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On the automaticity and flexibility of covert attention: A speed-accuracy trade-off analysis

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Abstract

Exogenous covert attention improves discriminability and accelerates the rate of visual information processing (M. Carrasco & B. McElree, 2001). Here we investigated and compared the effects of both endogenous (sustained) and exogenous (transient) covert attention. Specifically, we directed attention via spatial cues and evaluated the automaticity and flexibility of exogenous and endogenous attention by manipulating cue validity in conjunction with a response-signal speed-accuracy trade-off (SAT) procedure, which provides conjoint measures of discriminability and information accrual. To investigate whether discriminability and rate of information processing differ as a function of cue validity (chance to 100%), we compared how both types of attention affect performance while keeping experimental conditions constant. With endogenous attention, both the observed benefits (valid-cue) and the costs (invalid-cue) increased with cue validity. However, with exogenous attention, the benefits and costs in both discriminability and processing speed were similar across cue validity conditions. These results provide compelling time-course evidence that whereas endogenous attention can be flexibly allocated according to cue validity, exogenous attention is automatic and unaffected by cue validity.

Keywords

covert attention; exogenous; endogenous; automaticity; flexibility

Introduction

Attention allows us to select visual information and grant it priority in processing. Covert attention allows us to do so without eye movements. Covertly attending to a location improves spatial resolution (Carrasco, Williams, & Yeshurun, 2002; Golla, Ignashchenkova, Haarmeier, & Thier, 2004) and contrast sensitivity (Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lu & Doshier, 1998) in tasks such as visual search (Carrasco & McElree, 2001; Nakayama & Mackeben, 1989) and texture segmentation (Yeshurun & Carrasco, 1998, 2000).

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Covert attention has two subsystems. *Endogenous attention* is the voluntary focus on a location (manipulated with a central cue), where the observer intentionally allocates attention to a specific location. Its effect is known to be sustained; it takes ~300 ms from the onset of the attention-directing cue to be effective. *Exogenous attention* is an involuntary focus on a location (manipulated with a peripheral cue), and its effect is known to be transient; it peaks ~120 ms after cue onset (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989). Our study varied cue validity and conjointly assessed processing speed and accuracy to investigate the respective flexibility and automaticity of these two systems, while maximizing their effect by manipulating them according to their respective temporal dynamics.

As endogenous attention requires voluntary deployment, resource allocation should be more flexible. Indeed, using a dual task paradigm, Kinchla (1980) demonstrated that observers could flexibly allocate resources to two tasks when told to pay more attention to one of them, with performance in one task improving at the expense of the other. This discriminability trade-off is captured in attentional operating characteristic (AOC) curves (Kinchla, 1980; Sperling & Melchner, 1978). Other research lines provide converging evidence for the flexibility of endogenous attention. Jonides (1981) reported that observers could ignore cues used to manipulate endogenous attention, and that endogenous attention, unlike exogenous, is affected by cognitive load (reaction times increase with memory load). “Inhibition of return” occurs with exogenous but not with endogenous attention, suggesting that observers can exercise voluntary control over the latter (Shepard & Muller, 1989). Finally, endogenous attention flexibility has been demonstrated in the temporal domain: When observers know that a target is likely to appear at a certain time, they can allocate their attention accordingly (e.g., Coull & Nobre, 1998).

The effects of exogenous attention have been argued to be more automatic. A peripheral cue eliciting exogenous attention cannot be ignored even when known to be uninformative and irrelevant (Montagna, Pestilli, & Carrasco, in press; Müller & Rabbitt, 1989; Pestilli & Carrasco, 2005; Pestilli, Viera, & Carrasco, 2007). When instructed to sustain attention to a target location, the appearance of an abrupt-onset stimulus at another location hinders observer's performance at the target location (Theeuwes, Kramer, Hahn, & Irwin, 1998). Conversely, performance reflects a peripheral cue benefit, even when observers report not being able to see subthreshold cues (McCormick, 1997). These findings suggest that exogenous attention has an automatic bottom-up component that may be beyond voluntary control.

Studies on attentional capture by an abrupt-onset stimulus have also addressed the automaticity of exogenous attention. Some authors have shown that abrupt onset of peripheral stimuli capture attention automatically (e.g., Remington, Johnston, & Yantis, 1992; Yantis & Jonides, 1984). Similarly, contingent capture studies typically used task-relevant top-down information to determine under what conditions capture can occur; an irrelevant stimulus can induce attentional capture of a target only if the target shares a similar property of the irrelevant stimulus (e.g., its color), suggesting the involvement of intentional task-relevant goals (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). Note that in our study the cue is independent of the task—it provides the observers with no information regarding the features of the target. Hence, it should not be assumed that uninformative, peripheral cues would necessarily have a top-down component.

