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A unique role of endogenous visual-spatial attention in rapid processing of multiple targets

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Abstract

Visual spatial attention can be exogenously captured by a salient stimulus or can be endogenously allocated by voluntary effort. Whether these two attention modes serve distinctive functions is debated, but for processing of single targets the literature suggests superiority of exogenous attention (it is faster acting and serves more functions). We report that endogenous attention uniquely contributes to processing of multiple targets. For speeded visual discrimination, response times are faster for multiple redundant targets than for single targets due to probability summation and/or signal integration. This redundancy gain was unaffected when attention was exogenously diverted from the targets, but was completely eliminated when attention was endogenously diverted. This was not due to weaker manipulation of exogenous attention because our exogenous and endogenous cues similarly affected overall response times. Thus, whereas exogenous attention is superior for processing single targets, endogenous attention plays a unique role in allocating resources crucial for rapid concurrent processing of multiple targets.

Introduction

A salient event such as an abrupt onset of a high-contrast visual stimulus captures attention relatively independently of an observer's intention. This phenomenon is known as exogenous (a.k.a., stimulus-driven or reflexive) orientation of visual spatial attention. Exogenous orienting of attention is typically demonstrated with an uninformative peripheral cue. When an onset cue is not predictive of the upcoming target location (i.e., when the target is equally likely to appear at an uncued location), an observer has no incentive to voluntarily shift attention to the cue. Nevertheless, visual processing transiently improves at the cued location (e.g., Eriksen & Collins, 1969; Posner, 1980; Posner & Cohen, 1984; Nakayama & Mackeben, 1989; Hawkins, Hillyard, Luck, Mouloua, Downing, & Woodward, 1990; Yantis & Johnson, 1990; Cheal & Lyon, 1991; Hikosaka, Miyauchi, & Shimojo 1993; Yantis, 1996; Yeshurun & Carrasco, 1998; Pestilli & Carrasco, 2005; Hickey, McDonald, & Theeuwes, 2006). An observer can also voluntarily shift attention in the absence of a salient peripheral event, and this phenomenon is known as endogenous (a.k.a., voluntary) orientation of visual spatial attention. Endogenous orienting of attention is typically demonstrated with a central symbolic cue that predicts the upcoming target location with a high probability. An observer voluntarily shifts attention according to the informative cue, and visual processing improves at the location of the voluntarily focused attention (e.g., Posner, 1980; Posner, Snyder, & Davidson 1980; Posner & Cohen, 1984;

Downing & Pinker, 1985; Cheal & Lyon, 1991; Ling & Carrasco, 2006; Kim, Grabowecky, Paller, Muthu, & Suzuki, 2007; Guzman-Martinez, Leung, Grabowecky, Franconeri, & Suzuki, 2009). Both exogenously and endogenously oriented attention facilitate visual processing at an attended location, but the two attention modes differ in strength and time course, and can influence each other (e.g., Müller & Rabbitt, 1989; Yantis & Jonides, 1990; Cheal & Lyon, 1991; Hikosaka, et al., 1993; Suzuki & Cavanagh, 1997; Egeth & Yantis, 1997; Berger, Henik & Rafal, 2005; Horowitz, Wolfe, Alvarez, Cohen, & Kuzmova, 2009).

Relatively few studies have investigated qualitative differences between the two attention modes, however. Those studies generally reported superiority for exogenously oriented attention. Briand (1998) showed that both exogenous (with peripheral cueing) and endogenous (with central cueing) orienting of attention to a target location speeded both feature and conjunction searches, but exogenous orienting was especially effective in speeding conjunction search. Lu and Doshier (2000) showed that both modes of orienting attention modulated pattern discrimination at threshold, but whereas endogenously oriented attention only reduced external noise, exogenously oriented attention increased stimulus strength as well as reduced external noise. Ling and Carrasco (2006) showed that, whereas endogenously oriented attention modulated pattern discrimination for low to medium image contrasts, exogenously oriented attention modulated pattern discrimination over a broader range of contrasts including high contrasts, suggesting that endogenously oriented attention induced only contrast gain whereas exogenously oriented attention induced response gain as well as contrast gain. Some of these exogenous superiority effects, however, might reflect the fact that the peripheral cues engaged endogenous as well as exogenous orienting of attention because the cue validity was 100% in Lu and Doshier (2000) and Ling and Carrasco (2006), though Briand (1998) verified his results with 50% (chance) cue validity. Even with this caveat, both Lu and Doshier (2000) and Ling and Carrasco (2006) suggest that exogenously orienting attention adds qualitatively different functions, signal enhancement and response gain, respectively, which are not achieved by endogenously orienting attention, and Briand (1998) suggests that exogenous orienting selectively speeds processing of feature conjunctions.

