Journal of Experimental Psychology: General
2005, Vol. 134, No. 2, 207–221

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0096-3445/05/$12.00 DOI: 10.1037/0096-3445.134.2.207

Competition Between Endogenous and Exogenous Orienting of Visual Attention

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The relation between reflexive and voluntary orienting of visual attention was investigated with 4 experiments: a simple detection task, a localization task, a saccade toward the target task, and a target identification task in which discrimination difficulty was manipulated. Endogenous and exogenous orienting cues were presented in each trial and their validity was manipulated orthogonally to examine whether attention mechanisms are mediated by separate systems and whether they have additive and independent effects on visual detection and discrimination. The results showed that each orienting mechanism developed its typical and independent effect in every case except for the difficult identification task. A theoretical framework for understanding the relationship between endogenous and exogenous orienting of attention is proposed, tested, and confirmed.

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With the evolution of more complex behavior, brain mechanisms for selective attention have emerged that provide the organism with greater flexibility to respond to environmental events in one way under one set of circumstances, to respond a different way under another, to not respond at all, or to delay a response pending further information. It is through such mechanisms that past learning, motivation, and emotion may influence behavior.

This selectivity of adaptive behavior is achieved through an orchestration of subcortical reflex circuits by cortical processes that can activate or inhibit them (Easton, 1973). Neural machinery for visual orienting is the product of its evolutionary history (Ingle, 1973), and it offers an attractive model system for developing a biological framework for understanding automaticity and control from an evolutionary perspective because it fosters a convergence of psychology and neurophysiology in both humans and animals. Because the orienting of attention to detect a visual signal is a relatively simple cognitive act that humans share with other animals, performance studies in humans and neurophysiologic studies in animals converge to provide an understanding of the neural processes underlying visual attention. The simplicity of the task has also made it possible to study the development of visual orienting in human infants (Johnson, 1990).

All vertebrates have midbrain circuits for reflexively orienting the eyes toward salient events occurring in the visual periphery, which is known as the visual grasp reflex. Although this visual grasp reflex plays a critical defensive role in ensuring survival, reflexive eye movements must also be integrated with cortical mechanisms involved in strategic search under voluntary control. In everyday life, there are constantly competing demands on systems for visual orienting by the outside world as well as from internally generated goals. Thus, the orienting of attention reflects a competition between inner goals and external demands: It may be triggered voluntarily (endogenously), as when a person looks both ways before crossing the street, or be captured by an external stimulus (exogenously), as when a person turns toward a sudden movement seen "out of the corner of the eye." Although orienting of attention is usually carried out overtly by moving the eyes and head, many studies have focused on covert orienting (orienting without moving the eyes; Eriksen & Yeh, 1985; Jonides, 1981; Muller & Rabbitt, 1989; Posner, 1980; Posner & Cohen, 1984; Shepherd & Muller, 1989; Yantis & Jonides, 1990).

The current article focuses on the relation between reflexive and voluntary orienting of attention. In it, we specifically test the hypothesis that these attention mechanisms are mediated by separate systems, and we explore whether they have additive and independent effects on visual detection and discrimination. Because much is known about the neural systems controlling reflexive and voluntary eye movements, we have been able to achieve an understanding of the neural interactions between cortical and subcortical circuits that enable oculomotor reflexes to be controlled in the service of goal-directed behavior (Rafal, 2002). Much empirical effort has also been invested in understanding the relationship between voluntary and reflexive covert shifts of attention. Converging strands of research on this issue have addressed three related questions: Do voluntary and reflexive attention shifts have different effects of performance in terms of both their time course and the aspects of performance that they influence? What are the neural systems involved in regulating voluntary and reflexive attention shifts? Are their effects on performance additive and independent—consistent with independent functional and neural systems—or do they share common resources? We briefly review the first two issues and then focus on the literature addressing the last to introduce the current experiments.

Measuring Voluntary and Reflexive Attention

In the paradigm developed by Michael Posner, benefits and cost of orienting are measured at cued and uncued locations (Posner,

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We thank Desiree Meloul for all of her help.

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1980; Posner, Snyder, & Davidson, 1980). Endogenous orienting is commonly triggered by an arrow presented at fixation. In most of the trials, the arrow validly points to the target location. Because orienting is based on the symbolic meaning of the arrow and its predictive value, it must be generated internally, and it is thought to be voluntary and controlled (Jonides, 1981). Exogenous orienting can be triggered by a random brightening in the periphery of the visual field. Because subjects cannot ignore the cue in spite of the fact that it has no predictive value, orienting is thought to be reflexive and automatic (Jonides, 1981; Rafal & Henik, 1994).

Differences Between Endogenous and Exogenous Orienting

Jonides (1981) compared the effects elicited by exogenous and endogenous cues using criteria for automaticity (load-insensitivity criterion and intentionality criterion as defined by Hasher & Zacks, 1979; Logan, 1978; and Shiffrin & Schneider, 1977). He suggested that there were four essential differences between the two kinds of cues: (a) exogenous orienting was less affected by cognitive load than endogenous orienting was, (b) subjects were able to ignore endogenous cues but were unable to ignore exogenous cues, (c) exogenous cues had bigger effects than endogenous cues did (see also Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989), and (d) expectancies about cue validity and predictive value affected endogenous orienting more than exogenous orienting. Furthermore, it has later been found that reflexive covert orienting can occur without awareness of the exogenous cue evoking it. Evidence supporting this claim comes from studies with normal subjects (McCormick, 1997) and from patients with visual extinction (Danziger, Kingstone, & Rafal, 1998).

Another essential difference between the two kinds of orienting is found in the time course of their development. Endogenous orienting develops gradually; an initial broad focus is followed by a narrow one. Shepherd and Muller (1989) found the broadest focusing at a stimulus onset asynchrony (SOA) between cue and target of 150 ms and the narrowest focusing at an SOA of 500 ms. In contrast, they found that exogenous orienting developed a rapid and narrow facilitatory effect, reaching maximal facilitation at an SOA of 50 ms (see additional evidence for time course differences in the effect of endogenous vs. exogenous cues in Cheal & Lyon, 1991). In addition, the effect of exogenous orienting is biphasic. The initial facilitation is replaced by inhibition 200 to 300 ms after cue onset. This phenomenon is called *inhibition of return* (IOR) and was first reported by Posner and Cohen in 1984 (Maylor, 1985; Maylor & Hockey, 1985, 1987). It was suggested that this inhibition serves to favor novelty in visual scanning (Cheal & Chastain, 1999; Clohessy, Posner, Rothbart, & Vecera, 1991; Klein, 1988; Klein & MacInnes, 1999; Maylor, 1985; Maylor & Hockey, 1985, 1987; Posner & Cohen, 1984; Rafal & Henik, 1994; Rothbart, Posner, & Boylan, 1991). Usually IOR is not found with endogenous orienting unless the endogenous cue triggers the oculomotor system to prepare or execute a voluntary saccade (Rafal, Calabresi, Brennan, & Sciolto, 1989; see comprehensive reviews of the IOR phenomenon in Klein, 2000, and Taylor & Klein, 1998).

Endogenous and Exogenous Attention: Neural Substrates

All vertebrates have midbrain circuits for reflexively orienting the eyes toward salient events occurring in the visual periphery: the visual grasp reflex (Ingle, 1973). It is reasonable to postulate, therefore, that the midbrain superior colliculus (SC) might also be involved in reflexive covert orienting as well, and evidence indeed supports this hypothesis. Covert shifts of exogenous attention are impaired in patients with midbrain degeneration due to progressive supranuclear palsy (PSP) in the same directions in which their eye movements are impaired (Rafal, Posner, Friedman, Inhoff, & Bernstein, 1988). Nevertheless, the SC is a final common pathway for all saccades, including endogenous saccades commanded by the frontal eye fields; and although exogenous covert orienting was more impaired in PSP patients than endogenous covert orienting was, the latter was also affected in those patients.

Further evidence for collicular involvement in exogenous covert orienting also derives from observations that under conditions of monocular viewing, exogenous shifts of attention are more effectively summoned toward cues in the temporal hemifield, which has been postulated to have more direct access to the SC (Hubel, LeVay, & Wiesel, 1975; Lewis & Maurer, 1992; Rafal, Smith, Krantz, Cohen, & Brennan, 1990; Sherman, 1974; Wilson & Toyne, 1970). However, a more recent neuroanatomical study has questioned the validity of using nasotemporal asymmetries as a marker for collicular mediation (Williams, Azzopardi, & Cowey, 1995).

