how the attentional mechanism operates in settings where resources must be allocated to more than one spatial location at a time is not only of great scientific interest but can have practical value (e.g., in the design of human-machine interfaces where operators must monitor more than one parameter concurrently). Many studies have investigated whether attention can be divided and simultaneously allocated to noncontiguous regions in the visual field (e.g., Awh & Pashler, 2000; Kramer & Hahn, 1995; Malinowski, Fuchs, & Müller, 2006; McCormick, Klein, & Johnson, 1998; Posner, Snyder, & Davidson, 1980; Shim, Alvarez, & Jiang, 2008) and two quite different perspectives have emerged to account for the empirical findings.

The unified attentional focus theory asserts that we cannot simultaneously divide attention among separated locations (e.g., Eriksen & St. James, 1986; Jans, Peters, & De Weerd, 2010; McCormick et al., 1998; Posner et al., 1980; Tsal, 1983). Keeping track of multiple items is thought to be achieved by either quickly switching attention among the locations (e.g., in the spotlight model, Posner, 1980; Tsal, 1983; Oksama & Hyönä, 2004) or by expanding the area of attentional focus to cover multiple locations (e.g., in the zoom-lens model or grouping strategy, Eriksen & St. James, 1986; Jonides, 1983; McCormick et al., 1998; Yantis, 1992). The unified focus view has received support in several experiments. For example, when multiple locations were cued, speeded reaction times were found only at one of the cued locations, suggesting that only one location was attended to at a time (Eriksen & Yeh, 1985; Posner et al., 1980). In other studies (Heinze et al., 1994; McCormick & Klein, 1990; Pan & Eriksen, 1993), participants failed to suppress the processing of a distractor presented between the two cued locations, indicating that attention had been simultaneously captured by not only the target locations but also those in between.

The alternative multiple-foci perspective proposes that attention is deployed selectively at noncontiguous locations and is not allocated to other locations, such as intervening positions (e.g., Awh & Pashler, 2000; Baldauf & Deubel, 2008; Castiello & Umiltà, 1992; Cavanagh & Alvarez, 2005; Cave, Bush, & Taylor, 2010; Golomb, Marino, Chun, & Mazer, 2011; Hamker, 2004, 2005; Kramer & Hahn, 1995; Müller, Malinowski, Gruber, & Hillyard, 2003; Niebergall, Khayat, Treue, & Martinez-Trujillo, 2011; Scharlau, 2004; Zirnsak, Beuth, & Hamker, 2011). Experimental data show that distractors are ignored even when presented between the two targets (Bichot, Cave, & Pashler, 1999; Kramer & Hahn, 1995) and strengthened activation was observed in cortical representations of the targets but not in those of distractors presented in between (McMains & Somers, 2004). Attention was divided among multiple distinct locations during the preparation of sequential saccades to these locations (Baldauf & Deubel, 2008) and during an early stage of processing multiple locations (Dubois, Hamker, & VanRullen, 2009; Hamker, 2004; Zirnsak et al., 2011). This division of spatial attention can persist for some time (Müller et al., 2003) and is more effortful when the spatially separated locations are aligned vertically compared to horizontally (Awh & Pashler, 2000).

Since both the unified-focus and multiple-foci models are well supported by empirical data, it seems unlikely that one of these models is wrong and the other is correct. It is

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more likely that the occurrence of a single focus or multiple foci is the product of particular experimental conditions. Indeed, a recent study using a neural network to simulate the attentional process has shown that separation between attended locations is an important constraint. In that study (Standage, Trappenberg, & Klein, 2005), a continuous attractor neural network model successfully simulated multiple foci of attention with individual attentional distributions allocated at different spatial locations. When sustained visual inputs were provided in the simulation, network activity resulted in attention being spatially divided among various locations. However, the simulation showed that the spatial division of attention was much easier when the locations were relatively distant compared to the spread of each individual distribution. As the size of a single focus is thought to be at least 1° of visual angle (Intriligator & Cavanagh, 2001), the neural network model predicts that division of attention may not be possible at a small distance.