Overall, the previous research demonstrated that both exogenous and endogenous visual spatial attention produced similar modulatory effects on many visual tasks, and that when the two modes produced differential effects exogenous attention modulated processes over and above those modulated by endogenous attention (see Funes, Lupiáñez, & Milliken, 2005 for a review). These previous studies examined the processing of single targets.

In contrast, here we report that endogenous orienting of visual spatial attention plays a crucial role in the rapid concurrent processing of multiple targets. Presenting multiple targets (compared to presenting a single target) generally facilitates response times in speeded visual discrimination, a phenomenon known as *redundancy gain*. For example, if you need to respond as quickly as possible whenever either of two targets (e.g., a blue square or a red square) is presented, your response will be faster when both targets (e.g., both a blue square and a red square) are simultaneously presented compared to when only one target (e.g., a blue square) is presented. Such redundancy gains are thought to be mediated by probability summation and in some cases by an additional process of signal integration (see the General Discussion section).

When two spatially separated visual targets are simultaneously presented, they are processed in parallel at least in low-level visual processing where neural receptive fields are small (e.g., Felleman & Van Essen, 1991; Kastner & Ungerleider, 2001; Suzuki, 2001). Upon presentation of targets, evidence of target features accumulates over time and when the evidence exceeds a threshold above the level of sensory noise, the observer makes the

decision that a target is present. Because the rate of accumulation of target information stochastically fluctuates due to processing noise, the time it takes to obtain sufficient target evidence from at least one of two simultaneously processed targets is statistically faster than the time it takes to obtain sufficient target evidence from a single target — called *probability summation*. Probability summation is a basic mechanism for taking advantage of redundant information based on parallel noninteractive processing of spatially separated stimuli.

In general, different values of the same feature (e.g., red color and blue color) tend to be processed separately rather than to be integrated into a unified representation, especially when they belong to spatially separated items (e.g., Krummenacher, Müller & Heller, 2002). In this case, redundancy gains do not exceed those expected by probability summation. In contrast, when targets are defined by two separate features such as the color and shape of an item (e.g., a red circle), the processing of the two target features can be integrated to produce redundancy gains over and above those expected by probability summation. It has been shown that this feature-integration process may require attention (see the General Discussion section for details). In contrast, our goal was to investigate the effects of exogenous and endogenous visual spatial attention on the basic process of probability summation. We thus used spatially separated redundant targets defined by different values of a single feature (e.g., color). Theoretically, if probability summation is the only reason for the faster responses to redundant targets than to single targets, response time data should not violate the race-model inequality (e.g., Ulrich, Miller, & Schröter, 2007). We verified that the race-model inequality was not violated in any of our experiments (see the Results sections).

In four experiments, we determined how the advantage of probability summation depended on exogenous and endogenous allocation of visual spatial attention. In Experiments 1A and 1B, we strongly manipulated visual spatial attention using a peripheral luminance-onset cue with high validity (80%). In this case, a peripheral cue exogenously captures attention even when the cue is uninformative and the observer makes no voluntary effort to shift attention to the cued location (see above). Because the peripheral cue is informative with high validity, it is likely that the observer also endogenously (i.e., voluntarily) shifts attention to the cued location. An fMRI result (Vossel, Thiela, & Fink, 2006) has suggested that high cue validity (90% compared to 60%) engages mechanisms that mediate endogenous allocation of attention. It is thus reasonable to assume that the peripheral onset cues with high validity used in Experiments 1A and 1B directed visual spatial attention toward or away from targets by engaging both exogenous and endogenous mechanisms.

In Experiment 2, we selectively engaged exogenous orienting of attention by reducing the cue validity to chance (50%), thereby rendering the cue uninformative of the target location. In Experiment 3, we selectively engaged endogenous orienting of attention by using a centrally presented symbolic cue with high validity (80%).