We sought to determine whether the two attention mechanisms could be clearly delimited at their most basic functional level. Exogenous attention has two primary effects: it improves discriminability and accelerates the speed of information accrual (Carrasco & McElree, 2001). Here, we assessed whether endogenous attention likewise affects concurrently

discriminability and information accrual speed. Crucially, with both types of attention, we investigate how cue validity influences speed and accuracy. A purely automatic process should be unaffected by cue validity in terms of cost and benefits; in contrast, an intentional process should engender cost-benefit effects that are modulated by cue validity (Kinchla, 1980; Shaw & Shaw, 1977; Sperling & Melchner, 1978; Vossel, Thiel, & Fink, 2006).

Most investigations of attention examine processing speed or accuracy, but not both. Accuracy measures alone cannot assess the effects of covert attention on processing speed. Processing speed is often investigated with response time (RT) tasks, but RT differences can be due to changes in decision criteria or discriminability alone (Reed, 1973; Wickelgren, 1977). For instance, variations in decision criteria across conditions can lead to RT differences, usually with concomitant changes in accuracy. Even when decision criteria remain constant, differences in discriminability can lead to RT differences: for example, a response threshold can be reached at an earlier point in time when a stimulus is more discriminable, even when the speed of information accrual is the same as for a less discriminable stimulus (McElree & Doshier, 1989).

A solution to the problems inherent in accuracy and RT paradigms is to employ the response-signal speed-accuracy trade-off (SAT) procedure. SAT controls for trade-offs and provides conjoint measures of discriminability and information accrual, enabling the measurement of processing speed in circumstances in which discriminability varies (Reed, 1973; Wickelgren, 1977). Using SAT, we demonstrated that a parallel processing mechanism underlies both feature and conjunction searches (McElree & Carrasco, 1999), that exogenous attention improves discriminability and accelerates processing speed at the cued location (Carrasco & McElree, 2001), that information accrual is faster at more eccentric locations (Carrasco, McElree, Denisova, & Giordano, 2003), and that exogenous attention speeds accrual to a similar degree across eccentricities (Carrasco, Giordano, & McElree, 2006). Additionally, SAT analysis has revealed that information processing is not uniform across isoeccentric locations, and exogenous attention speeds up information accrual more at disadvantaged locations (Carrasco, Giordano, & McElree, 2004). Therefore, by improving discriminability, attention enables us to extract relevant information in a noisy environment; by accelerating processing, it enables us to extract information efficiently in a dynamic environment, before potentially interfering stimuli occur.

In this study, we used the SAT procedure to examine the effects of exogenous and endogenous attention on the discriminability and speed of information accrual in visual search, as a function of cue validity. The design of this study allowed for a direct comparison of endogenous and exogenous attention effects, while ensuring optimal conditions for both types of attention. We kept task and stimuli identical for both endogenous and exogenous conditions to ensure that any differences in performance between the two can be attributed to the nature of the attentional mechanism. However, to maximize the effect of each type of attention, it was necessary for the cue location and the timing between the cue onset and the stimulus onset (SOA) to differ for exogenous and endogenous attention, as the former exerts its strongest effects with a peripheral cue presented with an SOA of ~120 ms while the latter reaches its maximal effects with a central cue presented with an SOA of at least ~300 ms (e.g., Cheal & Lyon, 1991; Hein, Rolke, & Ulrich, 2006; Liu, Stevens, & Carrasco, 2007; Nakayama & Mackeben, 1989).

While comparing endogenous and exogenous attention using these different cue locations and SOAs to maximize their respective benefits, previous studies from our lab have demonstrated that endogenous attention operates strictly via a contrast gain mechanism while exogenous attention operates via a response gain mechanism (Ling & Carrasco, 2006; Pestilli, Ling, & Carrasco, in press). We have also shown that in a texture segmentation task

that is constrained by spatial resolution, whereas exogenous attention improves performance where resolution is too low—but hampers it where resolution is too high—for the task at hand (consistent with Yeshurun & Carrasco, 1998), endogenous attention can optimize performance at all eccentricities (Yeshurun, Montagna, & Carrasco, 2008).