It has been noted that the attentional resource is limited (Eriksen & St. James, 1986; Kahneman, 1973). If so, spreading attention among more than one location should lead to poorer performance at the individual locations (McMains & Somers, 2005). Clearly, also, distributing a limited attentional resource to multiple individual locations constrains the number of locations that can be attended to (Franconeri, Alvarez, & Enns, 2007). A limited resource in conjunction with the capacity to attend to multiple distinct locations suggests a possible mechanism of selective spatial attention with the following properties: (1) a two-dimensional distribution of spatial selective attention is created at any cued location; (2) the distribution is single-peaked and falls off rapidly with increasing distance from the cued location (LaBerge, Carlson, Williams, & Bunny, 1997); (3) when more than one location is cued, attention is divided, creating two or more unimodal distributions of attention (Standage et al., 2005); (4) the resulting joint distribution of attention across the attentional visual field is the mixture (in the usual statistical sense, e.g., McLachlan & Peel, 2000) of the individual attentional distributions; (5) the total attentional resource available is the same regardless of whether the joint distribution is unimodal (single cue) or a mixture of distributions (multiple cues) (Carlson, VanRullen, Hogendoorn, Verstraten, & Cavanagh, 2007; Franconeri et al., 2007). The last assumption implies that when attention is divided, the individual peaks will be lower, corresponding to the distribution of a fixed resource among two or more locations, resulting in a reduced capacity to allocate attention simultaneously at the individual locations. For convenience (Figure 2, model panel), we have assumed that the attentional distribution at any cued location is a circular bivariate Gaussian; but it is important to note that the distributional form is not central to our argument. The particular bivariate density function chosen is not critical and virtually any unimodal distribution would serve as well.

When only one location is cued, the joint distribution of attention across the attentional visual field reduces to the unified focus case (Müller et al., 2004). When two separated locations are cued, the joint distribution is a mixture of unimodal distributions; and attention is maximal (and equal, if the cues have identical salience) at the cued locations. Attention at other locations, including intervening locations, will be lower than at the cued locations. However, if the distance separating the cues is small, the reduction in attention at intervening points will be scarcely noticeable. In practical terms, the joint distribution will be indistinguishable from that in a unified focus model. However, if the separation of cues is large, attention at an intervening location will be less than at the cued locations; in particular, the allocation of attentional resources will be much less at a point midway between equally salient cues. In that case, the joint distribution will be consistent with a multiple-foci model (Awh & Pashler, 2000; Kawahara & Yamada, 2006; Kramer & Hahn, 1995).

We used a multiple cuing paradigm to examine the distribution of spatial selective attention (Awh & Pashler, 2000). Our first experiment examined how attention is deployed when a single cue or two spatially separated cues are presented. The second experiment investigated how the distribution of attention is affected by varying the spatial separation between the two cues.

Experiment 1

We investigated the deployment of attention to a single cued location and to two noncontiguous cued locations.

Method

Participants

Twelve university undergraduates (three males and nine females; age range: 18–25 years) participated for course credit.

Stimuli

The experimental region was an invisible 5 × 5 grid area (15° × 15°) centered on a uniform light gray screen (Figure 1). Each trial began with a centered, dark gray fixation cross (1.2° × 1.2°) presented for 800 ms. In the single location condition, a cue (the equals sign "=", 1.2° × 1.2°) appeared adjacent to the center in one of four possible directions (left/right/above/below, balanced, and randomized) for 800 ms (Figure 1a). This was followed by the stimulus display consisting of 24 distractors (capitalized letters, each unique) and a single target (a digit, randomly selected from the set 3, 4, 5, 6, 7) which could appear either at the cued location (C), or a near uncued location (N), or a far uncued location (F). In the two noncontiguous locations conditions, two cues (horizontally or vertically opposed) appeared for 800 ms followed by the targets (unique digits from the set 3, 4, 5, 6, 7) occupying either the cued locations (C) or locations on the orthogonal to the cues through the grid center (N, F). As before, the remaining positions were filled with distractors (letters). The two targets could appear at the