Redundancy gains were eliminated when attention was both exogenously and endogenously diverted from the targets (Experiments 1A and 1B) and when attention was endogenously diverted from the targets (Experiment 3). However, redundancy gains were unaffected when attention was exogenously diverted from the targets (Experiment 2). Our results thus suggest that endogenously diverting attention renders the visual system unable to take advantage of redundant information in speeded visual discrimination, even in the form of probability summation. Implications of these results are discussed in the General Discussion section.

Experiment 1A: Manipulating both endogenous and exogenous orienting of visual spatial attention

We presented single or redundant targets (red and/or blue squares) either within a rectangular region pre-cued by a peripheral onset cue (a thickening outline) or within an uncued rectangular region on the opposite side. The high cue validity (80%) facilitated an engagement of endogenous as well as exogenous orienting of visual spatial attention. We determined whether the magnitude of redundancy gains differed between the cued and uncued regions.

Methods

Participants—Twenty-two undergraduate students from Northwestern University gave informed consent to participate for partial course credit. All participants had normal or corrected-to-normal visual acuity and had normal color vision, and were tested individually in a normally lit room.

Apparatus—The stimuli were displayed on a 19" color LCD monitor (60 Hz, 800 by 600 resolution). The experiment was controlled with a PowerMac G4 using Psyscope experimental software. A chin rest was used to stabilize the head position at a viewing distance of 45 cm.

Stimuli—Outline stimuli were drawn with 0.1° thick (all degrees are of visual angle) black lines against a white background. The central fixation cross subtended 0.63° by 0.63° . On each trial, either a pair of vertical rectangles (one to the left and the other to the right of the fixation cross; Fig. 1A) or a pair of horizontal rectangles (one above and the other below the fixation cross; Fig. 1B) was presented with equal probability. These rectangles (10.1° by 2.5°) were presented 3.8° away (center-to-center) from the fixation cross. The contours of one of the rectangles briefly thickened to 0.35° to exogenously draw attention (e.g., Egly, Driver, & Rafal, 1994). These rectangles thus served as the cued (attended) and uncued (ignored) regions in which colored squares (0.63° by 0.63°) were presented. Red and blue squares were targets, and green and yellow squares were distractors. On each trial, either a single target (red or blue with 50% probability), a pair of redundant targets (each red or blue with 50% probability), a single distractor (green or yellow with 50% probability), or a pair of redundant distractors (each green or yellow with 50% probability) were presented at the end locations of a rectangular region (at 5.38° eccentricity from the fixation point) (see Fig. 1).

There were four intermixed conditions for the target trials, (1) Cue-Valid Single target, (2) Cue-Valid Redundant targets, (3) Cue-Invalid Single target, and (4) Cue-Invalid Redundant targets. On a cue-valid trial, a single target or redundant targets were presented within the cued rectangle. On a cue-invalid trial, a single target or redundant targets were presented within the uncued rectangle.

There were 420 target trials, including 210 single-target trials (168 cue-valid and 42 cue-invalid) and 210 redundant-target trials (168 cue-valid and 42 cue-invalid). The cue validity was high (80%), so that attention was strongly modulated by engaging both the exogenous and endogenous orienting mechanisms. The 64 distractor trials had the same cue validity and the same proportions of single- and redundant-distractor trials as did the target trials. The target and distractor trials were randomly intermixed with the constraint that the exact same single or redundant targets were never repeated on consecutive trials.

Procedure—Each trial began with a 750 ms warning display with a central dot, which was followed by a fixation display containing a central fixation cross and a pair of vertical or horizontal rectangles, lasting 750 ms. The contours of one of the rectangles then briefly thickened (for 30 ms), providing a peripheral onset-based attention cue. Following a stimulus onset asynchrony (SOA) of 120 ms, a single target square, a pair of redundant target squares, a single distractor square, or a pair of redundant distractor squares, was flashed for 50 ms, followed by a random-dot mask lasting 2500 ms. Participants were instructed to press the response key as quickly and accurately as possible when single or redundant targets (red and/or blue) appeared. They were instructed to withhold a response when single or redundant distractors (green and/or yellow) appeared instead. Response time (RT) and accuracy were recorded on each trial. RTs more than three standard deviations from the mean for each condition for each participant were considered to be outliers and were excluded from the analyses.