In addition, to characterize the temporal dynamics of exogenous and endogenous systems and to show that their effects on performance are contingent on timing, many authors have used a lengthened cue-to-target SOA for exogenous attention and a shortened SOA for endogenous attention. Longer SOAs (>150 ms) have been shown to be less effective for exogenous attention (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989), while shorter SOAs (<200 ms) have been shown to be less effective for endogenous attention (Cheal & Lyon, 1991). Studies have shown that when the SOA for exogenous attention was increased from 120 to 500 ms, exogenous attention effects were extinguished (Carrasco et al., 2004; Fuller, Rodriguez, & Carrasco, 2008; Liu, Fuller, & Carrasco, 2006; Turatto, Vescovi, & Valsecchi, 2007). Conversely, the effect of endogenous attention elicited by a 300-ms SOA disappeared with a shortened 150-ms SOA (Liu et al., 2007).

In sum, we used the SAT procedure to examine the effects of exogenous and endogenous attention on the discriminability and speed of information accrual in visual search. We manipulated cue validity to assess the degree of automaticity and flexibility of both types of attention by obtaining separate estimates of discriminability and processing time for various cue validities, ranging from chance to 100%. For both attentional conditions, we examined cue benefits and costs separately, while keeping task and stimuli constant and maximizing the effects of both exogenous and endogenous attention.

Experiment

Hypothetical SAT functions, plotting discrimination performance as a function of processing time, illustrate how this procedure provides measures of both discriminability and processing dynamics (Figure 1). A difference in asymptote results in functions with different levels of discriminability at a given time. A difference in either rate or intercept results in disproportional SAT dynamics with the functions reaching a given proportion of their respective asymptotes at different times. The circles show the corresponding RT points from a typical RT task in SAT coordinates, illustrating that RT differences can arise from differences in either discriminability (top panel) or dynamics (bottom panel). We used a range of response times to sample the full time course of processing, from early on when discrimination is near chance level to later times when it has reached its asymptotic level.

In a two-alternative forced choice discrimination, observers performed an orientation discrimination feature search task with Gabor patches (sinusoidal gratings vignettted by a Gaussian envelope, see Figure 2).

Methods

Observers

Six undergraduate NYU students, who were naïve to the purpose of the study and the first author (AMG) participated in this study. All seven observers had normal or corrected-to-normal vision. Three naïve observers and the non-naïve observer AMG were tested in each attention condition, exogenous and endogenous, yielding four observers per condition.

Apparatus

The stimuli were created using Matlab and the Psychophysics Toolbox (Brainard, 1997). Observers viewed the stimuli on a gamma-corrected monitor. Background luminance was set to the middle of the monitor's range (16 cd/m²).

Stimuli and design

The stimuli, 2-cpd Gabor patches subtending 2° of visual angle at 114 cm viewing distance, were randomly presented at eight equidistant locations at 4° eccentricity. The target was a tilted Gabor patch, presented alone or with 7 vertical distracters. Target tilt was $\pm 15^\circ$ for the endogenous condition and $\pm 30^\circ$ for the exogenous condition across observers, to equate overall percent correct levels for the baseline neutral conditions (~80%, with a ~10% stimulus contrast). A fixation dot was present at the screen's center, and observers were instructed to keep fixation during the entire experiment.

Procedure

Endogenous attention was manipulated by presenting a 150-ms central cue (0.8° black line extending from fixation pointing to target location). Exogenous attention was manipulated by presenting a 67-ms peripheral cue (0.3° black circle, 2° from target center). Both cues indicated target location and onset, but not orientation (Figure 2). The neutral cue in both conditions (small circle at fixation) indicated display onset only. The target and distracters appeared for 40 ms after a 150-ms (endogenous) or 53-ms (exogenous) inter-stimulus interval (ISI). The interval between cue and target onsets maximized the attentional benefit for each attention condition (endogenous: ~300 ms; exogenous: ~120 ms; Cheal & Lyon, 1991; Nakayama & Mackeben, 1989). To ensure that no eye movements were made, observers' eye position was recorded using an iSCAN infrared camera pointed at one of the eyes.

Observers responded whether the target was tilted right or left. Following stimulus display, a response tone occurred at one of 7 time lags, to sample the full time course of processing, from early on when discrimination is near chance level to later times when it has reached its asymptotic level. Observers completed 2 practice sessions to learn to respond within 350-ms of the auditory response tone. Throughout the experiment, any trials that fell outside this temporal window (<2%) were discarded. Feedback after each trial indicated whether observers responded correctly, incorrectly, or timed out.

Set size (1 or 8) and response tone (40, 94, 200, 350, 600, 1000, and 2000 ms) were randomly presented within each block. Cue validity was blocked by session for both endogenous and exogenous conditions: 12% (chance), 33%, 50%, 66%, and 100%. The exogenous attention condition consisted of randomized neutral and peripheral cue trials, whereas the endogenous attention condition consisted of randomized neutral and central cue trials, for each blocked cue-validity session. Observers participated in an experimental session per day. They were always informed of the cue validity before beginning each experimental session. Each session consisted of 8 blocks of 112 trials, for a total of 896 trials. Each observer completed 45 sessions (40,320 trials). The order with which observers participated in sessions with the different cue validities was counterbalanced.