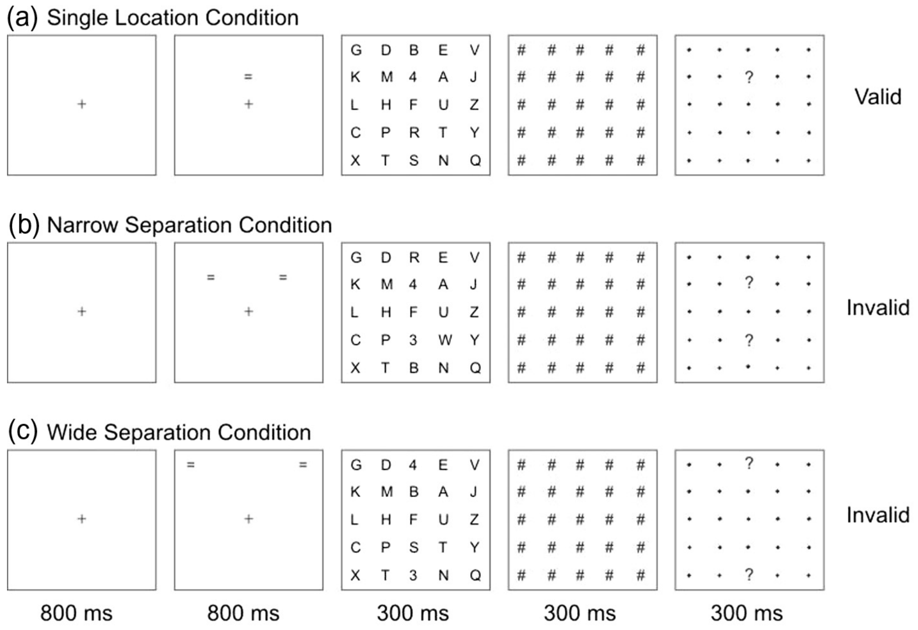

Figure 1. Sample display sequences for valid and invalid trials in (a) the single location condition, (b) the narrow separation condition, and (c) the wide separation condition. Participants identified the digit(s) among the letters.

two cued locations (C), or one at the location between the two cued locations (N) and the other at the location that was symmetrically on the other side of the center (F) (Figure 1a). In the narrow separation condition, the cues were located at adjacent corners of the central 3 × 3 grid (Figure 1b) and, in the wide separation condition, the cues were located at the adjacent corners of the whole 5 × 5 grid (Figure 1c). After 300 ms, all items were masked using the pound symbol, "#", for an additional 300 ms. The response cue consisted of a 5 × 5 array of dots, ".", at the distractor locations, and a question mark, "?", at the target location(s). When the response cue appeared, participants typed the target digit(s) as accurately as they could. Note that Figures 1b and c show two horizontally arranged cues at the top of either the 3 × 3 grid or the 5 × 5 grid, as would have occurred on one quarter of the trials. On the remaining trials, the cues would have appeared either at the bottom of the grid or aligned vertically at the left or right sides of the grids.

Procedure

Three factors were varied: cues (one or two), spatial separation (narrow or wide separation), and target location (C or N or F). Each participant experienced three blocks of trials: single cue, two cues with narrow separation, and two cues with wide separation. The order of the three blocks was counterbalanced over participants. The order of the valid and invalid trials was randomized within each block.

All participants completed a supervised practice session before each experiment session. During the practice session, participants had to learn to direct attention to the two cued locations while holding fixation on the center. The practice trials used the same conditions as those in the subsequent experimental session. At the end of the practice session, participants were questioned about their ability to divide attention. Participants reported that they could do this but only with considerable effort.

In the single cue block, all participants completed a supervised practice session of 48 trials followed by 120 experimental trials. There were 72 (60%) valid trials (target presented at the cued location), 24 (20%) invalid-near (target presented at the near uncued location), and 24 (20%) invalid-far trials (target presented at the far uncued location).

In both two-cue blocks, all participants completed a supervised practice session of 51 trials followed by 130 experiment trials (120 regular trials and 10 irregular trials). There were 72 (60% of regular trials) valid trials (targets presented at the cued locations) and 48 (40% of regular trials) invalid trials (targets presented at the uncued locations). In an irregular trial, the targets appeared in random locations other than the usual valid or invalid locations. Three irregular trials were inserted among the regular ones in the practice session and ten irregulars were inserted in the experimental session to discourage participants from forming expectations regarding the locations where the targets were likely to occur. Participants were instructed to hold fixation on the center while simultaneously trying to distribute attention optimally to maximize accuracy at the cued locations. In addition, they were instructed to perform as much as possible when the targets appeared at uncued locations. Participants entered the target digit(s) using the number keys near the top of the keyboard. In the two-cue condition, participants were instructed to enter the digit of which they were more certain first.

