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Serial Deployment of Attention During Visual Search

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This study examined whether objects are attended in serial or in parallel during a demanding visual search task. A component of the event-related potential waveform, the N2pc wave, was used as a continuous measure of the allocation of attention to possible targets in the search arrays. Experiment 1 demonstrated that the relative allocation of attention shifts rapidly, favoring one item and then another. In Experiment 2, a paradigm was used that made it possible to track the absolute allocation of attention to individual items. This experiment showed that attention was allocated to one object for 100–150 ms before attention began to be allocated to the next object. These findings support models of attention that posit serial processing in demanding visual search tasks.

The primate visual system must solve complex computational problems to process scenes that contain more than one object (Feldman, 1985; Moran & Desimone, 1985; Mozer, 1991; Neisser, 1967). In the ambient environment, however, almost all scenes contain multiple objects. The present study addressed the question of whether serial shifts of covert attention are sometimes used in the perception of objects in multiple-element scenes.[1]

Vision scientists have attempted to address this question in controlled laboratory settings using visual search tasks, examples of which are shown in Figure 1. In these tasks, observers typically view arrays of objects and indicate whether a specific target object is present or absent. Many experiments have varied the number of items in each array (the *set size*), the nature of the target, and the nature of the distractors. Under some conditions, observers can quickly detect the target, regardless of the set size (see Figure 1A). For example, if the target is white and the distractors are black, the observers will be able to detect the presence of the white target just as quickly whether the array contains 1 or 100 black distractors. Under these conditions, researchers agree that the processes underlying target detection must be operating in parallel without any capacity limitations (Bundesen, 1990; Duncan & Humphreys, 1989; Treisman, 1988). That is, because adding more distractors does not decrease the efficiency of target detection, the process of determining whether a given item is a target must occur in parallel with, and independent of, the process of determining whether each of the other items is a target.

Under other conditions, the amount of time required to detect the target increases sharply as the set size increases. This pattern is often found when the target and distractors contain the same parts but differ in the spatial arrangement of the parts. For example, several experiments have involved the use of the letter *T* as the target and the letter *L* as the distractor (Bergen & Julesz, 1983; Egeth & Dagenbach, 1991; Kwak, Dagenbach, & Egeth, 1991); both are composed of horizontal and vertical lines, but they vary in the spatial arrangement of these parts. In such experiments, reaction times (RTs) typically increase by 20–100 ms for each distractor that is added to the search array (see Figure 1B). That is, the function relating RT to set size has a slope of 20–100 ms per item. We refer to search tasks with steep slopes (i.e., greater than 20 ms per item) as *demanding* search tasks. The purpose of the present study was to determine whether performance of demanding search tasks involves serial application of attention to individual objects within the arrays.

Not all demanding search tasks would be expected to yield serial search. Contemporary models of serial search include a parallel, preattentive stage followed by a serial, attentive stage (Luck, Girelli, McDermott, & Ford, 1997; Treisman, 1988; Wolfe, 1994), and nonzero slopes might sometimes result from the parallel, preattentive stage. In particular, each item represented by the preattentive stage adds noise, and larger set sizes therefore create more noise in the decision process. This can lead to increased errors or, if increased processing time is used to offset the increase in errors, increased RTs (Palmer, 1998). This is called the *decision-noise* explanation of nonzero search slopes (for extensive discussions, see Palmer, Verghese, & Pavel, 2000; Sperling & Dosher, 1986). To determine whether search might sometimes be

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[1] Observers make serial eye movements during search tasks with stimuli that are too small to be resolved without foveation. This is an uncontroversial case of serial search, but it is consistent with all theories of attention. In the present study, we asked whether *covert* attention also shifts serially, which is an issue of considerable theoretical interest.