Prior to the experimental trials, eighty-four practice trials were given with feedback. The 484 experimental trials (420 target trials plus 64 distractor trials) were run without feedback in six blocks (five blocks of 80 trials and a final block of 84 trials). Short voluntary breaks were given between blocks, but a mandatory 5-min break was given between the 3rd and 4th blocks.

We collapsed the data across the vertical and horizontal orientations of the rectangles because there was no significant effect of rectangle orientation and it did not interact with any of the reported effects. This was true for all four experiments.

Results and discussion

The overall error rates were low (3.0% misses and 3.9% false positives), and there were no significant effects associated with errors. The attention manipulation was confirmed by the overall significantly faster RT in the cue-valid trials (471 ms) compared to the cue-invalid trials (487 ms), $t(21) = 4.230$, $p < 0.0004$, $d = 0.902$.

Planned comparisons were made to evaluate redundancy gains in the cue-valid and cue-invalid conditions. When the targets were presented within the cued (attended) rectangle, target detection was significantly faster for the redundant targets than for the single targets, $t(21) = 11.472$, $p < 0.0001$, $d = 2.446$ (Fig. 2A). In contrast, when the targets were presented within the uncued (ignored) rectangle, the RTs were statistically equivalent for the single and redundant targets, $t(21) = 0.217$, *n.s.* This attention dependence of redundancy gains was confirmed by the significant ANOVA interaction between the cue validity (valid or invalid) and the target redundancy (single or redundant), $F(1, 21) = 17.277$, $p < 0.0005$, $\eta_p^2 = .451$.

The redundancy gains obtained in the cue-valid condition did not violate the race model inequality based on the race-model test (Ulrich, et al., 2007). At no quantile was the sum of the Cumulative Density Functions (CDFs) for the cue-valid single-target trials below the CDF for the cue-valid redundant-target trials, demonstrating that the gains did not exceed those expected by probability summation. The results thus suggest that the visual system is unable to take advantage of probability summation in speeded visual discrimination when attention is diverted from the targets by engaging both exogenous and endogenous orienting mechanisms.

Experiment 1B: A replication of Experiment 1A using letters

The goal of this experiment was to determine whether the strong effect of attention on redundancy gains obtained in Experiment 1A for color targets would generalize to a different type of targets. We chose letters because they have been frequently used in prior

studies of redundancy gains (e.g., Miller, 1982; Mordkoff & Yantis 1991; Mordkoff & Miller, 1993).

Methods

Participants, apparatus, stimuli, and procedure—We recruited 15 Northwestern University undergraduate students who gave informed consent to participate for partial course credit. The stimuli and procedure were identical to those used in Experiment 1A except that we used letters instead of colored squares as targets. The letters (courier font) were black, and they subtended approximately 0.63° by 0.63° of visual angle. “X” and “O” were the targets, and “I” and “S” were the distractors.

Results and discussion

The overall error rates were low (5.2% misses and 5.1% false positives), and there were no significant effects associated with errors. The attention manipulation was confirmed by the overall significantly faster RT in the cue-valid trials (422 ms) compared to the cue-invalid trials (444 ms), $t(14) = 6.010$, $p < 0.0001$, $d = 1.551$.

Planned comparisons were made to evaluate redundancy gains in the cue-valid and cue-invalid conditions. When the targets were presented within the cued (attended) rectangle, target detection was significantly faster for the redundant targets than for the single targets, $t(14) = 5.801$, $p < 0.0001$, $d = 1.497$ (Fig. 2B). In contrast, when the targets were presented within the uncued (ignored) rectangle, the RTs were statistically equivalent for the single and redundant targets, $t(14) = 0.444$, *n.s.* This attention dependence of redundancy gains was confirmed by the significant ANOVA interaction between the cue validity (valid or invalid) and the target redundancy (single or redundant), $F(1, 14) = 43.075$, $p < 0.0001$, $\eta_p^2 = .754$.

As in Experiment 1A, the redundancy gains obtained in the cue-valid condition did not violate the race model inequality. At no quantile was the sum of the CDFs for the cue-valid single-target trials below the CDF for the cue-valid redundant-target trials (Ulrich et al., 2007).