Moreover, a recent study by Sumner, Adamjee, and Mollon (2002) has shown a dissociation in the neural substrates involved in reflexive saccades and those involved in covert shifts of attention. While confirming the critical role of the retinotectal pathway in reflexive saccades, their findings suggest that reflexive covert orienting is not entirely dependent on it. Using s-cone sensitive stimuli (that do not activate either retinotectal or magnocellular visual pathways), they showed that the remote distractor effect was not activated by these stimuli, whereas reflexive covert attention shifts were preserved.

Moreover, an imaging study by Rosen et al. (1999) showed that although there is some overlap between the brain areas involved in exogenous and endogenous shifts of attention, there are also differences between them. For example, the right dorsolateral prefrontal cortex was selectively activated in endogenous but not in exogenous orienting (see also Friedrich, Egly, Rafal, & Beck, 1998).

In summary, although phylogenetically primitive visual pathways to the midbrain do make a special contribution to reflexive orienting, the cumulative evidence from neuroscience does not show a clear segregation of neural systems for reflexive and voluntary orienting. It also does not resolve the question of whether these systems can function independently and make additive and independent contributions to performance.

The Relation Between Endogenous and Exogenous Orienting

In light of the mentioned differences between endogenous and exogenous cues, some researchers have suggested that these two kinds of orienting may involve separate attention mechanisms (Briand & Klein, 1987; Friedrich et al., 1998; Henderson, 1991;

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Muller & Humphreys, 1991; Reuter-Lorenz & Frendrich, 1992; Taylor & Klein, 1998). However, these different effects could reflect different operating modes of a single attention system. A critical test for independent systems requires an examination of whether the two systems can influence perception at the same time without interacting. In the present research, we carried out this critical test with a paradigm that manipulated the two kinds of cues in each trial.

Several studies have already addressed this question (Muller & Humphreys, 1991; Muller & Rabbitt, 1989; Tanaka & Shimojo, 1993; Theeuwes, 1991; Warner, Juola, & Koshino, 1990; Yantis & Jonides, 1990; and more recently Berlucchi, Chelazzi, & Tassinari, 2000). However, there was never a genuine, full, and fair competition between the cues tested in any of these studies. For example, Yantis and Jonides tested the hypothesis that an abrupt visual onset captures attention automatically. They described the abruptness of stimulus onset as the basis of exogenous orienting. In their research, they used a discrimination task: After an endogenous cue, one of two letters appeared (e.g., *E* or *H*) embedded in an array of distracter letters, and they measured choice reaction time (RT) to it. There were two kinds of target presentations, *abrupt onset targets* and *nonabrupt onset targets.* In all of the displays, one stimulus (either the target or one of the distracters) had an abrupt onset; the remaining letters did not. Yantis and Jonides found that (a) the subject's state of attentional readiness modulated the effectiveness of an abrupt onset in drawing attention; (b) an endogenous cue presented 200 ms before the target eliminated the effect of abrupt onset, leading to similar performance for abrupt onset and nonabrupt onset targets; and (c) when attention was highly focused as a result of a 100% valid central cue, attentional capture by an abrupt onset was overcome. In contrast, when the predictive validity of the central cue was smaller than 100%, attentional capture was not overcome. The overall conclusion was that when attention was highly focused, a visual onset did not automatically capture attention. Hence, they suggested that the abrupt onset mechanism was not strongly automatic because it did not satisfy the intentionality criterion for automaticity. However, the timing parameters used by Yantis and Jonides may not have been optimal for revealing the effect of the exogenous (abrupt onset) cue. The exogenous cue in their experiment did not precede the target, so it might not have had sufficient time to manifest its effects. In addition, they did not manipulate the validity and cue type orthogonally.

Another test of the independence of endogenous and exogenous systems was reported by Muller and Rabbitt (1989). In their study, the subject's attention was deployed to one of four boxes by a central endogenous cue. At various intervals after the cue onset, a distracting flash appeared (the exogenous cue). Subjects were asked to ignore the flash. Muller and Rabbitt measured the probability of correct recognition and found that even when the endogenous cue was valid, an exogenous flash elsewhere in the visual field interfered with performance. They concluded that endogenous and exogenous orienting are served by separate mechanisms that share the same limited-capacity attention pool and that exogenous orienting can interfere with endogenous orienting. These conclusions are not entirely convincing for three reasons. First, Muller and Rabbitt used only long SOAs (600 ms and 1,200 ms). Because the two cues have different time courses, a full picture of the relationship between the cues requires testing under short SOAs as well. Second, the predictive validity of the endogenous cue was low (50%), in contrast to the more conventional predictive validity of 80%. Because endogenous orienting is critically affected by the predictive validity of the cue (Jonides, 1981), the effect of the endogenous cue in these experiments may have been less than optimal. Third, because their paradigm was based on a discrimination task, it might not be possible to generalize their findings to much of the literature in which the effect of covert orienting using detection rather than discrimination was examined.

Some years ago, we designed a paradigm that allows for a full competition between exogenous and endogenous cues. Our paradigm overcomes the limitations of the previous attempts to deal with the relations between endogenous and exogenous orienting. In our paradigm, the cues were manipulated orthogonally, they were given enough time to develop their optimal effects, and a broad range of SOAs was tested. Our results were briefly reported by Rafal and Henik (1994) and cited in several articles since then, but, until now, they were never published. Recently, we have replicated and extended our earlier findings, using manual choice RT instead of the original simple RT responses. Moreover, we have extended our findings to overt orienting with saccadic responses. We include here all of these experiments: Experiment 1 is a replication of the original experiment reported in Rafal and Henik, Experiment 2 is a replication with manual choice RTs, and Experiment 3 is an extension of our findings using saccadic responses. Last, in Experiment 4, we show how load demands of the task affect the relationship between endogenous and exogenous orienting.

General Method

Apparatus and Stimuli Display

An IBM-compatible Pentium desktop computer controlled the presentation of the stimuli and the acquisition of data throughout the experiments. Subjects were seated in a dimly illuminated and silent room, and they viewed an NGE VGA display monitor with white stimuli on a black background from a distance of 54 cm. The subject's head rested loosely on a chin rest. For experiments with keypress responses (Experiments 1 and 2), the index finger of the preferred hand rested on a response key placed on the table between the subject and the display. The method for saccadic responses will be explained in the *Method* section of Experiment 3.

Eye movements were monitored in Experiments 1, 2, and 4 with a sensitive Pulnix video camera. In Experiment 3, an Eye Trac Model 210 infrared scleral reflectance recording device (Applied Science Laboratories, Waltham, MA) was used.

A constant display consisted of three 2° boxes: one box at the center of the screen and two peripheral boxes 10° from fixation on the left and right side. At the beginning of each trial, subjects fixated on a dot that appeared in the middle of the central box. The endogenous cue consisted of an arrowhead that appeared inside the central box and pointed to the left or to the right. The neutral endogenous cue consisted of a double-headed arrow. The exogenous cue consisted of brightening of one of the three boxes. The brightening of the central box was the neutral exogenous cue. The target stimulus in Experiments 1, 2, and 3 was a 1° asterisk that appeared inside one of the peripheral boxes (50% of the trials in each box).

Procedure and Design

Each trial consisted of the sequence presented in Figure 1. The time parameters were chosen to give each orienting mechanism the optimal conditions to affect the subject's behavior. Because the two kinds of cues appeared in each trial, the exogenous cue was presented only after the

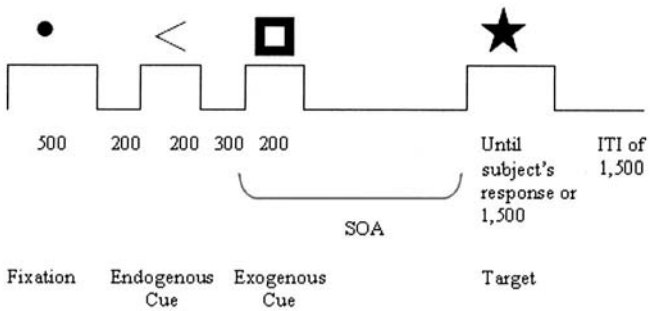

Figure 1. Timeline in milliseconds of stimuli presentation during a typical trial. SOA = stimulus onset asynchrony; ITI = intertrial interval.

endogenous cue had achieved maximal effect (500 ms, according to the findings of Shepherd & Muller, 1989). The target was displayed at one of the randomly selected SOAs relative to the onset of the exogenous cue (the exact value of the SOA between the exogenous cue and the target varied in the various experiments). The target appeared in one of the two peripheral boxes with equal frequency. In the various experiments, the response reflected either a simple RT, a saccade to the target, or a location choice RT in which one key was pressed for a target on the right side of fixation and another for a target on the left side. The effect of the side of the target was checked in the original study. Because it was found that this variable had no effect and did not interact with any other variable, in all of the present experiments, the data were collapsed across the left and right side: Therefore, this variable does not appear in these analyses.