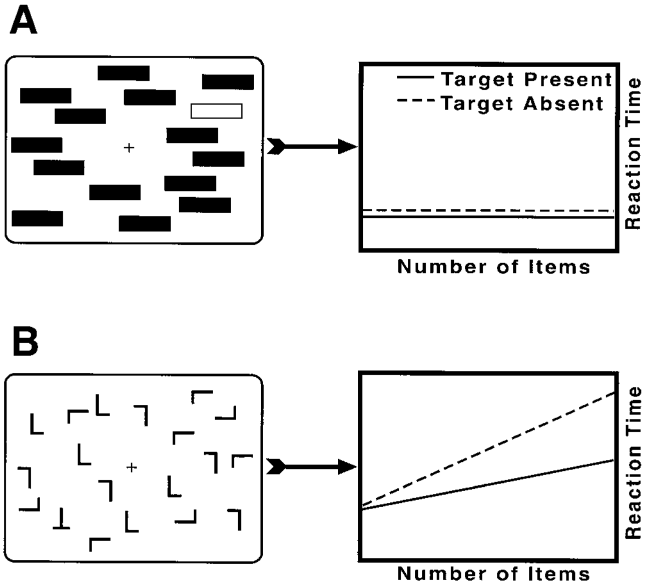

Figure 1. Stimuli and hypothetical data from an easy visual search task in which the target is a white rectangle among black rectangles (A) and from a demanding visual search task in which the target is a rotated *T* among rotated *L*s (B).

serial, it is therefore important to use a search task in which performance is not primarily limited by decision noise.

Several previous studies have attempted to distinguish between parallel and serial search through the use of tasks in which the target is defined by a conjunction of features, such as a red vertical target embedded in an array of green vertical and red horizontal distractors (e.g., Eckstein, 1998; McElree & Carrasco, 1999; Mordkoff, Yantis, & Egeth, 1990). However, the parallel, preattentive stage in serial models may sometimes make it possible for observers to avoid serial search with such stimuli. Specifically, spatially organized feature information might be used to direct attention immediately to the object that contains the greatest number of target features, eliminating the need to search through the distractors (Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). To test contemporary serial models, it is therefore necessary to use stimuli that do not allow this strategy.

In particular, these models clearly predict that serial processing will be necessary when the target and all of the distractors share the same features, but in different configurations. For example, Logan (1994) presented arrays containing pairs of dashes and plus symbols, and observers searched for a particular spatial arrangement, such as a dash-over-plus target among plus-over-dash distractors. These search tasks were very difficult, and the observed search rates were more than 100 ms per item. Steep search slopes have also been reported for color–color spatial pairs, such as red-over-blue targets among blue-over-red distractors (Luck, Hillyard, Mangun, & Gazzaniga, 1989; Wolfe et al., 1990). Similarly, Palmer (1994) conducted an experiment in which observers searched for a target defined by spatial relationships and found that the decrease in accuracy observed with larger set sizes was too great to be explained solely by decision noise, implying that a limited-capacity process was necessary to discriminate these targets. Thus, in the present study we used a task in which the target and all of the distractors contained the same features, differing only in the spatial arrangement of these features.

When trying to distinguish between parallel and serial models of visual search, it is important to realize that these are broad classes of models and that the serial class is actually a subset of the parallel class (Townsend, 1990). Imagine, for example, a parallel model in which different attentional weights can be assigned to different items in the search array and in which the weights can vary over time. In such a model, the weight for one item could be set to its maximum, and the weights for the other items could be set to zero; if no target is detected, the weights could then be adjusted such that the weight is set to maximum for a different item and maintained at zero for the other items. In this manner, attention could shift in serial from item to item. In fact, Bundesen (1990) described a parallel model that can emulate serial search in exactly this manner. Thus, it is impossible to rule out all parallel models without also ruling out all serial models (although it might be possible to rule out most parallel models without also ruling out most serial models).

Time Course of Attention

Because a highly flexible parallel model can emulate serial search, the goal of the present study was to distinguish between nonoverlapping subclasses of the general serial and parallel classes of models. Here we focus on a subclass of serial models that we label the *modal serial subclass,* indicating that it possesses the characteristics that are common to most contemporary serial models of search. Specifically, these models posit that (a) attention must be focused on one object at a time if certain difficult search tasks are to be performed with high accuracy, and (b) in these tasks attention switches from object to object at a rate that can be estimated from the search slope (which varies depending on the difficulty of the target–nontarget discrimination).

We contrast the modal serial subclass with a subclass of parallel models that we label the *slowly evolving parallel subclass,* indicating that attention can be focused on one or many objects at a given moment but cannot shift rapidly from object to object. That is, attention can be allocated flexibly in this subclass of models and can shift over time from one set of objects to another, but not at the rates posited by the modal serial subclass. In essence, the slowly evolving parallel subclass contains all parallel models except those that can emulate the modal serial models. In the remainder of this article, we use the terms *serial* and *parallel* to refer to the modal serial and slowly evolving parallel subclasses.