We thus replicated Experiment 1A, demonstrating that whether targets are defined by color or shape, the visual system is unable to take advantage of probability summation in speeded visual discrimination when visual spatial attention is both exogenously and endogenously diverted from the targets. In the following experiments, we directed attention either exogenously (Experiment 2) or endogenously (Experiment 3) to determine how each attention mode contributes to probability-summation-based redundancy gains.

Experiment 2: Manipulating exogenous orienting of visual spatial attention

This experiment was essentially the same as Experiment 1A except that the cue validity was reduced to chance (50%) so that endogenous attention was unlikely to be engaged.

Methods

Participants, apparatus, stimuli, and procedure—We recruited 22 Northwestern University undergraduate students who gave informed consent to participate for partial course credit. The stimuli and procedure were identical to those used in Experiment 1A except for the reduction in cue validity to 50%.

Results and discussion

The overall error rates were low (0.7% misses and 3.7% false positives), and there were no significant effects associated with errors. The attention manipulation was confirmed by the

overall significantly faster RT in the cue-valid trials (477 ms) compared to the cue-invalid trials (486 ms), $t(21) = 5.573$, $p < 0.0001$, $d = 1.188$.

Planned comparisons were made to evaluate redundancy gains in the cue-valid and cue-invalid conditions. When the targets were presented within the cued (attended) rectangle, target detection was significantly faster for the redundant targets than for the single targets, $t(21) = 5.064$, $p < 0.0001$, $d = 1.080$ (Fig. 3). Interestingly, an equivalently robust redundancy gain also occurred when the targets were presented within the uncued (ignored) rectangle, $t(21) = 5.397$, $p < 0.0001$, $d = 1.151$. There was no ANOVA interaction between the cue validity (valid or invalid) and the target redundancy (single or redundant), $F(1, 21) = 0.00001$, *n.s.*

At no quantile was the sum of the CDFs for the cue-valid single-target trials below the CDF for the cue-valid redundant-target trials (Ulrich et al., 2007). Thus, exogenously diverting attention did not affect redundancy gains attributable to probability summation. This suggests that the attention effects obtained in Experiments 1A and 1B were caused by an engagement of endogenous orienting of attention. We tested this hypothesis in the next experiment.

Experiment 3: Manipulating endogenous orienting of visual spatial attention

This experiment was essentially the same as Experiment 1A except that we used a symbolic central cue to selectively manipulate endogenous attention.

Methods

Participants, apparatus, stimuli, and procedure—We recruited 22 Northwestern University undergraduate students who gave informed consent to participate for partial course credit. The stimuli and procedure were identical to those used in Experiment 1A with the following exceptions. Instead of a peripheral onset cue, a small triangle was presented at the fixation point; the triangle acted as a symbolic spatial cue by pointing (left, right, up, or down) with 80% validity to the rectangular region in which the upcoming target(s) were presented. We also slightly increased the SOA between the cue and the targets (from 120 ms to 170 ms) to accommodate the slower engagement of endogenous orienting of attention with central symbolic cues compared to exogenous orienting with peripheral cues (e.g., Müller & Rabbitt, 1989; Cheal & Lyon, 1991; Suzuki & Cavanagh, 1997; Briand, 1998).

Results and discussion

The overall error rates were low (4.7% misses and 3.9% false positives), and there were no significant effects associated with errors. The attention manipulation was confirmed by the overall significantly faster RT for the cue-valid trials (467 ms) compared to the cue-invalid trials (478 ms), $t(21) = 3.758$, $p < 0.002$, $d = 0.801$.

Planned comparisons were made to evaluate redundancy gains in the cue-valid and cue-invalid conditions. When the targets were presented in the cued (attended) rectangle, target detection was significantly faster for the redundant targets than for the single targets, $t(21) = 8.034$, $p < 0.0001$, $d = 1.713$, replicating Experiments 1A, 1B, and 2 (Fig. 4). Furthermore, as in Experiments 1A and 1B (but unlike in Experiment 2), when the targets were presented within the uncued (ignored) rectangle, the RTs were statistically equivalent for the single and redundant targets, $t(21) = 0.205$, *n.s.* This attention dependence of redundancy gain was confirmed by the significant ANOVA interaction between the cue validity (valid or invalid) and the target redundancy (single or redundant), $F(1, 21) = 12.765$, $p < 0.002$, $\eta_p^2 = .378$.