The validity of the endogenous cue was always 80% (the target appeared at the indicated location with an 80% probability and in the other location with a 20% probability). The exogenous cue did not have any predictive value, and the brightening appeared randomly at each one of the three boxes (one third of the trials at each box). The various trial types were presented randomly during the session.

Each subject participated in only one of the experiments. In Experiment 1, subjects were tested in two sessions on different days. Each session always started with 40 trials of practice. Subjects were instructed about cue validities and were encouraged to keep fixation, pay attention to the endogenous cue, ignore the exogenous cue, and respond as fast as possible but not before the target appeared. During practice, subjects received feedback from the experimenter about their success in avoiding eye movements.

For responses made too soon (less than 100 ms from the appearance of the target), an error message was displayed, the trial was discarded from analysis, and a similar trial was added at the end of the experiment so that the total number of trials for each condition remained constant. These anticipatory responses were made in less than 1% of the trials. In Experiments 2, 3, and 4, which were all based on choice reaction times, only trials with correct responses were analyzed. In Experiments 2 and 3, all subjects had errors in less than 10% of their trials. In Experiment 4, only results from subjects who performed the discrimination task above chance level (less than 50% of trials with errors) were analyzed.

The experimental design in all the experiments was factorial and within subjects. The specific variables and their values are described for each experiment separately.

Experiment 1

This experiment pitted endogenous and exogenous orienting against each other in a simple luminance detection task. In each trial, the subject was presented with a predictive endogenous cue followed by a nonpredictive exogenous cue. We were interested in the capacity of each cue to orient attention under various validity conditions of the other cue. Note that in some trials, the two cues oriented attention to the same location, and, in others, attention was oriented to different locations. The target onset was 0, 100, or 750 ms after the onset of the exogenous cue. The motivation for the different SOAs was as follows:

1. An SOA of 0 ms created a condition similar to the abrupt onset used by Yantis and Jonides (1990). The difference between the current design and their design was that here the exogenous cue and the target were separate stimuli. In addition, the design of the present experiment made it possible to examine additional conditions, such as the effect of invalid and neutral exogenous cues.

2. An SOA of 100 ms was selected to be optimal for producing facilitation at the location of the exogenous cue.

3. An SOA of 750 ms was selected so that IOR would appear (Posner & Cohen, 1984). One interesting question was whether IOR could be eliminated or reduced by endogenous allocation of attention to that location.

Method

Apparatus, stimuli display, and design were described in the General Method. Specific SOAs were 0, 100, and 750 ms. Four factors, side (left, right), endogenous cue validity (valid, neutral, invalid), exogenous cue validity (valid, neutral, invalid), and SOA (0 ms, 100 ms, 750 ms), were manipulated factorially within subjects. Each subject was tested in two 1-hr sessions, each session consisting of four 219-trial blocks. The first 3 trials in each block served as buffer trials. In total, subjects were presented with 1,728 trials to be used for analysis: For each combination of endogenous cue validity, exogenous cue validity, SOA, and side, there were at least 16 trials (for conditions in which the endogenous cue was valid, there were 64 trials in each, because the endogenous validity was, as mentioned before, 80%).

Twenty-four undergraduates from the Department of Behavioral Sciences at Ben-Gurion University of the Negev participated in the experiment in partial fulfillment of a course requirement. They all had normal or corrected to normal vision. One subject was excluded from analysis because he did not succeed in maintaining fixation (avoiding eye movements) during the experiment.

Results

For each subject, median reaction times were calculated for each experimental condition. Mean reaction times for the various conditions are presented in Table 1.

A three-way repeated measures analysis of variance (ANOVA; endogenous cue validity, exogenous cue validity, and SOA) revealed two significant main effects: (a) SOA, $F(2, 44) = 43.0$, $MSE = 1{,}190$, $\eta_p^2 = .66$, $p < .01$; and (b) endogenous cue validity, $F(2, 44) = 31.9$, $MSE = 403$, $\eta_p^2 = .59$, $p < .01$. The exogenous cue did not have a significant main effect, but there was an interaction between it and SOA, $F(4, 88) = 107.0$, $MSE = 357$, $\eta_p^2 = .83$, $p < .01$. There was also a small-scale interaction between the endogenous cue validity and SOA, $F(4, 88) = 3.4$, $MSE = 130$, $\eta_p^2 = .13$, $p < .05$, which was due to the neutral condition and was not significant when the neutral condition was not included. There

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Table 1
Mean Reaction Times (in Milliseconds) and Standard Errors Across Subjects for the Different Conditions in Experiment 1

	End-valid			End-neutral			End-invalid		
SOA (ms)	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I
0									
M	366	390	380	377	406	388	387	413	397
SE	11.4	12.0	13.0	10.7	11.6	12.3	12.3	10.8	12.6
100									
M	339	360	359	339	369	369	352	374	373
SE	9.96	11.3	11.5	10.9	12.5	12.2	12.0	11.6	11.1
750									
M	396	338	350	394	346	354	403	352	366
SE	12.4	11.6	13.3	12.6	12.0	13.0	12.4	12.7	14.1

Note. End = endogenous; Exo = exogenous; V = valid; N = neutral; I = invalid; SOA = stimulus onset asynchrony.

was no significant interaction between cue types ($p = .10$) and no triple interaction ($F < 1$).

Both cues produced effects that did not interact with one another. The endogenous cue showed its typical validity effect irrespective of the exogenous condition, and the exogenous validity showed its typical validity effect irrespective of the endogenous condition, as can be seen in Figures 2, 3, and 4. Note that each cue had its typical effect even though, at the same time, the other cue was also affecting orienting. The endogenous cue had a facilitatory effect across all the SOAs; the costs + benefits of this cue was approximately 20 ms at the shortest SOA and decreased to 12 ms in the others.

For the exogenous cue, the typical biphasic pattern appeared; the advantage of the cued location grew from an SOA of 0 ms to an SOA of 100 ms; at an SOA of 750 ms, this advantage was replaced by IOR (a negative validity effect). Analyses of the simple main effects of the interaction between validity and SOA showed that at an SOA of 0 ms, there was a significant effect of the exogenous cue, $F(1, 22) = 17.0$, $MSE = 264$, $\eta_p^2 = .43$, $p < .01$. At an SOA of 100 ms, the benefits and costs were the greatest, $F(1, 22) = 43.9$, $MSE = 433$, $\eta_p^2 = .66$, $p < .01$. At an SOA of 750 ms, the exogenous cue effect (IOR) was significant, $F(1, 22) = 91.5$, $MSE = 622$, $\eta_p^2 = .8$, $p < .01$.

Discussion

The results of the first experiment demonstrate separate effects for each type of orienting cue. Both types of cues had their typical effects independent of each other. The differences in the time course of the endogenous and exogenous effects can be easily seen in Figures 2 and 3. The endogenous orienting develops benefits at the cued location and costs at the uncued location (Jonides, 1981; Posner, 1980; Posner & Cohen, 1984), which remain stable over a wide range of SOAs. The exogenous orienting, in contrast, develops two different stages: first shorter RTs at the cued location than at the uncued location, and then the opposite is found, longer RTs at the cued location than at the uncued one (Maylor, 1985; Maylor & Hockey, 1985; Posner & Cohen, 1984). These two stages are reflected in the fact that the exogenous cue produced an interaction between validity and SOA. At an SOA of 0 ms, there was already an effect for the exogenous cue. This finding contradicts those of Yantis and Jonides (1990), who, as mentioned, found that an abrupt onset appearing 200 ms after the endogenous cue did not have any distractive effect. However, in their paradigm, the abrupt onset was both an exogenous cue and a target, so as a cue it was always valid. In our design, we compare the valid condition and the invalid one and can see that even at an SOA of 0 ms there is

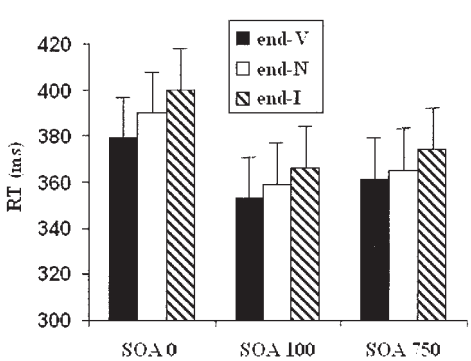

Figure 2. Mean simple reaction times and standard errors (shown by the error bars) in the different conditions of the endogenous cue at various stimulus onset asynchronies (SOAs; in milliseconds) in Experiment 1. RT = reaction time; end-V = valid; end-N = neutral; end-I = invalid. Standard errors range between 18.48 and 22.92 ms.