Results

To conjointly measure asymptotic discriminability and temporal dynamics, the time-course data for each observer and for the average over observers were fit with an exponential approach to a limit, providing a quantitative summary of the shape of the SAT function (Reed, 1973; Wickelgren, 1977):

$$d'(t) = \lambda(1 - e^{-\beta(t-\delta)}), \quad \text{for } t > \delta, \text{ else } 0, \quad (1)$$

where λ = asymptotic parameter, reflecting discriminability at maximal processing time; δ = intercept parameter, reflecting the discrete time point when discriminability departs from chance ($d' = 0$); and β = rate parameter, indexing the speed with which discriminability grows from chance to asymptote by determining how much time it takes to reach 2/3 of the asymptote. The rate measures the underlying rate of information processing if the process in question is continuous, or it reflects the underlying finishing-time distribution if the process in question is discrete or quantal.

Exponential fits

A hierarchical model-testing scheme (Carrasco & McElree, 2001; McElree & Doshier, 1989) was used to determine how the experimental factors (set size \times cue type) affected the parameters of Equation 1 for each of the cue validities in each attentional condition, endogenous and exogenous, independently. The three parameters were fit to each observer's data and the averaged data. Models ranged from a null model, where all functions were fit with a single asymptote (λ), rate (β), and intercept (δ) to a fully saturated model in which each function was fit with a unique set of parameters. Three criteria determined fit quality: The value of an adjusted- R^2 statistic, where the proportion of variance accounted for by a model was adjusted by the number of free parameters; the consistency of parameter estimates across observers; and an evaluation of systematic residuals (Carrasco & McElree, 2001; Carrasco et al., 2003). Adequate model fits required a separate asymptote (λ) for each of the 4 conditions [cue (valid, neutral) \times set size (1 or 8)] in the 100% cue validity and each of the 6 conditions [cue (valid, neutral, invalid) \times set size (1 or 8)] in the 12%, 33%, 50%, and 66% cue validities. One rate (β) was required for each of the cue types (i.e., one for neutral and another for valid for 100% cue validity; and one for neutral, another for valid, and a third for invalid for all the other cue validities: 12%, 33%, 50%, and 66%). All functions shared a common intercept (δ). Simpler models that did not allocate separate asymptotes for cue type and set size or separate rates for cue type resulted in lower adjusted- R^2 statistics across all observers. Model fits that varied intercept or rate as a function of set size reduced the adjusted- R^2 for each observer and for the average data, indicating that the additional parameters were not accounting for systematic variance in the data.

Repeated measures ANOVAs (cue validity \times cue type \times set size) were conducted on the parameter estimates. Consistent with previous studies (Carrasco et al., 2003, 2004, 2006; Carrasco & McElree, 2001), set size affected discriminability but not processing speed (i.e., the best fitting model did not allow for separate rate and intercept parameters according to set size). Figure 3 shows SAT curves fit to data for a low validity, 33%, and the highest validity, 100%, i.e., without invalid condition. We include these two validity conditions for the purpose of illustrative simplicity; the other cue validity conditions had correspondingly intermediate graphs, as shown in Figure 4. These functions differ as a function of cue validity for the endogenous, but not for the exogenous condition. Similarly, intercepts, slopes, and asymptotes differ for endogenous attention but were comparable for exogenous attention. Below we further explore these differential findings.

Endogenous attention

Discriminability—Endogenous attention improved discriminability as a function of cue validity across the full time course of processing (Figure 4). Across cue validity, there was a significant main effect of cue type ($F(1,2) = 23.68, p < 0.01$; valid $>$ neutral $>$ invalid) and set size ($F(1,1) = 310.10, p < 0.01$; 1 $>$ 8). The significant 3-way interaction ($F(1,6) = 8.76$;

$p < 0.001$) indicated that as validity increases, the effect of cue type and set size was more pronounced.

When assessing the differences among cue types across cue validity, a significant interaction between cue validity and set size emerged ($F(1,3) = 14.17$; $p < 0.01$), with cue validity effects being more pronounced for set size 8 than 1. This interaction was driven by the benefits (difference between valid and neutral cue asymptotes; validity \times set size: $F(1,4) = 6.25$; $p < 0.01$) and not the costs (difference between invalid and neutral cue asymptotes; validity \times set size: $F = 1$).