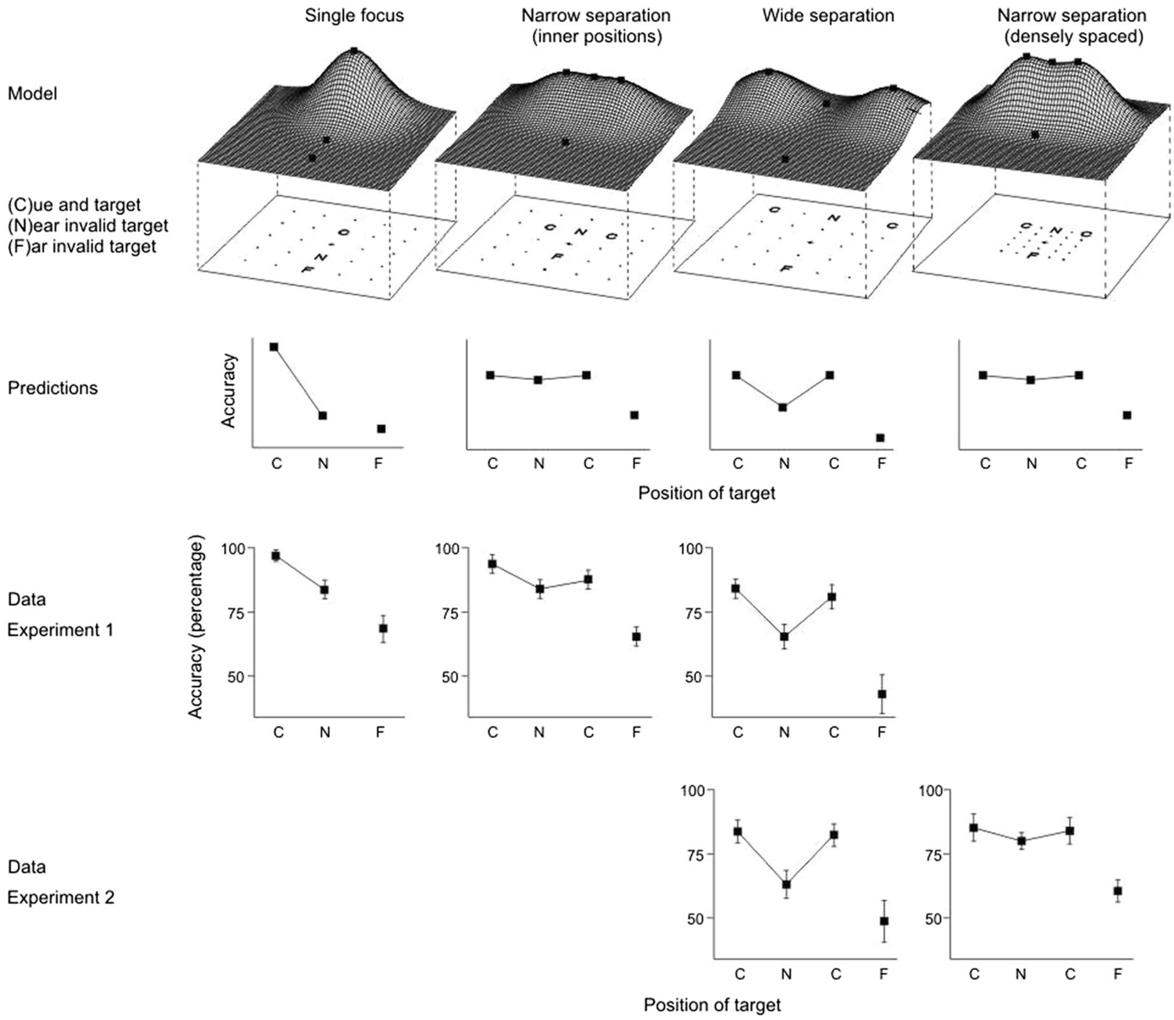

Figure 2. Model illustrations, predictions, and data from two experiments. Model: Illustration of the formation of a single attentional distribution when one location is cued (single focus), and a mixture of two distributions when two locations are cued. Predictions: Accuracies at cued (C), near invalid (N), or far invalid (F) locations in different conditions. Data: Accuracies in the single focus (first left panel), narrow separation (middle panel), and wide separation (right panel) conditions in Experiment 1, and in wide separation (left panel) and narrow separation (right panel) conditions in Experiment 2. Error bars represent ±1 *SE*.