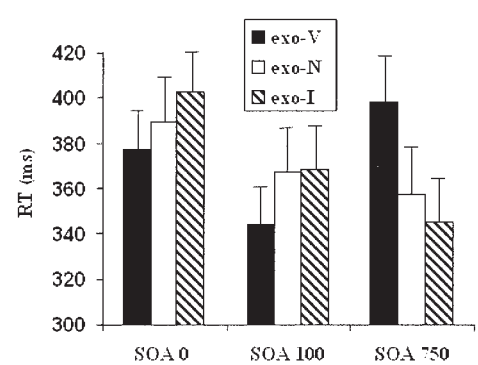

Figure 3. Mean simple reaction times and standard errors (shown by the error bars) in the different conditions of the exogenous cue at various stimulus onset asynchronies (SOAs; in milliseconds) in Experiment 1. RT = reaction time; exo-V = valid; exo-N = neutral; exo-I = invalid. Standard errors range between 18.72 and 21.95 ms.

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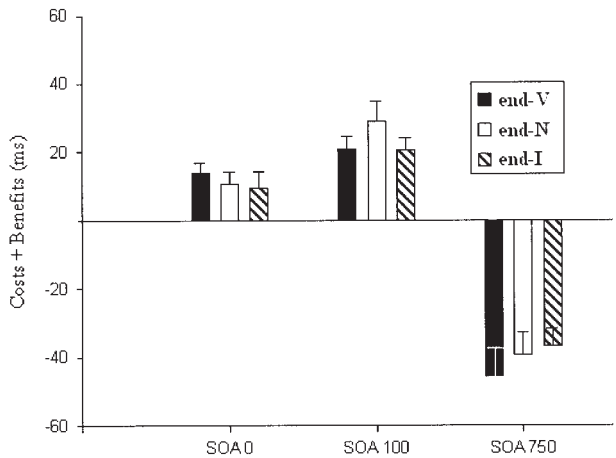

Figure 4. Exogenous cue costs + benefits and standard errors (shown by the error bars) at the different stimulus onset asynchronies (SOAs; in milliseconds) and conditions of the endogenous cue in Experiment 1. end-V = valid; end-N = neutral; end-I = invalid. Standard errors range between 2.7 and 6.7 ms.

a difference between them. At an SOA of 100 ms, there was still a significant effect of the exogenous cue. Of special interest is the finding that the IOR at the longest SOA (750 ms) is the same regardless of whether the target appears at an expected or unexpected location.

Comparison of Figures 2 and 3 reveals that at an SOA of 100 ms, the effects of both types of cues are of similar direction. At this SOA, our results are consistent with those of Warner et al. (1990). In their study, no difference was found between the endogenous and exogenous effect sizes. As we mentioned in the introduction, they used SOAs shorter than 150 ms. Warner et al. concluded from their study that there is no essential difference between the two orienting modes and that they both trigger the same mechanism. We disagree with this conclusion and believe that our results show that to reveal the differences between the cue effects, it is essential to use a full range of SOAs, including short and long ones.

In summary, Experiment 1 showed that both types of cues could affect detection and that the temporal patterns were similar to the effects typically found when each type of cue was studied separately. The IOR generated by exogenous cues was independent of the effect of endogenous orienting.

To determine whether the trend ($p = .1$) observed in Experiment 1 is replicable and general, we conducted Experiments 2 and 3 using the same paradigm but with different response requirements. In Experiment 2, a choice localization task was used in which subjects indicated the location (left or right) of the target by a keypress response. Experiment 3 also used a choice localization task, but participants made an eye movement toward the target.

Experiment 2

Several studies have found that the emergence of IOR depends on task demands and that there are differences between detection and discrimination tasks in the time course of exogenous orienting and IOR (Lupianez, Milan, Tornay, Madrid, & Tudela, 1997; Lupianez & Milliken, 1999; Terry, Valdes, & Neill, 1994). These kinds of differences have also been found between location discrimination and identity discrimination (Pratt, Kingstone, & Khoe, 1997). In light of these results, we wanted to know whether the results of Experiment 1 would also hold for tasks other than simple detection tasks. Therefore, we slightly modified our paradigm to be a location-discrimination task in which we measured choice reaction time.

Method

Apparatus, stimuli, display, and design were the same as in Experiment 1, with three exceptions: (a) The specific SOAs between the exogenous cue and target were 100, 200, 300, and 750 ms; (b) each subject was tested in a 1-hr session that consisted of five 144-trial blocks; and (c) responses were a choice of left or right, according to the location of the target. The responses were made with the index and middle fingers of the preferred hand. The experimental design was a three-way factorial within-subjects design, where the factors were endogenous validity (valid, neutral, invalid), exogenous validity (valid, neutral, invalid), and SOA (100 ms, 200 ms, 300 ms, 750 ms).

Twenty-seven undergraduates from the Department of Behavioral Sciences at Ben-Gurion University of the Negev participated in the experiment in partial fulfillment of a course requirement. They all had normal or corrected to normal vision.

Results

For each subject, median reaction times were calculated for each experimental condition and are presented in Table 2. As can be seen, reaction times in this task were somewhat longer than in the previous simple reaction task.

A three-way repeated measures ANOVA (endogenous cue validity, exogenous cue validity, and SOA) revealed three significant main effects.

1. For SOA, $F(3, 75) = 126.6$, $MSE = 1{,}714$, $\eta_p^2 = .83$, $p < .01$. Shorter RTs accompanied increases in SOA, an effect that is commonly found in this kind of experiment, which can be due to the increasing certainty of the subject that a target is going to appear as the interval gets longer or, as recently suggested by Los and Van Den Heuvel (2001), due to trace conditioning effects from the preceding trial.

2. For endogenous cue validity, $F(2, 50) = 14.8$, $MSE = 3{,}251$, $\eta_p^2 = .37$, $p < .01$, showing shortest RTs in the valid trials (452 ms) and longer RTs in the neutral (470 ms) and the invalid (476 ms) conditions. Planned comparisons showed significant differences between valid and invalid conditions and between valid and neutral conditions but only a marginally significant effect between invalid and neutral conditions: $F(1, 25) = 22.3$, $MSE = 4{,}007$, $\eta_p^2 = .47$, $p < .01$; $F(1, 25) = 13.0$, $MSE = 3{,}766$, $\eta_p^2 = .34$, $p < .01$; $F(1, 25) = 3.0$, $MSE = 1{,}980$, $\eta_p^2 = .1$, $p = .09$, for the three comparisons, respectively.

3. For exogenous cue validity, $F(2, 50) = 46.4$, $MSE = 2{,}042$, $\eta_p^2 = .64$, $p < .05$. The interaction between exogenous cue validity and SOA was significant, $F(6, 150) = 16.7$, $MSE = 1{,}014$, $\eta_p^2 = .4$, $p < .05$. As can be

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Table 2
Mean Reaction Times (in Milliseconds) and Standard Errors Across Subjects for the Different Conditions in Experiment 2

	End-valid			End-neutral			End-invalid		
SOA (ms)	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I
100									
M	454	482	498	458	496	521	481	511	518
SE	17.9	17.6	17.2	15.4	19.0	16.2	20.4	18.6	16.7
200									
M	456	486	450	462	506	511	478	504	522
SE	15.0	18.6	17.2	17.0	17.0	18.7	18.0	18.4	18.6
300									
M	407	444	452	431	464	475	422	471	482
SE	16.3	19.0	16.3	18.0	17.9	17.6	16.2	19.8	18.1
750									
M	418	407	418	444	433	435	449	436	437
SE	15.5	17.3	17.7	18.9	19.0	20.1	22.1	18.0	20.1

Note. End = endogenous; Exo = exogenous; V = valid; N = neutral; I = invalid; SOA = stimulus onset asynchrony.

seen in Table 2, there was a trend toward IOR; however, it was not fully apparent at 750-ms SOA: Although the exogenous-valid trials were almost significantly slower than the exogenous-neutral ones, $F(1, 25) = 4.0$, $MSE = 1{,}261$, $\eta_p^2 = .14$, $p = .055$, they were not significantly slower than the exogenous-invalid ones, $F(1, 25) = 1.0$, $MSE = 1{,}744$, $\eta_p^2 = .04$, $p = .33$.