Processing speed—Processing speed is best captured with a composite measure, $\delta + \beta^{-1}$, which gives an average processing time in milliseconds. It guards against potential parameter trade-offs (e.g., a faster rate but a later intercept) and enables cross-condition comparisons with differing rates and intercepts. Endogenous attention sped information accrual as a function of cue validity (Figure 5). Both main effects were significant, validity ($F(1,3) = 5.36$; $p < 0.03$) and cue type ($F(1,2) = 15.09$; $p < 0.01$), as was their interaction ($F(1,6) = 3.73$; $p < 0.02$) with the cue-type effect increasing with cue validity. Assessing the differences among cue types across cue validity yielded a significant main validity effect, which was driven by costs ($F(1,3) = 3.92$; $p < 0.05$), not benefits ($F < 1$).

Taken together, the discriminability and processing speed results for endogenous attention indicate that observers' performance was affected by cue type and that observers were able to flexibly allocate endogenous attention as a function of cue validity.

Exogenous attention

Discriminability—Exogenous attention improved discriminability to a similar degree regardless of cue validity (Figure 4). Across cue validity, there is a significant main effect of cue type ($F(1,2) = 123.25$; $p < 0.01$; valid $>$ neutral $>$ invalid) and set size ($F(1,1) = 79.48$; $p < 0.01$; $1 > 8$). Neither the effect of validity nor the 3-way interaction was significant ($F = 1$). When analyzing the differences among cue type across cue validity, neither the main effects of cue validity and set size nor their interaction were significant ($F = 1$).

Processing speed—Exogenous attention sped information accrual regardless of cue validity across the full time course of processing (Figure 5). There was no significant interaction of validity and cue type ($F < 1$). Analyzing the differences among cue type across cue validity yielded no significant main effect of cue validity ($F < 1$).

Taken together, the discriminability and processing speed results for exogenous attention indicate that observers' performance under exogenous attention is affected by cue type but not by cue validity.

Discussion

This study demonstrated that endogenous, like exogenous attention (Carrasco & McElree, 2001), improves discriminability and speeds visual information processing conjointly. By varying cue validity from chance to 100%, we found clear evidence that endogenous attention was flexible, it varies according to task demands, i.e., cue validity. In contrast, the benefits and costs of exogenous attention were independent of cue validity, even though allocating attention based on cue validity would have been an optimal strategy. This indicates that exogenous attention is automatic.

The design of this study allowed for a direct comparison of endogenous and exogenous attention effects. As in previous studies, the same task, design, and stimuli were used in both

exogenous and endogenous conditions to ensure that differences in the results would reflect differences in the attentional mechanisms rather than in methodology, while maximizing the effect of each type of attention by presenting a cue at the optimal location and time with respect to the stimuli (e.g., Cheal & Lyon, 1991; Ling & Carrasco, 2006; Liu et al., 2007; Montagna et al., in press; Nakayama & Mackeben, 1989; Yeshurun et al., 2008). One might assume that cue validity information may be more likely to be used with the time course we used for endogenous attention. However, with longer SOAs approaching those of the endogenous system, the exogenous system is no longer active (e.g., Carrasco et al., 2004; Cheal & Lyon, 1991; Fuller et al., 2008; Hsieh, Caplovitz, & Tse, 2005; Liu et al., 2006; Nakayama & Mackeben, 1989; Remington et al., 1992; Turatto et al., 2007). Thus, with long SOAs we would not have been able to evaluate the automaticity of the exogenous system. Our experimental design also prevented the possible contamination of conceptually driven influences in the exogenous condition. When a peripheral cue is always valid in terms of location, it is possible that some of its effect could be due to a conceptually driven, voluntary component of attention. We manipulated cue validity to assess the degree of automaticity in the two types of attention.

The SAT analysis provides a detailed picture of how patterns of speed and discriminability differ with both types of attention. With endogenous attention, performance varied with cue validity. Discriminability differences were mainly manifested as benefits: Valid cue effects increased with cue validity. Conversely, processing speed differences were mainly manifested as costs: Invalid cue effects increased with cue validity. With exogenous attention, the cue benefits and costs in both discriminability and processing speed were similar regardless of cue validity.

Notably, observers were always given explicit knowledge of cue validity prior to each session. The performance differences with endogenous attention suggest that observers were able to utilize this knowledge to conduct some form of probability matching. The flexible nature of endogenous attention appears to enable observers to allocate attentional resources according to cue validity (less attentional weight to the cue in low validities and more in higher validities). Previous studies report this effect with accuracy-AOC curves (Kinchla, 1980; Sperling & Melchner, 1978). The present study shows flexibility when accuracy and speed are assessed concurrently.