Duncan and his colleagues have made a similar distinction, attempting to provide evidence that attention shifts too slowly to be consistent with the modal serial subclass (Chelazzi, Duncan, Miller, & Desimone, 1998; Duncan, 1996; Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996). Duncan (1996) described two main sources of evidence for the claim that attention shifts slowly rather than rapidly. The first source derives from studies of the *dwell time* of attention (Duncan et al., 1994; Ward et al., 1996). In dwell-time experiments, each trial consists of a target and a mask at one location followed by a target and a mask at another location, and observers make unspeeded responses at the end of each trial to indicate the identities of both targets. The main independent variable is the delay between the two targets. When the delay is greater than approximately 500 ms, observers can accurately identify both targets, indicating that they are able to process the first target and then shift attention to the second target in this period of time. However, accuracy for the second target is impaired when it is presented less than 500 ms after the first target, suggesting that attention cannot shift rapidly from one target to another. From these results, Duncan (1996) concluded that the focus of attention shifts too slowly to be consistent with serial models of attention.

There are two reasons to doubt this conclusion. First, the dwell-time paradigm used by Duncan and colleagues (Duncan et al., 1994; Ward et al., 1996) is quite different from typical visual search tasks, and it is possible that attention can shift much more quickly during visual search tasks than during dwell-time tasks. For example, the first target in the dwell-time paradigm is masked, which might increase the amount of time required to perceive that target; indeed, the dwell time of attention is decreased by approximately 50% when the mask is eliminated (Moore, Egeth, Berglan, & Luck, 1996). A second problem with comparing dwell-time and search results is that the dwell-time paradigm is really a variant of the *attentional blink* paradigm, and several studies have shown that the attentional blink paradigm depends primarily on the operation of attention in working memory and not in perception (e.g., Maki, Frigen, & Paulson, 1997; Shapiro, Driver, Ward, & Sorensen, 1997; Vogel, Luck, & Shapiro, 1998). There is no reason to believe that the temporal dynamics of the attentional system tapped by the dwell-time paradigm will be similar to the temporal dynamics of the attentional system tapped by demanding visual search tasks.

Duncan (1996) also cited evidence from single-unit recordings in monkeys performing visual search tasks (e.g., Chelazzi, Miller, Duncan, & Desimone, 1993). Electrophysiological data are particularly useful in this context because they provide a continuous, millisecond-by-millisecond measure of the time course of processing. For example, Chelazzi et al. (1993, 1998) recorded single-unit activity from the inferotemporal cortex while monkeys performed a visual search task and found that the neurons initially responded to the stimulus array in a nonselective manner; that is, the responses were not initially influenced by whether the stimuli were targets or nontargets. Beginning approximately 175 ms after the onset of the search array, however, the neurons began to respond as if the nontargets were not present. This modulation began approximately 125 ms before the behavioral response to the target and continued for hundreds of milliseconds. Duncan (1996) argued that results of this nature were consistent with a slowly evolving attentional state rather than with high-speed shifts of attention.

By considering the time course of preattentive and attentive processing in more detail, however, it is possible to view these results as evidence that attention actually shifts rapidly rather than slowly. When a search array is first presented, a significant period of time will be required for the information to reach the cortex and for preattentive processing to make feature information available to higher level systems. Given that visual information does not reach most neurons in the inferotemporal cortex until 75–150 ms poststimulus (Chelazzi et al., 1993; Lueschow, Miller, & Desimone, 1994), it is reasonable to suppose that preattentive processing is not complete until at least 100 ms poststimulus. The finding that the first shift of attention occurs at approximately 175 ms after the onset of the search array is therefore compatible with a search mechanism that can shift in less than 100 ms from the time that preattentive information becomes available. Moreover, attention effects have been observed as early as 140 ms poststimulus in the prefrontal cortex (Rainer, Asaad, & Miller, 1998) and as early as 100 ms in the frontal eye fields (Schall & Hanes, 1993). Thus, these single-unit data are consistent with the hypothesis that the first shift of attention occurs tens rather than hundreds of milliseconds after the completion of preattentive processing.

Duncan (1996) also noted that the attention effects observed by Chelazzi et al. (1993) endure for hundreds of milliseconds, but serial models of attention are compatible with the proposal that, once the target is found, attention remains focused on it for a long period of time. Thus, there is no compelling evidence supporting the claim that attentional states evolve too slowly to be compatible with serial models of visual search.