Results

Accuracy was worse with two cues (Figure 2), $F(1, 11) = 32.54, p < .01, \eta^2 = .75$, and accuracy was worse when the cues were widely separated as opposed to narrowly separated, $F(1, 11) = 92.48, p < .01, \eta^2 = .89$. With a single cue, accuracy was significantly lower with increasing distance from the cued location (C-97%, N-85%, F-69%) (Figure 2), $F(2, 22) = 96.31$, $p < .01$, $\eta^2 = .90$. When the cues were widely separated, accuracy differed considerably among the cued locations (C-84% and C-81%), the intervening location (N-65%), and the far location (F-43%), $F(2, 22) = 71.62$, $p < .01$, $\eta^2 = .87$; accuracy at the intervening location was poorer than at the cued locations, $t(11) = 6.33$, $p < .01$, and $t(11) = 5.33$, $p < .01$. With the narrow separation of cues, the accuracies (C-94% and 88%, N-84%, F-67%) differed considerably, $F(2, 22) = 64.87, p < .01, \eta^2 = .86$. However, the differences were much less than when the cues were widely separated, $F(1, 11) = 57.16, p < .01, \eta^2 = .84$. Distinct peaks of attention were much less obvious with reduced spatial separation.

Discussion

As predicted, with a single cue, attention was maximal at the position of the cue and dropped off with increasing distance from the cue. When attention had to be deployed to two locations simultaneously, the data were consistent with the formation of a mixture of two distributions of attention. The mixture model asserts that the available attentional resource will be allocated as predicted by a mixture of two distributions, each centered at one of the two cued locations; consequently, the accuracies at the two cued positions are predicted to be lower than in the single cue condition. This is precisely what we found. From the participants' point of view, maintaining attentional foci simultaneously at two locations is a difficult task which requires a great deal of effort and is more prone to error. The reduction in accuracy at the intervening location, compared to the two cued locations, was greater when the cues were widely separated than when narrowly separated. Again, this is precisely what the mixture distribution predicts.

It should be noted that the spatial arrangements of the cue and distractor locations were different in the wide separation condition (three distractors between the cued locations, Figure 2) than in the narrow separation condition (only one distractor between the cued locations, Figure 2). To isolate the effect of separation from the configuration of distractors, our second experiment explored whether a decrease in spatial separation alone would produce similar effects.

Experiment 2

In this experiment, we varied the spatial separation between cues while keeping the spatial arrangement of targets and distractors constant. The wide separation condition of Experiment 1 was replicated and served as a baseline control.

Method

Participants

Twelve university undergraduates (2 males and 10 females; age range: 18–24 years) participated for course credit. None had participated in Experiment 1.

Stimuli

When the cues were widely separated, all settings were the same as in Experiment 1. When the cues were narrowly separated, the spacing between items was reduced with the overall grid size changing from 15° × 15° to 9° × 9°; however, the sizes of individual items in the grid remained unchanged. The cue arrangements, display orders, and exposure durations were the same as in Experiment 1.

Procedure

There were two blocks of trials: one with widely separated cues and the other with narrowly separated cues. Within each block, the number of trials and the probabilities of valid and invalid trials was the same as in Experiment 1. The order of blocks was counterbalanced over participants, who received the same instructions as in Experiment 1.

Results

When the cues were widely separated, the accuracies were very similar to those in Experiment 1 (Figure 2). Performance differed among cue locations (C-83% and 82%, N-64%, F-50%), $F(2, 22) = 69.53$, $p < .01$, $\eta^2 = .86$; and the accuracy at the intervening location was much lower than at the cued locations, $t(11) = 4.75$, $p < .01$ and $t(11) = 4.50$, $p < .01$. In contrast, when the cues were narrowly separated, although the accuracies (C-85% and 84%, N-79%, F-61%) differed among locations, $F(2, 22) = 29.88$, $p < .01$, $\eta^2 = .73$, the accuracy at the intervening location was not inferior to those at the cued locations, $t(11) = 1.25$, $p = .15$, and $t(11) = 1.00$, $p = .26$.

Discussion

When the cues were narrowly separated, the mixture distribution predicted that accuracy at the intervening location would not be much different from that at the cued locations. This is what was found: the difference in accuracy at the intervening location (N) and the cued locations (C) was not significant. In contrast, and as predicted by the model, when the cues were widely separated, performance at the intervening location (N) was substantially inferior to performance at the cued locations (C).