Discussion

The critical finding of this experiment is that there was no interaction between cue types ($F < 1$). Both endogenous cues and exogenous cues exerted independent effects on discrimination. Whereas endogenous orienting confers benefits at the cued location and costs at the uncued location (Jonides, 1981; Posner, 1980; Posner & Cohen, 1984), which remain stable over a wide range of SOAs, exogenous orienting has two stages of development: First there is a shorter RT at the cued location than at the uncued location, and then the opposite is found, a longer RT at the cued location than at the uncued one (IOR; Maylor, 1985; Maylor & Hockey, 1985; Posner & Cohen, 1984). These two stages are reflected in the fact that the exogenous cue produced an interaction between validity and SOA. The typical effect of each cue was obtained across the different conditions of the other cue, even though in some of the trials the cues completely contradicted one another.

In comparison with the timing of IOR emergence in Experiment 1, IOR in Experiment 2 begins to emerge later. Although there is a hint of IOR, manifested as a decrease in the benefits of a valid exogenous cue as the SOA increases, this trend does not produce a reliable difference between valid and invalid exogenous cue conditions, even at the longest SOA. The delay in the emergence of IOR is consistent with previous reporting in cases of choice reaction times (Cheal & Chastain, 2002a, 2002b; Lupianez et al., 1997; Lupianez & Milliken, 1999), even though here the discrimination required was only of the location of the target.

Experiment 3

In Experiment 3, we examined whether the relation between endogenous and exogenous orienting might be different for covert versus overt orienting. This question is interesting, especially because qualitative differences between manual responses and saccadic movements in IOR (which is, as has been mentioned, one of the critical characteristics of exogenous orienting) have been reported recently (Abrams & Pratt, 2000). While acknowledging that this is still an open question, Berlucchi et al. (2000) favored the possibility that "cue-induced inhibition can be suppressed by a volitional overt orienting to the cued location, and by the maintenance of both attention and eye-gaze at this location" (p. 659).

Method

Apparatus, stimuli display, and design were the same as in Experiment 1, with four exceptions:

1. To shorten our procedure, we focused on the short SOAs (100 and 250 ms).
2. Because both SOAs were short, we increased the number of trials by 25% by adding catch trials (i.e., trials in which there was no target and no response was required) to ensure that the subjects detect the target before responding.
3. Each subject was tested in two 1-hr sessions, and each session consisted of two 260-trial blocks.
4. Responses were saccades toward the target.

An Eye-Trac Model 210 device measured saccadic latencies. The device was calibrated at the beginning of each session. The Eye-Trac 210 device was interfaced with the computer through an analog device (Greg Laird Associates, Portland, OR) that produced a velocity (first derivative) transformation of the Eye-Trac signal. The gain of this device was adjusted to send a response through the game port when eye velocity exceeded 60°/s.

The experimental design was a four-way factorial within-subjects design. The factors were side (left, right), endogenous cue validity (valid, neutral, invalid), exogenous cue validity (valid, neutral, invalid), and SOA (100 ms, 250 ms).

Sixteen undergraduates from the University of California, Berkeley, participated in the experiment in partial fulfillment of a course requirement. They all had normal or corrected to normal vision.

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Results

For each subject, median saccadic reaction times were calculated for each experimental condition (see Table 3). A three-way repeated measures ANOVA (endogenous cue validity, exogenous cue validity, and SOA) revealed a significant main effect of the endogenous cue, $F(2, 30) = 4.6$, $MSE = 1{,}157$, $\eta_p^2 = .24$, $p < .01$, revealing that RT was shorter for valid (280 ms) than for invalid trials (313 ms). Saccade latencies were shorter, $F(1, 15) = 39.1$, $MSE = 2{,}250$, $\eta_p^2 = .72$, $p < .01$, and the benefits of a valid exogenous cue decreased at the 250-ms SOA, $F(2, 30) = 5.6$, $MSE = 2{,}296$, $\eta_p^2 = .27$, $p < .01$. This interaction suggests that IOR may be starting to emerge at the SOA of 250 ms. However, the difference between the exogenous-valid trials and the exogenous-invalid trials at this SOA was not significant. There was no interaction between the two cue types ($p = .27$) and no three-way interaction ($F < 1$).

Discussion

In Experiment 3, we found separate and typical effects of endogenous and exogenous cues. Endogenous cues produce a facilitation effect in which RTs for valid trials are faster than RTs for invalid trials, regardless of the SOA. In contrast, exogenous cues interact with SOA in such a way that the initial facilitation found at short SOAs decreases rapidly, suggesting that IOR is beginning to emerge. These results show that our general conclusions concerning the independence of exogenous and endogenous covert orienting can be generalized also to overt orienting. These results partly contradict the predictions made by Berlucchi et al. (2000), who, as mentioned previously, predicted that a volitional overt orienting to the cued location would suppress cue-induced inhibition, whereas covert orienting would not. According to such a prediction, endogenously preparing a saccade in response to an endogenous cue should affect the validity effect of the exogenous cue that is presented in the same trial, leading to an interaction between endogenous and exogenous cues. However, this was not found. Moreover, we should have found less inhibition of the exogenous cue (smaller IOR) in the endogenous-valid condition. There is a small hint toward this direction in the group means; however, as mentioned in the *Results* section, this was not significant. What we did obtain was a strong and characteristic effect of each cue, including a characteristic interaction between the exogenous cues and SOA.

Saccadic responses were found to be faster than the manual responses obtained in Experiments 1 and 2. This seems to be consistent with previous findings from experiments in which saccadic and manual responses were measured in the same paradigm (Taylor & Klein, 2000). Note that although the difference between valid and invalid RTs at the 250-ms SOA was not significant (RTs for invalid cues were 11 ms faster than those for valid cues), a crossover was evident. Hence, IOR seems to appear earlier with saccadic responding than with manual responses, which is consistent with previous reports (Maylor, 1985). Although the mean RTs, presented in Table 3, seem to show a trend for a smaller IOR in the endogenous-valid condition, this effect was far from significant.

Discussion of Experiments 1–3

Our aim in this research was to examine whether there are two separate mechanisms of orienting attention that can act simultaneously without interfering with one another. We pitted endogenous and exogenous orienting against each other. Both cues appeared in every trial and were manipulated orthogonally. The uniqueness of the present research is that endogenous and exogenous orienting were manipulated at the same time under optimal conditions.

Our results show that each kind of cue produces independent effects with either manual (simple or choice) or saccadic responses. We found that the two mechanisms developed their characteristic effects even when they were in conflict. Moreover, no significant interaction was observed between the two cue types in any of the three experiments. In each case, the characteristic patterns of the cues were obtained, including the interaction between exogenous cue validity and SOA, indicating that IOR impairs responses to targets at actively attended locations as well as when they appear at an unexpected location.

These results suggest that there are two independent systems, each one having its own characteristics and its own at least partially independent resource pool. Deployment of one kind of attention to a certain location does not prevent or even interfere with the ability of the second system to deploy attention. It seems adaptive that even when voluntary attention is focused at a certain location, some resources would still be available to respond to an abrupt external stimulus (e.g., an approaching predator). Therefore, the exogenous mechanism should have at least some attention resources available, no matter how much attention is being voluntarily deployed. However, one needs to be able to concentrate on

Table 3
Saccadic Mean Reaction Times (in Milliseconds) and Standard Errors Across Subjects for the Different Conditions in Experiment 3

	End-valid			End-neutral			End-invalid		
SOA (ms)	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I
100									
M	261	308	308	291	328	319	289	314	311
SE	12.0	9.4	6.3	14.2	8.1	8.3	14.0	13.8	7.4
250									
M	258	267	269	276	278	269	280	275	242
SE	14.3	15.6	9.7	10.4	14.2	15.5	13.8	13.3	19.9

Note. End = endogenous; Exo = exogenous; V = valid; N = neutral; I = invalid; SOA = stimulus onset asynchrony.

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a task without being constantly interrupted by external stimulation; therefore, the endogenous mechanism should have at least some attention resources, even if attention is being reflexively summoned.

In this study, the exogenous cue was presented after the endogenous orienting effect fully developed. Even in this case, the exogenous cue did not affect its efficiency at all, and neither was the exogenous cue prevented from producing its own, sometimes even contradicting, effect. Although previous findings from our lab (Berger & Henik, 2000) suggested that some kind of interference could be found when the cues were presented in a reversed order, that is, an endogenous cue summoned attention after IOR already began to develop, the interference with IOR development (i.e., a reduction in the effect) was observed only in the nasal hemifield. Even in this restricted case, IOR was significant.

Still, it seems adaptive to be able to use resources flexibly by the different mechanisms according to the situational demands. It is possible that the experimental conditions of the previous experiments did not create high demand for cognitive resources and that some interference between the two systems might occur if more cognitive resources were required under conditions of greater perceptual demand. For example, if there were high demands for endogenous attention, moving resources to cope with these demands could hinder effects of the exogenous orienting mechanism that until now (Experiments 1–3) did not reveal interference due to endogenous orienting. This notion fits the results showing that IOR is not completely eliminated but just deferred when there is a change from a detection to a discrimination task (Lupianez et al., 1997).