As in all of the preceding experiments, the redundancy gains obtained in the cue-valid condition did not violate the race model inequality. At no quantile was the sum of the CDFs for the cue-valid single-target trials below the CDF for the cue-valid redundant-target trials (Ulrich et al., 2007).

We have thus demonstrated that redundancy gains attributable to probability summation are selectively eliminated when attention is endogenously diverted from the region in which the targets are presented.

General Discussion

Previous research has demonstrated that both exogenously and endogenously focused visual spatial attention produce similar facilitative effects on visual tasks (albeit with different strengths and time courses). Previous research has also demonstrated that exogenously focused attention serves more functions than endogenously focused attention, such as strongly facilitating processing of feature conjunctions, enhancing signals in addition to reducing external noise, and inducing response gain in addition to contrast gain (e.g., Posner, 1980; Posner & Cohen, 1984; Müller & Rabbitt, 1989; Cheal & Lyon, 1991; Yantis & Jonides, 1990; Egeth & Yantis, 1997; Suzuki & Cavanagh, 1997; Briand, 1998; Lu & Doshier, 2000; Funes et al., 2005; Ling & Carrasco, 2006). However, the effects of exogenously and endogenously directed visual spatial attention were previously compared primarily for processing of single targets. Thus, the implications are that for processing of single targets, endogenous orienting of attention engages only a subset of the spatial attention mechanisms engaged by exogenous orienting of attention. For taking advantage of multiple targets for speeded identification, however, our results suggest that it is endogenous rather than exogenous orienting of attention that plays a crucial role.

We demonstrated that redundancy gains disappeared when attention was endogenously diverted from the targets in Experiments 1A, 1B, and 3, but redundancy gains were unaffected when attention was exogenously diverted in Experiment 2. Importantly, it was not the case that our manipulation of exogenous orienting was weak. If anything, the overall size of the cue validity effect on response times was slightly larger for exogenous orienting ($d = 1.188$ in Experiment 2) than for endogenous orienting ($d = 0.801$ in Experiment 3). Our results thus suggest that the mechanisms that produce redundancy gains are selectively disrupted when targets are presented away from the focus of endogenous attention.

Understanding what this implies about the function of endogenously focused attention requires a discussion of the literature on redundancy gains. Extensive research has revealed that redundancy gains are mediated by two classes of underlying mechanisms. Probability summation seems to be a default mechanism (the *race model*; e.g., Miller, 1982; Mordkoff, Miller, & Roch, 1996). However, redundancy gains in some cases exceed what is expected from probability summation and require an explanation based on non-linear signal integration (the *coactivation model*; e.g., Miller, 1982; Mordkoff & Yantis, 1993; Miller, 2007; Ulrich et al., 2007).

Signal integration (beyond probability summation) appears to occur when redundant targets are defined by different visual features (e.g., red and right tilt) or different sensory modalities (e.g., Miller, 1982; Mordkoff & Yantis, 1991; Mordkoff & Yantis, 1993; Mordkoff & Miller, 1993; Mordkoff, Miller, & Roch, 1996; Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Feintuch & Cohen, 2002; Diederich & Colonius, 2004; Miller, Kühlwein, & Ulrich 2004; Molholm, Ritter, Javitt, & Foxe, 2004; Gondan & Röder, 2006). The potential reason why signal integration does not occur when redundant targets are defined along a single feature dimension (e.g., different colors) is that processing within each feature

dimension is contrastive, designed to mark the unique region bearing an odd feature value distinct from the remaining regions (e.g., Wolfe, 1994, 1998; Itti & Koch, 2001; Krummenacher et al., 2002; Müller & Krummenacher, 2006).

Signal integration may also require that redundant features belong to a single object (e.g. Mordkoff & Halterman, VSS 2008) or that attention is distributed over redundant features when they are spatially separated (e.g., by pre-cueing the relevant region; Feintuch & Cohen, 2002). Because features belonging to the same object tend to be attended together (e.g., Duncan, 1984; O'Craven, Downing, & Kanwisher, 2000), these results may suggest that attending to redundant features may enable signal integration.