General Discussion

Our results suggest that separation between two cued locations is critical when attention is distributed. Participants were better at identifying the targets on valid trials when the cued locations were more widely separated. Although participants were instructed and trained to maintain fixation at the center while attending to two cued locations, the cue exposure time (800 ms) and the stimulus display time (300 ms) in both experiments might have allowed participants to make eye movements toward cued location(s). However, this possibility is unlikely; the data suggest that eye movements did not play a significant role. Consider the accuracies at the cued and intervening locations: to make an eye movement, a participant may choose either to fixate at the intervening location or at one of the cued locations in order to improve target identification. However, an eye movement toward the intervening location would diminish the advantage at the cued locations compared to the intervening location (Awh & Pashler, 2000); however, our data show a clear advantage at the cued locations. In the other possible case, if participants were to make an eye movement to fixate at one of the cued locations, target identification at this fixated cued location would be close to perfect. In contrast, target identification at the other cued location would be much lower than at the intervening location (the single target condition in Experiment 1 showed that accuracy decreases when the target location is farther from fixation). Consequently, accuracy in target identification at the other cued location (when identification is essentially perfect at one location) should be comparable to the accuracy at the far location in the single target condition. However, this was not true in Experiment 1. In the wide separation condition, when the target at one of the cued locations was correctly identified, the accuracy at the other location was 82%, significantly higher than the accuracy at the far location in the single target condition (F-69%), $t(11) = 3.60$, $p < .01$. This was also true even when the cues were narrowly separated (91% vs. N-85%), $t(11) = 2.51$, $p < .05$. In Experiment 2, these conditional accuracies were just as high (83% when widely separated, 84% when narrowly separated). If our experiment had used a shorter exposure (but sufficient to perform the task), and included eye movement monitoring (Cave et al., 2010; Jans et al., 2010), these modifications would have complicated the participants' task in what was, for them, already a complex and difficult experiment.

A Mixture Model of Attention

The allocation of attention may be considered analogous to a mixture of two-dimensional probability distributions (Standage et al., 2005). The height of the attentional surface (the analog of probability density) represents the attentional intensity. When attention is allocated in response to a single cue, the distribution of attention is unimodal with the attentional intensity decreasing with distance from the location of the cue. When attention is deployed to more than one location, the resulting distribution of attention is the mixture of the individual attentional distributions. Because attention is a limited resource, this implies that the height of the attentional surface is lower, on average, when there is more than one cued location.

The mixture model makes a number of specific predictions, which were confirmed by our experiments: (1) when a location is cued, accuracy in detecting the target is maximal and falls off with increasing distance from the cue; (2) target detection becomes more difficult as the number of targets increases; (3) when two simultaneous cues are separated spatially, but still close, attentional performance at an intervening location is not appreciably lower than at the cued locations; (4) however, if the spatial separation is sufficiently large, attentional performance at an intervening location is worse than at the cued locations. The mixture model resolves the apparent paradox presented by two seemingly dissimilar models (unified focus vs. multiple foci) both of which are capable of providing good accounts of empirical data under particular experimental conditions. Our results support the speculation regarding the importance of separation implied by a neural network simulation (Standage et al., 2005). When the cued locations are more widely separated, the attentional surface predicted by the mixture model is consistent with a multiple-foci perspective. When there is only one cue, or multiple closely-spaced cues, the attentional surface predicted by the mixture model will be almost identical to the predictions of a single focus model. In other words, the two perspectives will generate predictions that are indistinguishable, for all practical purposes.

Neurophysiological Basis

Recent research (Shim, Alvarez, Vickery, & Jiang, 2009; Standage et al., 2005; Zirnsak et al., 2011) has suggested a plausible brain mechanism to explain how the attentional surface might develop. Since activity in posterior parietal cortex is correlated with the number of attentional foci (Shim et al., 2009), posterior parietal cortex may be involved in determining the number and location of the attentional distributions that make up the attentional surface. Additionally, activity in frontal eye fields and early visual areas is associated with the precision of each focus (Shim et al., 2009), suggesting that these areas may be involved in determining the attentional intensity (height of the surface) of the individual attentional distributions. The development of the attentional surface may be reflected in activity in the frontal eye fields over time (Zirnsak et al., 2011). In a neural network simulation, Standage et al. (2005) proposed that division of attention can be achieved by information processing in posterior parietal cortex as long as sustained visual signals are available; and such division becomes more likely as the foci are more distant. In the mixture model, separation is a key factor in determining the overall shape of the attentional surface.