Experiment 4

The last experiment was designed to test the prediction that an interaction between the two orienting mechanisms will arise when the perceptual task is more demanding of endogenous attention. Specifically, in a high-demand situation, we expect that the exogenous cue effect will be smaller when it contradicts the endogenous orienting, that is, in the endogenous-invalid condition. In contrast, when the demands are low, we expect that, as in the previous experiments, the cue effects will not interact with one another.

Each subject was tested in two separate sessions, each session with a different discrimination task. The tasks were identical except for the targets that were to be discriminated. In the difficult task, the discrimination was between two similar letters: *O* and *Q*. In the easy task, the discrimination was between the letter *P* and an asterisk (*).

Method

Apparatus, stimuli display, and design were described in the General Method. Specific SOAs were 100, 200, 300, and 1,000 ms. Each subject was tested with a difficult discrimination task (*O* vs. *Q*) and with an easy discrimination task (*P* vs. *). Half of the subjects participated in the difficult task in their first session and the easy one in their second session, and half of them performed the tasks in a reverse order. For each task, the response key corresponding to each target was balanced across subjects.

We used a within-subject factorial design with the following four factors: endogenous cue validity (valid, neutral, invalid), exogenous cue validity (valid, neutral, invalid), SOA (100 ms, 200 ms, 300 ms, 1,000 ms), and target location (left, right). Consistent with our method in the previous experiments, the side or location was not included in the analysis, although it was fully balanced within the design. Each subject was tested in two 1-hr sessions, each one consisting of 1,032 trials.

Twenty-six undergraduates from the Department of Behavioral Sciences at Ben-Gurion University of the Negev participated in the experiment in partial fulfillment of a course requirement. They all had normal or corrected to normal vision.

Because we used a difficult discrimination task in this experiment, accuracy was analyzed, and data from subjects having too low accuracy were excluded from the analysis. On the basis of this criterion, the data of 3 subjects who were not above chance in all the conditions were excluded. Mean error percentage was below 40% for each one of the remaining subjects.

Results

For each subject, median reaction times were calculated for each experimental condition. Because target side was not found to have any effect in the previous experiments, the analysis was carried out across the position of the target.

Error percentages were submitted to a four-way repeated measures ANOVA: task difficulty (difficult, easy), endogenous cue validity (valid, invalid, neutral), exogenous cue validity (valid, invalid, neutral), and SOA (100 ms, 200 ms, 300 ms, 1,000 ms). The only effect that was found was for task difficulty, $F(1, 22) = 60.9$, $MSE = 1{,}287$, $\eta_p^2 = .734$, $p < .001$, as there were more errors in the difficult task (16%) than in the easy task (2.25%). Error percentages and standard deviations in the different experimental conditions can be seen in Table 4.

Mean reaction times for the various conditions across subjects are presented in Table 5. A four-way repeated measures ANOVA with task difficulty (difficult, easy), endogenous cue validity (valid, invalid, neutral), exogenous cue validity (valid, invalid, neutral), and SOA (100 ms, 200 ms, 300 ms, 1,000 ms) was conducted. This analysis revealed significant main effects of all the variables: $F(1, 22) = 85.3$, $MSE = 105{,}527$, $\eta_p^2 = .79$, $p < .01$; $F(2, 44) = 14.8$, $MSE = 2{,}307$, $\eta_p^2 = .4$, $p < .01$; $F(2, 44) = 14.0$, $MSE = 1{,}741$, $\eta_p^2 = .39$, $p < .01$; and $F(3, 66) = 26.4$, $MSE = 4{,}816$, $\eta_p^2 = .54$, $p < .01$, for task difficulty, endogenous cue validity, exogenous cue validity, and SOA, respectively. Moreover, there was a significant interaction between the endogenous cue validity and task difficulty, $F(2, 44) = 11.8$, $MSE = 1{,}032$, $\eta_p^2 = .34$, $p < .01$, showing an overall smaller endogenous effect in the easy task than in the difficult one. There were two interactions with SOA: Task Difficulty × SOA, $F(3, 66) = 3.6$, $MSE = 2{,}325$, $\eta_p^2 = .14$, $p < .01$, and Exogenous Cue Validity × SOA, $F(6, 132) = 6.7$, $MSE = 1{,}342$, $\eta_p^2 = .23$, $p < .01$. Moreover, there was an interaction between the four variables: Task Difficulty × Endogenous Cue Validity × Exogenous Cue Validity × SOA, $F(12, 264) = 1.9$, $MSE = 1{,}369$, $\eta_p^2 = .07$, $p < .05$; therefore, further analyses were carried out separately for each level of task difficulty.

Easy discrimination task. There were simple effects of SOA, $F(3, 66) = 67.3$, $MSE = 1{,}471$, $\eta_p^2 = .97$, $p < .01$, and exogenous cue validity, $F(2, 44) = 14.6$, $MSE = 662$, $\eta_p^2 = .39$, $p < .01$, and a marginal simple effect of endogenous cue validity, $F(2, 44) = 14.0$, $MSE = 979$, $\eta_p^2 = .12$, $p = .054$. Moreover, there was an SOA × Exogenous Cue Validity interaction, $F(6, 132) = 7.4$, $MSE = 797$, $\eta_p^2 = .25$, $p < .01$, showing a classic crossover pattern

Table 4
Mean Error Percentages and Standard Errors Across Subjects for the Different Conditions in Experiment 4

	End-valid			End-neutral			End-invalid		
SOA (ms)	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I
				Difficult task					
100									
M	16.0	15.8	15.4	17.5	19.1	12.2	16.9	15.4	16.7
SE	1.9	2.2	2.0	2.7	2.8	2.3	2.8	2.8	2.9
200									
M	16.6	16.9	17.5	20.1	16.2	16.8	14.2	16.2	15.0
SE	2.3	2.0	2.1	3.1	3.1	3.2	2.8	2.5	2.8
300									
M	14.8	15.4	16.5	14.0	12.3	19.0	17.0	15.1	15.0
SE	1.9	1.9	2.2	2.1	2.9	2.5	2.5	3.1	2.6
1,000									
M	15.6	16.7	15.4	16.3	15.4	16.0	16.9	15.3	15.4
SE	1.7	2.4	1.8	3.3	2.9	2.6	3.6	2.6	2.7
				Easy task					
100									
M	2.9	2.1	2.5	1.8	1.5	1.1	1.4	1.8	2.2
SE	0.7	0.5	0.7	0.7	0.9	0.6	0.7	0.9	0.8
200									
M	2.2	2.7	1.6	2.6	3.4	1.4	3.6	2.2	2.5
SE	0.4	0.6	0.6	1.0	1.1	0.7	1.5	0.9	1.1
300									
M	1.8	2.3	2.7	3.9	3.6	2.2	3.6	1.5	1.8
SE	0.5	0.6	0.6	1.3	1.0	0.8	1.2	0.9	0.7
1,000									
M	2.1	1.6	3.0	1.8	2.2	3.3	0.7	2.5	1.8
SE	0.4	0.7	0.7	0.9	1.1	1.1	0.5	1.3	0.9

Note. End = endogenous; Exo = exogenous; V = valid; N = neutral; I = invalid; SOA = stimulus onset asynchrony.

with RTs that were faster in the valid than in the invalid trials for the first three SOAs, $F(1, 22) = 21.9$, $MSE = 628$, $\eta_p^2 = .5$, $p < .01$; $F(1, 22) = 4.6$, $MSE = 894$, $\eta_p^2 = .17$, $p < .05$; and $F(1, 22) = 5.4$, $MSE = 1{,}122$, $\eta_p^2 = .2$, $p < .05$, for SOAs of 100 ms, 200 ms, and 300 ms, respectively; and RTs that were faster in the invalid than in the valid trials (IOR) for the long SOA, $F(1, 22) = 10.3$, $MSE = 628$, $\eta_p^2 = .32$, $p < .01$. No other effects were significant or even marginally significant, including the interaction between the cues ($p = .26$).