The exogenous attention results paint a different picture. Observers were not able to utilize knowledge of cue validity to redistribute their attention. The finding that cue benefits and costs remained similar across cue validity indicates that exogenous attention, when manipulated via spatial cues, is an automatic mechanism that functions independently of conceptually driven information. This result is consistent with studies showing that, with uninformative cues, exogenous attention improves performance at the attended location and hinders performance at the unattended location (Anton-Erxleben, Henrich, & Treue, 2007; Carrasco, Ling, & Read, 2004; Fuller & Carrasco, 2006; Fuller et al., 2008; Ling & Carrasco, 2007; Montagna et al., in press; Pestilli & Carrasco, 2005; Pestilli et al., 2007), as well as with an fMRI study demonstrating that an uninformative exogenous cue leads to increased stimulus-evoked activity at the attended location (Liu, Pestilli, & Carrasco, 2005). Together, these findings suggest that studies examining the effects of exogenous attention on various aspects of vision, such as contrast sensitivity (Carrasco et al., 2000; Ling & Carrasco, 2006; Lu & Doshier, 1998), spatial resolution (Golla et al., 2004; Yeshurun & Carrasco, 1998, 2000), and information accrual (Carrasco & McElree, 2001; Carrasco et al., 2004, 2006), may yield similar results with different cue validities.

Is there an alternative explanation for the different pattern of results for exogenous and endogenous attention? Some authors have explained precueing effects as the result of a

reduction of location or decisional uncertainty, inherent in the valid/invalid cue attentional manipulation paradigm. That is, given that the cue allows observers to monitor only the relevant location instead of all possible ones, it reduces the statistical noise introduced at the irrelevant locations. According to this view, the benefit in performance found at cued locations can be ascribed to a reduction of the statistical uncertainty in the decision process rather than to changes in the signal (e.g., Carrasco et al., 2000, 2002; Palmer, 1994; Sperling & Doshier, 1986). The present findings cannot be explained by location uncertainty or decisional uncertainty, as they are the same for both cueing conditions. Were the present findings simply due to location uncertainty or decisional uncertainty, both attention conditions would have yielded the same pattern of results. This was clearly not the case.

In this study, an optimal strategy would have been to always allocate attention based on validity. However, the automaticity and time course of exogenous attention appears to have prevented observers from employing the probability matching seen in the endogenous attention condition. Other studies have also demonstrated that the automatic nature and time course of exogenous attention can impair performance at the attended location. For example, in a texture segmentation task, exogenous attention improved performance in the periphery where spatial resolution was too low for the task but impaired performance at central locations where spatial resolution was already too high for the task (Carrasco, Loula, & Ho, 2006; Yeshurun & Carrasco, 1998, 2000). In contrast, in the same task, endogenous attention benefits performance across eccentricity, optimizing performance (Yeshurun et al., 2008).

The present study indicates that two distinct mechanisms underlie endogenous and exogenous attention. Accordingly, fMRI studies suggest two separate neural networks (e.g., Corbetta & Shulman, 2002; Kastner & Ungerleider, 2000). At a functional level, two different types of covert attentional mechanisms may allow us to better respond to and interact with our surroundings. Endogenous attention allows us to voluntarily monitor items or locations in the periphery. Based on these findings, as well as on findings showing differential effects of endogenous and exogenous attention on texture segmentation (Yeshurun et al., 2008), we can speculate that exogenous attention appears to be a phylogenetically older system that allows us to automatically respond to environmental demands and therefore react quickly to stimuli that may provide behaviorally relevant information.

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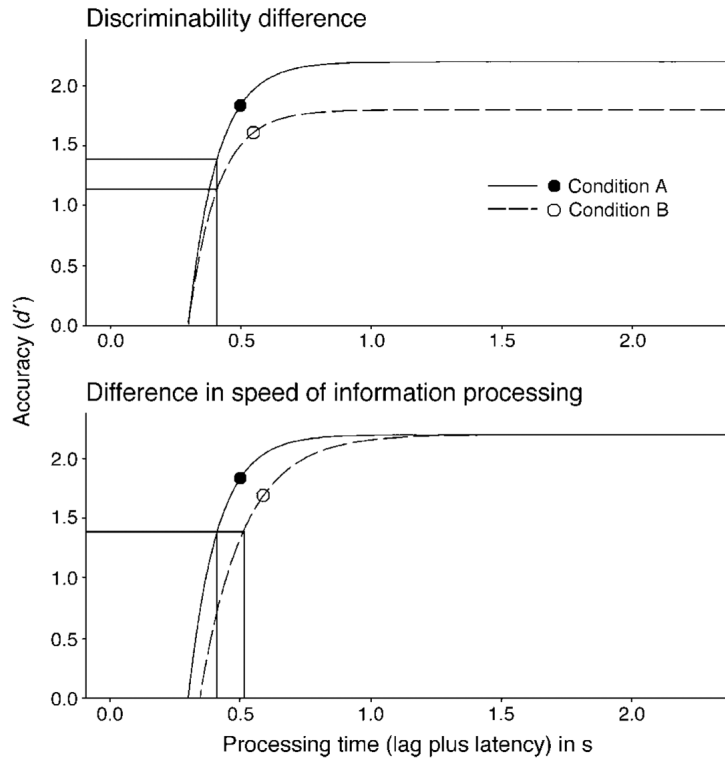