Implications of the Mixture Model

In addition to highlighting separation as an essential parameter, the mixture model raises several other interesting questions that deserve exploration. First, the eccentricity of each target or distractor may influence the formation of the attentional surface. Items closer to fixation are known to have an advantage in capturing attention (e.g., Ball, Beard, Roenker, Miller, & Griggs, 1988; Feng, Spence, & Pratt, 2007), largely due to the shared brain mechanisms involved in eye movements and the orientation of attention (Kowler, Anderson, Dosher, & Blaser, 1995). When the cued locations are aligned with the fixation, but on opposite sides of it, the intervening locations will involuntarily capture a significant portion of the attentional resource, since these locations are much closer to fixation, thus leading to considerable processing of distractors. This may be part of the reason why some studies only observed a single focus of attention (e.g., McCormick et al., 1998; Pan & Eriksen, 1993). Second, the cue-target interval will also affect the configuration of the attentional surface. It has been suggested that attention can only be equally divided between two targets within a limited period of time (Dubois et al., 2009). After that, the mixture distribution gradually weakens with attention finally settling back to a single distribution centered at a single location. Temporal factors undoubtedly influence the formation of the attentional surface. In a system-level model of visual attention (Zirnsak et al., 2011), feedback from neurons in frontal eye fields may cause attention to be divided among multiple location at first (see also an earlier version of this model in Hamker, 2004); but then over time, the feedback weakens the division of attention, which eventually reduces to a single focus. Similarly, in Standage et al. (2005), their continuous attractor neural network implements a winner-take-all principle; thus, given sufficient time for the network to stabilize, a divided attentional resource will eventually settle at a single location. Further empirical and theoretical work is needed to establish the important role of temporal factors.

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References

Awh, E., & Pashler, H. (2000). Evidence for split attentional foci. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 837–846.

Baldauf, D., & Deubel, H. (2008). Properties of attentional selection during the preparation of sequential saccades. *Experimental Brain Research, 184*, 411–425.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the American Optometric Association, 5*, 2210–2219.

Bichot, N. P., Cave, K. R., & Pashler, H. (1999). Visual selection mediated by location: Feature-based selection of non-contiguous locations. *Perception & Psychophysics, 61*, 403–423.

Carlson, T., VanRullen, R., Hogendoorn, H., Verstraten, F., & Cavanagh, P. (2007). Distinguishing models of multifocal attention: It's a matter of time [abstract]. *Journal of Vision, 7*, 641.

Castiello, U., & Umiltà, C. (1992). Splitting focal attention. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 837–848.

Cavanagh, P., & Alvarez, G. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Science, 9*, 349–354.

Cave, K. R., Bush, W. S., & Taylor, G. G. (2010). Split attention as part of a flexible attentional system for complex scenes: Comment on Jans, Peters, and De Weerd (2010). *Psychological Review, 117*, 685–695.

Dubois, J., Hamker, F. H., & VanRullen, R. (2009). Attentional selection of noncontiguous locations: The spotlight is only transiently "split". *Journal of Vision, 9*, 1–11.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception and Psychophysics, 40*, 225–240.

Eriksen, C. W., & Yeh, Y. Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 583–597.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science, 18*, 850–855.

Franconeri, S. L., Alvarez, G. A., & Enns, J. T. (2007). How many locations can be selected at once? *Journal of Experimental Psychology: Human Perception and Performance, 33*, 1003–1012.

Golomb, J. D., Marino, A. C., Chun, M. M., & Mazer, J. A. (2011). Attention doesn't slide: Spatiotopic updating after eye movements instantiates a new, discrete attentional locus. *Attention, Perception and Psychophysics, 73*, 7–14.

Hamker, F. H. (2004). A dynamic model of how feature cues guide spatial attention. *Vision Research, 44*, 501–521.

Hamker, F. H. (2005). The emergence of attention by population-based inference and its role in distributed processing and cognitive control of vision. *Journal of Computer Vision and Image Understanding, 100*, 64–106.

Heinze, H., Luck, S. J., Muente, T. F., Goes, A., Mangun, G. R., & Hillyard, S. A. (1994). Attention to adjacent and separate positions in space: An electrophysiological analysis. *Perception & Psychophysics, 56*, 42–52.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43*, 171–216.