Previous Evidence for Serial Search

Only a few studies have provided direct support for serial models of visual search. The main source of evidence for serial search has been the finding of linear RT functions with a 2:1 ratio of target-absent slopes to target-present slopes (e.g., Treisman & Gelade, 1980). However, this pattern is not always found (see Wolfe, 1998), and parallel search models can also predict linear search functions with a variety of slope ratios (see Townsend, 1990). Moreover, serial search may fail to produce a 2:1 slope ratio (e.g., if the observers recheck a proportion of the search items on target-absent trials).

Horowitz and Wolfe (1998) reported one of the few direct behavioral studies providing evidence for serial search[2] (see also Horowitz & Wolfe, 2001). Observers in this study searched for rotated *T* targets among rotated *L* distractors on two types of trials. In one type, the objects in the arrays changed locations every 100 ms; in the other type, the objects remained at the same locations throughout the trial. The slopes of the RT functions did not differ between these two types of trials, a finding that is consistent with some serial models of attention but not with most parallel models. In particular, these results support serial models in which no memory is maintained of which locations have been searched. That is, if attention shifts from location to location completely at random, then it should not matter if the objects shift locations. If attention shifts from object to object without repetitions, then search should become more difficult when the locations change from moment to moment. In addition, if the search array is processed in parallel, with information about each item accumulating gradually over time, then search should be greatly disrupted by shifts in location. Thus, these results provide direct evidence for a serial, memory-free search. However, this study has been controversial, with a report of a failure to replicate (Kristjánsson, 2000), a report of a successful replication (Horowitz & Wolfe, in press),

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[2] Egeth and Dagenbach (1991) also developed a means of distinguishing between parallel and serial processing on the basis of interactions with perceptual quality. As they noted, however, this technique can provide definitive evidence of parallel processing but cannot provide definitive evidence of serial processing. Thus, although they failed to find evidence of parallel processing in a search for a rotated *L* target among rotated *T* distractors, this was not definitive evidence for serial processing.

and a study demonstrating that shifts of gaze during search are guided by memory (Peterson, Kramer, Wang, Irwin, & McCarley, 2001).

Putative evidence for serial search has also been obtained with positron emission tomography. In particular, Corbetta and his colleagues found that conjunction search led to enhanced activity in a specific area of the posterior parietal cortex, but feature search did not (Corbetta, Shulman, Miezin, & Petersen, 1995; see also Donner et al., 2000). Because this same area is also activated when observers are explicitly instructed to make shifts of attention (Corbetta, Miezin, Shulman, & Petersen, 1993), Corbetta et al. (1995) argued that the conjunction search involves shifts of attention. However, Chelazzi (1999) noted that this area of parietal cortex can also be activated by tasks that do not involve shifts of spatial attention, making it difficult to draw conclusions about attention shifts from parietal activation. In general, current functional neuroimaging techniques lack the temporal resolution that is necessary to distinguish directly between serial and parallel search, which differ primarily in their timing. That is, parallel models do not imply that attention is never selectively focused on a subset of the input; instead, they imply that attention does not switch rapidly from item to item.

Putative evidence for serial search has also been obtained from event-related potential (ERP) recordings by Luck and Hillyard (1990). In this study, variations in the amplitude and latency of the P3 wave were used to draw inferences about serial versus parallel processing. However, the P3 wave reflects a late stage of processing (probably related to the updating of working memory), and the observed pattern of results of this study may reflect a parallel search process followed by serial transfer of information about the searched items into a working memory or decision stage.

As this brief review indicates, there is very little direct evidence supporting serial models of visual search (see Chelazzi, 1999, for a more extensive review). There are many clear demonstrations of parallel search, but the parallel stage of serial models can be used to explain most of these findings. The goal of the present study was therefore to provide new evidence that can distinguish between the modal serial and slowly evolving parallel subclasses of visual search models. Specifically, the present study was designed to look for evidence of serial shifts of attention in a visual search task designed to maximize the opportunity for such shifts of attention to be observed. That is, we hoped to demonstrate that attention *can* shift in the rapid manner suggested by serial models, at least under some conditions. A demonstration that serial search is possible would be important because it would falsify all theories in which serial search is not possible.