Note, however, that these and most previous research on redundancy gains used identification tasks (e.g., respond when a blue vertical bar, red tilted bar, or both are presented). Evidence suggests that signal integration can occur irrespective of attention when a task does not require feature identification. For example, feature-singleton search does not require feature identification because a singleton target can be detected on the basis of its difference from distractors without identifying the target features (e.g., Treisman & Gelade, 1980; Müller, Krummenacher, & Heller, 2004). Whether attention was directed toward or away from the singleton target (using a high-validity central pre-cue), a target redundantly defined by orientation and color (e.g., a white tilted target presented against black vertical distractors) was detected faster than a target defined by only one feature (e.g., a white vertical target presented against black vertical distractors), with the strength of facilitation indicating signal integration beyond probability summation (Krummenacher et al., 2002). This result suggests that, irrespective of the spatial focus of attention, redundant signals of feature contrast are integrated to increase the salience of a singleton target. Thus, directing attention to the redundant signals (e.g., by pre-cueing them or putting them within a single object) may be relevant only when signal integration is used for feature identification.

In general, attention is expected to play a role in integrating signals for perceptual identification because spatially focused attention may act to conjoin visual features into a unified representation of an object (e.g., Treisman & Gelade 1980; Treisman, 1991). In contrast, attention might not be relevant for utilizing redundant signals via probability summation because feature integration is not required for separately processing the signals from the redundant targets and responding as soon as one of the signals reaches the identification criterion. Indeed, redundancy gains at the level of probability summation were obtained for target identification whether or not the redundant target features belonged to the same object (e.g., Mordkoff & Halterman, VSS 2008), and whether or not attention was distributed over the region where targets were presented (e.g., Feintuch & Cohen, 2002). Prior studies, however, did not present redundant targets entirely within an uncued (ignored) region when attention was focused elsewhere. Thus, the potential role of attention in the parallel non-interactive processing that mediates probability summation has been unclear.

We presented both of the redundant targets either within a cued (attended) region or within an uncued (ignored) region. The fact that redundancy gains were completely eliminated when attention was endogenously diverted from the targets indicates that some attentional resource is essential even for the level of redundancy gains attributable to probability summation, and that endogenously (but not exogenously) diverting attention depletes this necessary resource.

It is possible, however, that endogenously directed attention was more narrowly focused on one visual hemifield compared to exogenously directed attention because the central symbolic cue used in the endogenous condition (Experiment 3) might have narrowly

focused the observers' initial attention at the center whereas their initial attention might have been more diffusely distributed in the exogenous condition (e.g., Goldsmith & Yeari, 2003). Although we did not use central cueing in Experiments 1A and 1B, one could argue that the high-validity peripheral onset cues used in those experiments strongly diverted attention from the targets by engaging both exogenous and endogenous orienting mechanisms. It is thus possible that redundancy gains were eliminated on the cue-invalid trials in Experiments 1A, 1B, and 3 because attention was strongly diverted away from the targets, but redundancy gains were unaffected in Experiment 2 because attention was less strongly diverted. Although we cannot conclusively rule out this degree-of-attention-diversion hypothesis, it is worth noting that the effects of exogenously and endogenously diverting attention on redundancy gains was all or none rather than graded in that exogenously diverting attention did not reduce redundancy gains at all whereas endogenously diverting attention completely eliminated redundancy gains. Furthermore, the hypothetically greater focusing of attention via endogenous orienting did not more strongly modulate the overall response time than exogenous orienting; if anything, the effect size of cueing on overall response time was greater for exogenous orienting (Experiment 2) than for endogenous orienting (Experiment 3) (see above). Thus, to the extent that modulation of the overall response time can be used as a measure of the strength of spatial attention orienting, our results suggest that parallel processing of multiple items is uniquely susceptible to endogenous (but not to exogenous) diversion of visual spatial attention.

Probability summation in the context of redundancy gains is typically modeled with a "horse-race" algorithm (e.g., Miller, 1982; Mordkoff, Miller, & Roch, 1996). In short, redundant targets are processed in parallel and the observer detects the presence of a target as soon as the processing of any one of the redundant-target signals reaches the decision criterion. Because neural processing is intrinsically noisy (e.g., Faisal, Selen, & Wolpert, 2008), picking whichever process reaches criterion first is statistically faster than waiting for the processing of any specific target to reach criterion. A simple explanation of our results would be that concurrent processing of redundant targets is impaired when the targets are presented outside the endogenous focus of attention. Only one target would then be initially processed, and other redundant targets would be processed subsequently with a delay. If this were the case, the RTs would primarily depend on a single (first engaged) target even in the presence of redundant targets, effectively eliminating a redundant-target advantage. Interestingly, a recent study showed that endogenous orienting of attention had no effect on redundancy gains when the task was simple detection (two stimuli were detected faster than one stimulus regardless of attention manipulation; Miller, Beutinger, & Ulrich, 2009). This suggests that the type of concurrent processing that requires resources that are depleted by endogenously diverting attention is at the stage of accumulating evidence for specific stimulus features for target identification rather than at the stage of detecting any activation greater than sensory noise.