Figure 1. Hypothetical SAT functions. Illustrative SAT functions, plotted in d' units versus processing time (time of the response cue plus observer's average latency to respond). *Top panel:* Expected pattern if an experimental factor increases target discriminability only. The functions differ in asymptotic accuracy but are associated with the same intercept (point when accuracy departs from chance) and proportional rate of information accrual. *Bottom panel:* One expected pattern if the experimental factor alters the speed of information accrual (intercept and rate) only. The functions display disproportional dynamics; they reach a given proportion of their asymptotes at different times. Circles show hypothetical results from a typical RT task plotted in SAT coordinates (abscissa = mean RT; ordinate = accuracy), illustrating that RT differences can reflect differences in discriminability (top panel) or information accrual (bottom panel). The position of the RT points on the corresponding SAT functions is determined by the decision criteria that an observer uses to balance speed and accuracy.

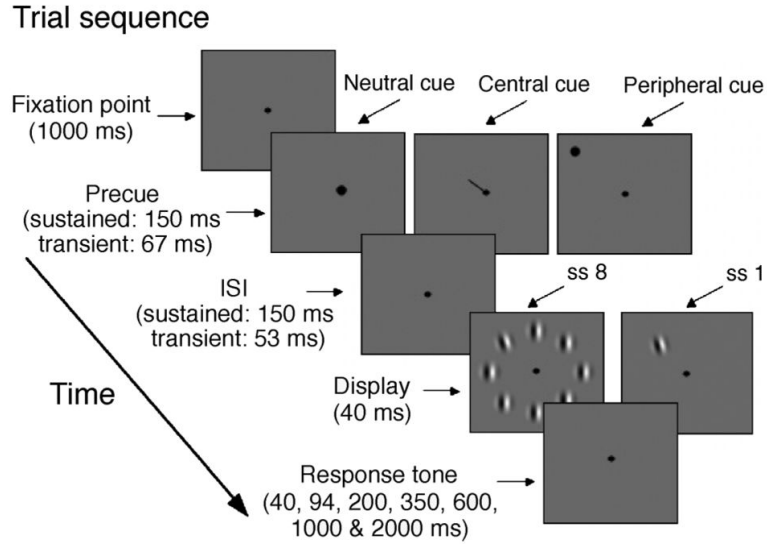


Figure 2. Sequence of events in a single trial. The stimuli were randomly presented at 8 equidistant locations from a central fixation point on an invisible polar grid at 4° eccentricity. The interval between the cue onset and the stimulus onset was optimum to facilitate endogenous or exogenous attention. Eyes were monitored in the endogenous condition to ensure no movements were made. Observers were required to respond whether the target was tilted to the right or the left within 350 ms of the response tone presented at one of 7 times after stimulus onset. Feedback was provided after each trial. All observers were informed of the validity of the cue prior to running in both endogenous and exogenous conditions.