Jans, B., Peters, J. C., & De Weerd, P. (2010). Visual spatial attention to multiple locations at once: The jury is still out. *Psychological Review, 117*, 637–682.

Jonides, J. (1983). Further toward a model of the mind's eye movement. *Bulletin of the Psychonomic Society, 21*, 247–250.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice Hall.

Kawahara, J.-I., & Yamada, Y. (2006). Two noncontiguous locations can be attended concurrently: Evidence from the attentional blink. *Psychonomic Bulletin & Review, 13*, 594–599.

Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research, 35*, 1897–1916.

Kramer, A. F., & Hahn, S. (1995). Splitting the beam: Distribution of attention over noncontiguous regions of the visual field. *Psychological Science, 6*, 381–386.

LaBerge, D., Carlson, R. L., Williams, J. K., & Bunny, B. G. (1997). Shifting attention in visual space: Tests of moving-spotlight models versus an activity-distribution model. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1380–1392.

Malinowski, P., Fuchs, S., & Müller, M. M. (2006). Sustained division of spatial attention to multiple locations within one hemifield. *Neuroscience Letters, 414*, 65–70.

McCormick, P. A., & Klein, R. M. (1990). The spatial distribution of attention during covert visual orienting. *Acta Psychologia, 75*, 225–242.

McCormick, P. A., Klein, R. M., & Johnson, S. (1998). Splitting versus sharing focal attention: Comments on Castiello and Umiltà (1992). *Journal of Experimental Psychology: Human Perception and Performance, 24*, 350–357.

McLachlan, G. J., & Peel, D. (2000). *Finite mixture models*. New York, NY: Wiley.

McMains, S. A., & Somers, D. C. (2004). Multiple spotlights of attentional selection in human visual cortex. *Neuron, 42*, 677–686.

McMains, S. A., & Somers, D. C. (2005). Processing efficiency of divided spatial attention mechanisms in human visual cortex. *Journal of Neuroscience, 25*, 9444–9448.

Müller, M. M., Malinowski, P., Gruber, T., & Hillyard, S. A. (2003). Sustained division of the attentional spotlight. *Nature, 424*, 309–312.

Müller, N. G., Mollnhauer, M., Rösler, A., & Kleinschmidt, A. (2004). The attentional filed has a Mexican hat distribution. *Vision Research, 45*, 1129–1137.

Niebergall, R., Khayat, P. S., Treue, S., & Martinez-Trujillo, J. C. (2011). Multifocal attention filters targets from distracters within and beyond primate MT neuron's receptive field boundaries. *Neuron, 72*, 1067–1079.

Oksama, L., & Hyönä, J. (2004). Is multiple object tracking carried out automatically by an early vision mechanism independent of higher-order cognition? An individual difference approach. *Visual Cognition, 11*, 631–671.

Pan, K., & Eriksen, C. W. (1993). Attentional distribution in the visual field during same-different judgements as assessed by response competition. *Perception & Psychophysics, 53*, 134–144.

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology, 32*, 3–25.

Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General, 109*, 160–174.

Scharlau, I. (2004). Evidence for split foci of attention in a priming paradigm. *Perception & Psychophysics, 66*, 988–1002.

Shim, W. M., Alvarez, G. A., & Jiang, Y. V. (2008). Spatial separation between targets constrains maintenance of attention on multiple objects. *Psychonomic Bulletin & Review, 15*, 390–397.

Shim, W. M., Alvarez, G. A., Vickery, T. J., & Jiang, Y. V. (2009). The number of attentional foci and their precision are dissociated in the posterior parietal cortex. *Cerebral Cortex, 20*, 1341–1349.

Standage, D. I., Trappenberg, T. P., & Klein, R. M. (2005). Modelling divided visual attention with a winner-take-all network. *Neural Networks, 18*, 620–627.

Tsal, Y. (1983). Movement of attention across the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 523–530.

Yantis, S. (1992). Multi-element visual tracking: Attention and perceptual organization. *Cognitive Psychology, 24*, 295–340.

Zirnsak, M., Beuth, F., & Hamker, F. H. (2011). Split of spatial attention as predicted by a system-level model of visual attention. *European Journal of Neuroscience, 33*, 2035–2045.

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