Difficult discrimination task. There were simple effects of all three variables: for SOA, $F(3, 66) = 6.5$, $MSE = 5{,}671$, $\eta_p^2 = .23$, $p < .01$; for exogenous cue validity, $F(2, 44) = 6.7$, $MSE = 2{,}452$, $\eta_p^2 = .23$, $p < .01$; and for endogenous cue validity, $F(2, 44) = 18.4$, $MSE = 2{,}361$, $\eta_p^2 = .45$, $p < .01$. Moreover, there was an SOA × Exogenous Cue Validity interaction, $F(6, 132) = 2.5$, $MSE = 1{,}854$, $\eta_p^2 = .1$, $p < .05$, showing smaller differences between the RTs in valid and invalid trials as the SOA got longer; however, there was no crossover of the effect at the longest SOA, that is, no full IOR. Planned comparisons showed that the valid trials were faster than the invalid trials only for the first two SOAs: There was a marginal difference of 18 ms for the 100-ms SOA, $F(1, 22) = 3.9$, $MSE = 2{,}761$, $\eta_p^2 = .15$, $p = .059$; a difference of 30 ms for the 200-ms SOA, $F(1, 22) = 12.8$, $MSE = 2{,}473$, $\eta_p^2 = .37$, $p < .01$; a nonsignificant difference of 7 ms for the 300-ms SOA, $F < 1$; and a nonsignificant difference of 3 ms for the 1,000-ms SOA, $F < 1$. However, the interaction between the exogenous cue and SOA was modulated by the endogenous cue, as the triple interaction between Endogenous Cue Validity × Exogenous Cue Validity × SOA was significant, $F(12, 264) = 2.1$, $MSE = 1{,}990$, $\eta_p^2 = .08$, $p < .05$. At the 100-ms SOA, both cues had significant effects, $F(2, 44) = 5.2$, $MSE = 1{,}911$, $\eta_p^2 = .19$, $p < .01$ (exogenous cue), and $F(2, 44) = 4.6$, $MSE = 3{,}882$, $\eta_p^2 = .17$, $p < .015$ (endogenous cue), and there was no interaction between them, $F < 1$. At the 200-ms SOA, both cues had significant effects, $F(2, 44) = 8.5$, $MSE = 2{,}200$, $\eta_p^2 = .28$, $p < .01$ (exogenous cue), and $F(2, 44) = 5.3$, $MSE = 2{,}258$, $\eta_p^2 = .19$, $p < .01$ (endogenous cue), and there was no interaction between them, $p = .2$. At the 300-ms SOA, only the endogenous cue had a significant main effect, $F(2, 44) = 6.5$, $MSE = 1{,}736$, $\eta_p^2 = .23$, $p < .01$, and there was an interaction between the cues, $F(4, 88) = 3.0$, $MSE = 2{,}315$, $\eta_p^2 = .12$, $p < .05$. Last, at the 1,000-ms SOA, only the endogenous cue had a marginal main effect, $p = .098$, and there was an interaction between the cues, $F(4, 88) = 2.8$, $MSE = 1{,}714$, $\eta_p^2 = .11$, $p < .05$. Note, however, that the latter interaction was mainly caused by the neutral condition, whereas both valid and invalid endogenous conditions showed a nonsignificant IOR of similar size (~10 ms).

Figure 5 presents the costs + benefits of the exogenous cue at the different SOAs and at the different endogenous cue conditions. Notice that the interaction between the cues is mostly evident at the intermediate SOAs, although it was significant only at the 300-ms SOA.

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Table 5
Mean Reaction Times (in Milliseconds) and Standard Errors Across Subjects for the Different Conditions in Experiment 4

	End-valid			End-neutral			End-invalid		
SOA (ms)	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I	Exo-V	Exo-N	Exo-I
				Difficult task					
100									
M	659	681	682	676	703	686	692	713	713
SE	18.0	16.4	17.0	18.2	20.0	19.2	22.5	22.5	29.7
200									
M	676	692	701	682	720	733	704	729	719
SE	14.4	15.0	17.2	19.0	18.7	23.3	21.6	16.8	19.0
300									
M	656	671	690	699	676	679	688	714	691
SE	15.7	17.9	17.0	26.2	16.0	20.6	22.6	20.4	17.6
1,000									
M	716	690	704	700	723	730	725	712	714
SE	19.4	16.2	18.0	18.1	21.3	20.6	18.0	21.0	18.2
				Easy task					
100									
M	511	541	533	512	545	541	528	550	537
SE	11.7	12.1	11.6	14.0	14.0	14.7	14.7	14.0	12.1
200									
M	548	563	556	553	570	572	556	569	562
SE	12.7	10.2	13.1	13.8	13.7	20.5	13.7	13.2	14.7
300									
M	522	536	531	516	535	538	531	543	531
SE	12.5	11.2	13.3	14.3	10.8	14.0	13.3	12.1	10.5
1,000									
M	584	565	575	590	581	577	582	575	564
SE	12.3	12.3	12.5	12.1	13.4	15.4	12.1	15.7	13.7

Note. End = endogenous; Exo = exogenous; V = valid; N = neutral; I = invalid; SOA = stimulus onset asynchrony.

To further understand the endogenous interference with exogenous orienting and the exogenous interference with endogenous orienting, two additional analyses were carried out on the data of the difficult task: (a) The endogenous cue effect was analyzed separately in the exogenous-valid and -invalid conditions and (b) the Exogenous Cue Validity × SOA interaction was analyzed separately in the endogenous-valid condition and the endogenous-invalid condition. See Figure 6.

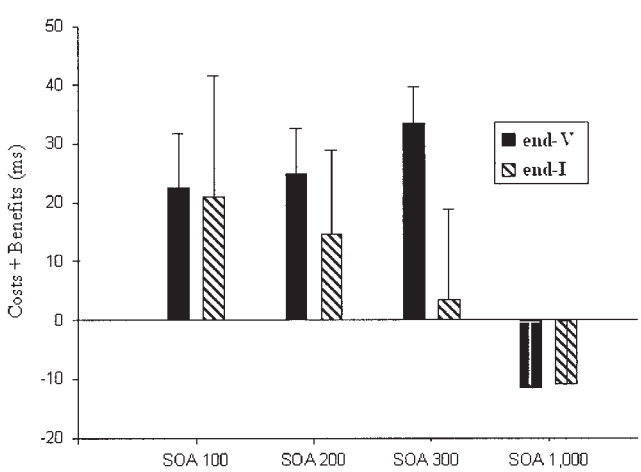

Figure 5. Exogenous cue costs + benefits and standard errors (shown by the error bars) at the different stimulus onset asynchronies (SOAs; in milliseconds) and conditions of the endogenous cue in the difficult task condition of Experiment 4. end-V = valid, end-I = invalid.

Endogenous interference with exogenous orienting. When the endogenous cue was valid, there was a significant overall exogenous cue effect of 18 ms, $F(2, 44) = 10.0$, $MSE = 706$, $\eta_p^2 = .31$, $p < .01$. Moreover, there was an interaction between the exogenous cue and SOA, $F(6, 132) = 5.8$, $MSE = 612$, $\eta_p^2 = .2$, $p < .01$. However, when the endogenous cue was invalid, the overall effect of the exogenous cue was only 7 ms and did not reach significance, nor did its interaction with SOA ($p > .1$ in both cases).

Exogenous interference with endogenous orienting. When the exogenous cue was valid, there was a significant 26-ms endogenous cue effect, $F(2, 44) = 8.4$, $MSE = 1{,}761$, $\eta_p^2 = .28$, $p < .001$. However, when the exogenous cue was invalid, the endogenous cue effect was only 15 ms and was only marginally significant, $F(2, 44) = 2.9$, $MSE = 2{,}104$, $\eta_p^2 = .12$, $p = .06$.

Discussion

Experiment 4 was designed to test the idea that the two orienting systems could interact when there is a high demand for attentional resources. According to this idea, in harder tasks, there would be mutual interference between the attentional mechanisms, whereas in easier tasks, there would not be such interference.

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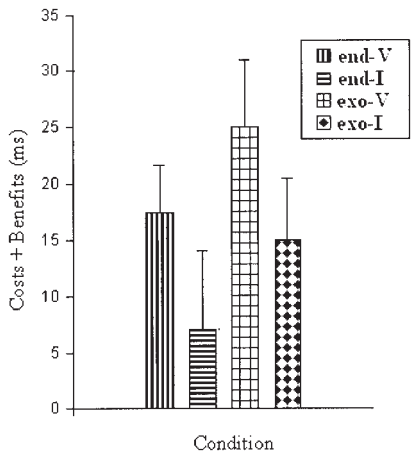

Figure 6. Combined representation of the costs + benefits and standard errors (shown by the error bars) of each cue type of the difficult task condition in Experiment 4. The two left bars represent the exogenous costs + benefits (a) within the endogenous-valid condition (vertical stripes) and (b) within the endogenous-invalid condition (horizontal stripes). The two right bars represent the endogenous costs + benefits (a) within the exogenous-valid condition (grid pattern) and (b) within the exogenous-invalid condition (diamond pattern).