There are four ways in which the present experiments were optimized to accomplish this goal. First, we used a search task in which the target was a square with a gap on a particular side and the distractors were squares with a gap on a different side. Because the target and distractors differed in terms of the relative location of the gap, they should have been difficult to distinguish on the basis of preattentive feature information, and virtually any contemporary serial model would predict that these stimuli would require the serial allocation of attention. Second, we used electrophysiological recordings to measure the moment-by-moment allocation of attention, making it possible to determine whether attention shifts in serial from item to item. Third, rather than simply examining the time course of the first shift of attention to a target (as in Chelazzi et al., 1993, 1998), we examined the time course of attention as it shifted from one distractor to another. This made it possible to measure the time required to shift attention from object to object rather than the combined time required to perform a parallel feature analysis and then execute a shift of attention. Finally, we chose a specific electrophysiological measure that corresponds to a perceptual-level attentional mechanism clearly involved in typical visual search tasks (in contrast to the dwell-time paradigm of Duncan et al., 1994, which stresses post-perceptual attention mechanisms).

An Electrophysiological Measure of Attention

In the present study, we used ERP recordings to provide a continuous, millisecond-by-millisecond measure of the allocation of attention between the onset of the search array and the behavioral response. ERPs are scalp-recorded voltage fluctuations that reflect neural activity associated with sensory, motor, or cognitive events (see reviews by Coles & Rugg, 1995; Hillyard & Picton, 1987; Luck & Girelli, 1998). ERPs arise primarily from the postsynaptic potentials generated by individual neurons during neurotransmission and contribute to the electroencephalogram (EEG). They can be extracted from the overall EEG by means of signal-averaging procedures, in which brain activity is time locked to an event (e.g., a stimulus) and then averaged across multiple instances of the same type of event. Any brain activity that is consistently triggered by the event remains in the averaged waveform, whereas any random brain activity averages to zero.

The typical visual ERP waveform consists of a series of negative and positive voltage fluctuations, as illustrated in Figure 2. The individual fluctuations are called *peaks, components,* or *waves,* and they are thought to reflect the temporal progression of processing, with early components reflecting sensory processing and later components reflecting higher level cognitive and response-related processes. Of primary interest in the current study was a component that reflects the allocation of perceptual attention during visual search. This component is called *N2pc* (N2–posterior–contralateral) to reflect its typical timing (at the time of the N2 family of components, approximately 200–300 ms), its scalp distribution (posterior), and its lateralization (contralateral with respect to the attended location). Specifically, when a visual search target is clearly visible among a set of distractors, the ERP waveform becomes more negative at contralateral scalp sites relative to ipsilateral scalp sites, beginning approximately 175 ms after the onset of the search array (see Figure 2). The difference in voltage between the contralateral and ipsilateral sites defines the N2pc component. A magnetoencephalographic study indicated that this component arises primarily from lateral extrastriate and inferotemporal visual areas, with a minor contribution from the posterior parietal cortex (Hopf et al., 2000).

Several sources of evidence indicate that the N2pc component reflects the deployment of perceptual-level attention to minimize interference between the attended item and nearby distractors. First, the N2pc component is absent for nontarget stimuli that can be rejected on the basis of preattentive feature information, but it is present both for target stimuli and for nontarget stimuli that require careful scrutiny to be distinguished from the targets (Luck & Hillyard, 1994). Second, the N2pc component is larger when distractors are near the target (Luck et al., 1997), and it is elimi-