It is still debated as to whether common or distinct networks of neural mechanisms mediate exogenous and endogenous visual spatial attention (e.g., Rosen, Rao, Cafarra, Scaglioni, Bobholz, Woodley, Hammeke, Cunningham, Prieto, & Binder, 1999; Corbetta & Shulman, 2002; Mayer, Dorflinger, Rao, & Seidenberg, 2004; Peelen, Heslenfeld, & Theeuwes, 2004; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005; Serences & Yantis, 2007). It is thus difficult to speculate on the neural mechanisms underlying the current results. Nevertheless, endogenously focusing attention has been shown to increase the baseline activity in the occipital and parietal areas (e.g., V1, V2, V4, TEO, and LIP) in the neural populations with receptive fields covering the spatial focus of attention (e.g., Colby, Duhamel, & Goldberg, 1996; Luck, Chelazzi, Hillyard, & Desimone, 1997; Kastner, De Weerd, Desimone, & Ungerleider, 1998; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; Reynolds, Chelazzi, & Desimone, 1999; Pessoa, Kastner, & Ungerleider, 2003). It is thus possible that

the top-down signals presumably originating from the prefrontal and parietal cortices (e.g., Kastner & Ungerleider, 2000; Pessoa et al., 2003; Reynolds & Chelazzi, 2004) that boost the background neural activity for visual processing in the endogenously attended region facilitate rapid parallel processing of targets for speeded identification.

In summary, we have demonstrated that endogenously diverting attention can eliminate redundancy gains in speeded visual discrimination. Importantly, exogenously diverting attention to an equivalent extent had no effect. Thus, whereas exogenous attention appears to be superior (e.g., faster acting and serving more functions) for processing of single targets, endogenous attention plays a crucial role in rapid concurrent processing of multiple targets.

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Figure 1.

An illustration of the stimuli and trial sequence. On half of the trials, a single target, two redundant targets, a single distractor, or two redundant distractors were presented within a vertical rectangle (A). On the remaining trials, these stimuli were presented within a horizontal rectangle (B). The targets were red and blue squares, and the distractors were yellow and green squares in Experiments 1A, 2, and 3. The targets were letters “X” and “O,” and the distractors were “I” and “S” in Experiment 1B. The location of one of the rectangles was pre-cued either by a peripheral onset cue (thickening of the rectangle; Experiments 1A, 1B, and 2) or by a central symbolic cue (a triangle pointing to a rectangle; Experiment 3). The target and distractor stimuli were presented either within the cued rectangle (cue valid) or within the other uncued rectangle (cue invalid). The dashed ovals in the figure illustrate the presumed foci of spatial attention.

Peripheral cue (80% validity)

Figure 2.

Response times for the single or redundant targets when they were presented within the cued (Cue Valid) or uncued (Cue Invalid) rectangle, (A) for color targets (Experiment 1A) and (B) for letter targets (Experiment 1B). Attention was manipulated with a peripheral onset cue with 80% validity, engaging both exogenous and endogenous modes of visual spatial attention. The error bars represent ± 1 SEM (adjusted for repeated-measures comparisons).

Figure 3.

Response times for the single or redundant targets when they were presented within the cued (Cue Valid) or uncued (Cue Invalid) rectangle. Attention was manipulated with a peripheral onset cue with 50% validity, selectively engaging the exogenous mode of visual spatial attention. The error bars represent ± 1 SEM (adjusted for repeated-measures comparisons).

Figure 4.

Response times for the single or redundant targets when they were presented within the cued (Cue Valid) or uncued (Cue Invalid) rectangle. Attention was manipulated with a central symbolic cue with 80% validity, selectively engaging the endogenous mode of visual spatial attention. The error bars represent ± 1 SEM (adjusted for repeated-measures comparisons).