It was first critical to verify that the difficult task was indeed harder and that more attention resources were used in it. Three different findings confirmed that this was the case: (a) Overall RTs were longer in the difficult than in the easy task; (b) overall accuracy was lower in the difficult than in the easy task; and (c) there was a larger effect of endogenous cue validity in the more difficult task, suggesting that more endogenous attention was deployed in the more difficult discrimination task.

We then turned to the question of whether exogenous and endogenous orienting might be more interactive in a more difficult discrimination task. The results were in agreement with our predictions. In a task demanding small amounts of attention resources, endogenous and exogenous orienting had separate and independent effects. When more perceptual resources were required, they interacted; that is, smaller effects were found for the exogenous cue when it contradicted the endogenous deployment of attention, and smaller effects were found for the endogenous cue when it contradicted the exogenous deployment of attention. We suggest that this interaction reflects sharing of resources.

An alternative explanation of the results has been suggested by one of the reviewers of a previous version of this article. It relies on the time course of this interaction (which is evident at the intermediate SOA) and suggests that in the more difficult task, the subjects adopt some idiosyncratic strategy in which after the initial exogenous orienting, they shift their attention back to the center when the endogenous cue contradicts the exogenous one, and they leave it longer at the cued location when the endogenous cue agrees with the exogenous cue (suppressing IOR). Although we cannot completely rule out this possibility, we raise two objections. First, it is not clear why a strategic orienting of attention would affect the exogenous attention instead of the endogenous attention. Second, it is not clear why the subjects would adopt such a strategy only in the hard task and not in the easy one. However, although we are not inclined toward the "attention-shifting strategy" explanation, we do need to consider the time course of the interaction between endogenous and exogenous attention. As shown in Figure 5, the interaction is more evident at the intermediate SOAs (although it was significant only at the 300-ms SOA) and, in fact, there was no interaction between the cues at the extreme SOAs. This may imply that at a short SOA, endogenous and exogenous orienting have separate effects, as we saw in all the previous experiments and in the easy task. At this SOA, the exogenous cue reflexively triggers orienting of attention, and this orienting is not affected by endogenous orienting. In addition, at this SOA, the endogenous cue has a significant effect. It should be kept in mind that the timing of the target appearance relative to the endogenous cue was long enough to enable full development of its effect. However, at the longest SOA, again, there was no interaction between the cues. How can we explain this? An exogenous cue seems to be powerful enough to evoke a fast and reflexive orienting of exogenous attention, as Yantis and Jonides's (1990) abrupt onset data demonstrated. At short SOAs, this orienting does not compete and does not interfere with endogenous orienting. At long SOAs, the inhibitory IOR process seems to be inexorable (see also Berger & Henik, 2000). So far, the idea of competition for resources does not seem to fit with the data. However, there was a clear competition between exogenous and endogenous orienting in this experiment, and, exactly as predicted, it appeared only in the hard task. This competition appeared at the intermediate SOAs, which are the transition time between the phases of the exogenous effect. At this time, facilitation usually decays and is superceded by IOR. The postponement of IOR and the need for facilitatory attentional resources can be related to the resource requirements of the task. There is evidence in the literature that IOR is affected by the difficulty of the discrimination task (Cheal & Chastain, 1999; Lupianez, Milliken, Solano, Weaver, & Tipper, 2001). Moreover, it has been specifically suggested that "easier discriminations may allow more IOR than more difficult discriminations because they take less attentional capacity" (Cheal & Chastain, 1999, p. 386).

Reaction times in this experiment were markedly longer than in all the previous experiments, even in the easy task. However, this should not be surprising given the differences between the tasks used in the different experiments. Manual responses were collected in two experiments: The task was a simple detection task in Experiment 1, and it was a location discrimination one in Experiment 2. These tasks seem to be easier than the discrimination between two stimuli, as in Experiment 4, even when this discrimination is as easy as the one between an asterisk and a letter.

General Discussion and Conclusions

In four experiments, we manipulated endogenous and exogenous cuing simultaneously and orthogonally under conditions that optimized the effects of each on performance. The results showed that each orienting mechanism developed its typical effect independent of the other one. This was true for simple detection (Experiment 1), localization (Experiment 2), and saccadic responses (Experiment 3). There was no interaction between the cue effects in any of these experiments, nor in Experiment 4 (easy condition) when we used choice RT in an identification task in which the discrimination was not difficult. In contrast, Experiment 4 revealed mutual interference between cue effects when the task was more demanding. Endogenous interference with exogenous orienting was found during the transition between the facilitatory

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phase and IOR, but it did not prevent the eventual appearance of IOR.

We conclude that exogenous and endogenous orienting are mediated by dissociable mechanisms. Because this conclusion is based on the lack of an interaction and might thus be vulnerable to lack of statistical power, we conducted a meta-analysis of the interaction across the four experiments, pooling the *z*s of the interactions and dividing by the square root of *x* (Rosenthal & Rosnow, 1991), and confirmed a nonsignificant interaction ($p = .8289$). Moreover, because medians are sometimes subject to biases when cell sizes are relatively small (Miller, 1988; Van Selst & Jolicoeur, 1994), we ran the analyses of all four experiments using means instead of medians and confirmed the lack of an interaction between exogenous and endogenous cues ($F < 1$ in all four cases).

Berlucchi et al. (2000) have also examined the relation between endogenous and exogenous orienting of attention and showed that volitional covert orienting to the cued location can suppress cue-induced inhibition. We believe our results complement their findings and extend them in several aspects:

1. They show that the independence between the systems can be shown even in more restricted situations. Berlucchi et al. (2000) manipulated endogenous orienting in blocks by instructing the subjects to focus their attention at a certain location during the whole block. In contrast, we manipulated endogenous orienting in each trial.

2. The present results show that the independence between the systems can also be found with saccade response.

3. Whereas Berlucchi et al. (2000) only tested whether endogenous orienting could affect exogenous orienting, we demonstrated independence for both modes of orienting.

The relationship between voluntary and reflexive attention has been considered in several different models:

1. *One mechanism, two modes of action*: There is only one orienting mechanism that can be accessed in two different ways (Jonides, 1981; Posner, 1980).

2. *Two modes of action sharing the same attention pool, where voluntary-on-reflexive interference is possible and reflexive-on-voluntary interference is not*: According to this view, there are, again, two kinds of cues that operate the same orienting mechanism. However, because exogenous cues do not necessarily capture attention when attention is voluntarily focused, they violate the intentionality criterion of automaticity. Hence, the effects of exogenous cues are considered to be only partially automatic. In this model, endogenous orienting can inhibit exogenous orienting, but the opposite is not necessarily true (Theeuwes, l991; Warner et al., 1990; Yantis & Jonides, 1990; see a similar model but for saccadic control in Sereno, Pacht, & Rayner, 1992).

3. *Two separate mechanisms sharing the same attention pool, where reflexive-on-voluntary interference is possible and voluntary-on-reflexive interference is not*: According to this model, spatial orienting can be achieved by two separate mechanisms sharing a common attention pool. Regarding the possible interference between endogenous and exogenous cues, this model posits that because the reflexive mechanism engages attention automatically, reflexive-on-voluntary interference is possible, whereas voluntary-on-reflexive interference is not. Moreover, interference of reflexive orienting with voluntary orienting can be achieved only indirectly through action on the common pool (Muller & Rabbitt, 1989).

4. *Two separate mechanisms capable of mutual interference*: In this view, spatial orienting can be achieved by two separate and independent orienting mechanisms, and these two mechanisms (reflexive and voluntary orienting) interact in a mutually inhibitory way. The voluntary-on-reflexive interference is possible in this model because the exogenous orienting is construed as being only partially automatic (Muller & Humphreys, 1991).

In light of the current results, we suggest a fifth possibility, in line with Muller and Humphreys (1991): Option 4 above, but more specific. We suggest that endogenous and exogenous orienting are separate mechanisms that, under low demands, can lead to independent orienting effects, even under conditions in which they contradict each other. Increasing task demands leads to an interaction between the mechanisms as they compete for shared resources. Thus, under the appropriate conditions, interference would be possible in both directions: reflexive on voluntary and voluntary on reflexive.

This framework defines the reflexive-automatic process on the basis of the autonomy with which it is elicited rather than the amount of resources it requires or its sensitivity to load. By this definition, an automatic process is a process that is autonomous in the sense that it is reflexively elicited, without intention, even when it is not included in the requirements of the task (Tzelgov, 2000; Tzelgov, Yehene, Kotler, & Alon, 2000).

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Received February 12, 2003
Revision received November 17, 2004
Accepted November 17, 2004 ■

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