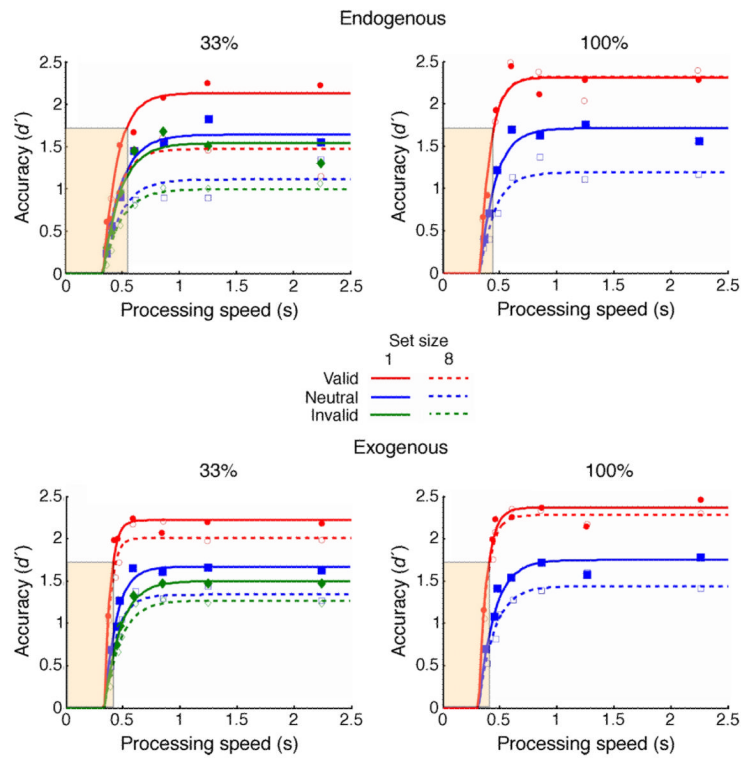


Figure 3.

Results: low and high cue validities. Average discrimination accuracy (in d' units) as a function of processing time in 33% (low) and 100% (high) cue validities for endogenous (top) and exogenous (bottom) conditions. Smooth functions show the best-fitting exponential model (Equation 1) for the valid (red lines), neutral (blue lines), and invalid (green lines) cueing conditions for set sizes 1 (solid lines) and 8 (dashed lines), based on fits of nested models that systematically varied the 3 parameters of Equation 1. In these SAT curves, the rate (valid condition rate indicated by shaded areas) differences across validity for endogenous are clearly shown. The endogenous cue benefit (valid-neutral) increases greatly, i.e., 396 ms, while the exogenous cue benefit increases slightly, i.e., 46 ms, as cue validity increases from 33% to 100%. With respect to discriminability (represented by the asymptotes), the endogenous cue benefit increases 0.44 d' units while the exogenous cue benefit only increases 0.12 d' units as validity increases from 33% to 100%. (endogenous: R^2 for 33% = 0.92, R^2 for 100% = 0.94; exogenous: R^2 for 33% = 0.96, R^2 for 100% = 0.96).

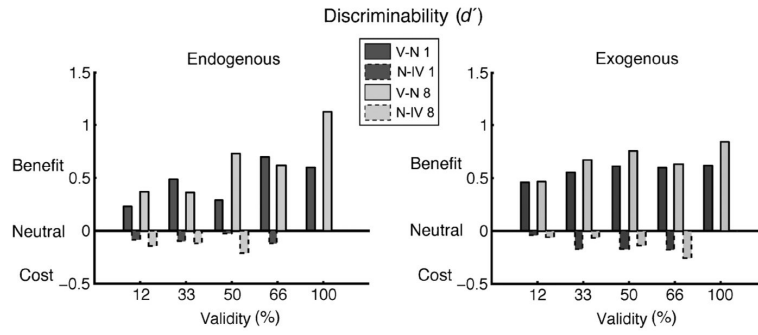


Figure 4. Discriminability differences. Average discriminability differences (in d' units) for set sizes 1 (dark gray bars) and 8 (light gray bars) as a function of cue validity for endogenous (left) and exogenous (right) conditions. Benefits (solid line bars) are differences between valid and neutral cue asymptotes while costs (dashed line bars) are differences between invalid and neutral invalid cue asymptotes. Benefits significantly increase with validity for both set sizes in endogenous conditions (left panel) while both benefits and costs remain constant across cue validity for exogenous conditions (right panel).

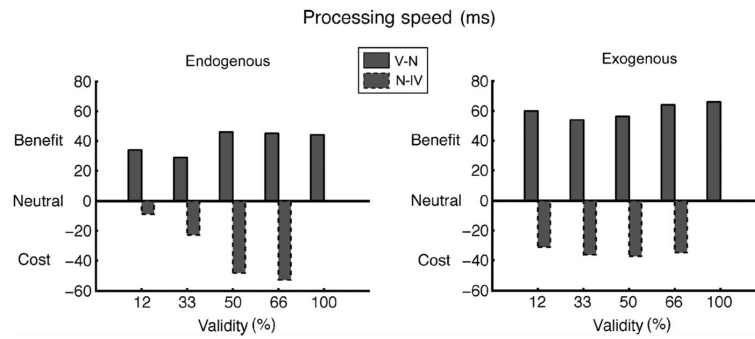


Figure 5. Processing speed differences. Average processing speed differences (in ms) as a function of cue validity for endogenous (left) and exogenous (right) conditions. Benefits (solid line bars) are differences between valid and neutral cue processing speeds while costs (dashed line bars) are differences between invalid and neutral invalid cue processing speeds. Costs significantly increase with validity in endogenous conditions while both benefits and costs remain constant across cue validity for exogenous conditions.