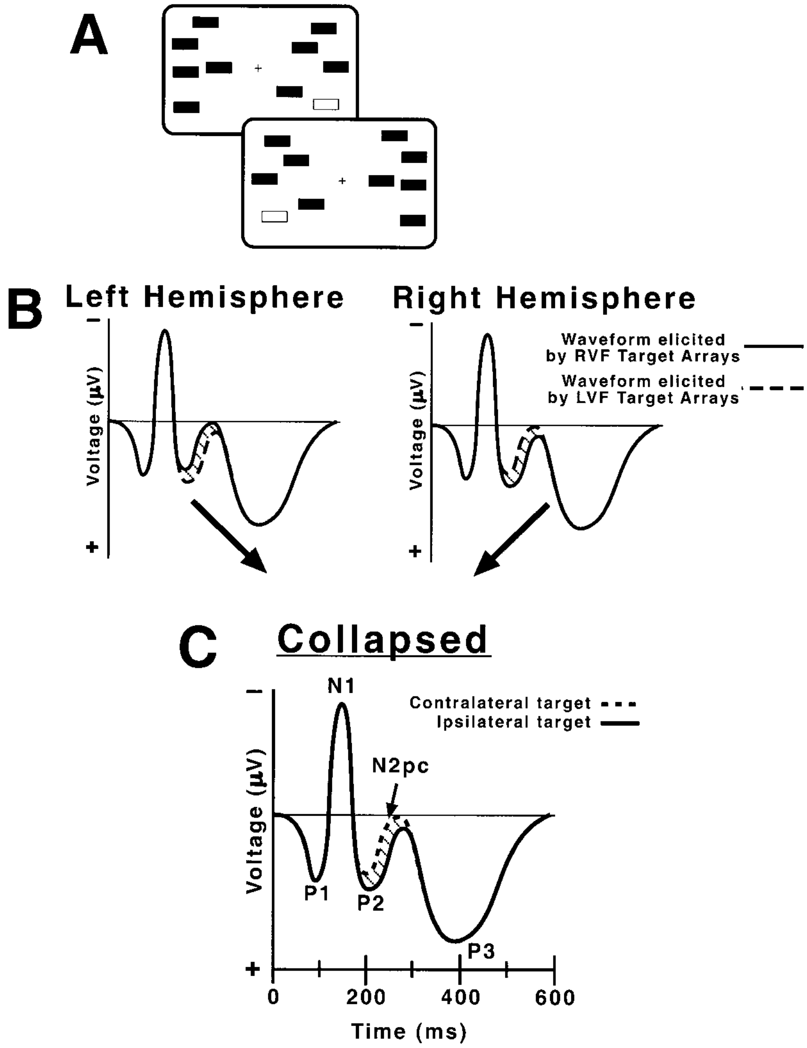

Figure 2. Example of a typical N2pc experiment. A: Stimulus arrays with a target (the white bar) on the right or left. B: Hypothetical waveforms recorded from posterior electrode sites over the left and right hemispheres. Note that, by convention, negative is plotted upward in this and all subsequent figures. The waveforms from the left hemisphere are more negative-going for right visual field (RVF) targets than for left visual field (LVF) targets, and the waveforms from the right hemisphere are more negative-going for LVF targets than for RVF targets. C: Waveforms that have been collapsed across hemispheres into ipsilateral and contralateral waveforms. The ipsilateral waveform is the average of the left hemisphere waveform for LVF targets and the right hemisphere waveform for RVF targets, and the contralateral waveform is the average of the left hemisphere waveform for RVF targets and the right hemisphere waveform for LVF targets. This difference in amplitude between the ipsilateral and contralateral waveforms defines the N2pc component and is indicated by the shaded region.

nated when distractors are completely removed (Luck & Hillyard, 1994). Third, the N2pc component is larger for conjunction targets than for feature targets (Luck et al., 1997), and it can be completely eliminated for feature targets under some conditions (Luck & Ford, 1998). Fourth, the N2pc component appears to reflect the same attentional mechanism observed by Chelazzi and his colleagues in single-unit recordings (Chelazzi & Desimone, 1994; Chelazzi et al., 1993, 1998). Specifically, both the N2pc component and these single-unit attention effects begin at approximately 175 ms post-stimulus, are larger for difficult discrimination tasks than for simple detection tasks, are larger when distractors are near the target, and are larger for tasks that require target localization.

The N2pc Component and Serial Search

The N2pc component is particularly useful for testing serial models of visual search because its lateralized scalp distribution provides a means of determining the general direction of attention at a given moment. That is, the N2pc wave is more negative over the left hemisphere when attention is directed to an object in the right visual field (RVF) and more negative over the right hemisphere when attention is directed to an object in the left visual field (LVF). If attention shifts rapidly from one item to another during visual search, the N2pc component should shift from one hemisphere to the other as attention shifts from one visual field to the other. More specifically, if a search array contains just two items that might be the target, one in each hemifield, serial models would predict that attention would shift rapidly from one item to the other, accompanied by a rapid shift in N2pc lateralization. The present study was designed to test this prediction.

This prediction is difficult to test because it is usually impossible to predict the order in which objects will be searched. That is, on some trials an observer might search the LVF first and then the RVF, and on other trials the observer might first search the RVF. It is not possible to identify the N2pc component on single trials, and it is therefore necessary to average together trials involving the same search order to determine whether the N2pc component shifts rapidly between the left and right hemispheres. We have previously developed two methods for solving this problem, both of which involve biasing the participants to search in a particular order (Woodman & Luck, 1999). As illustrated in Figure 3A, the first method involves using four distinctively colored items, one of which is very likely to be the target, another of which is somewhat less likely to be the target, and two of which are never the target (and are used for counterbalancing purposes). As an example, for one participant the target shape would be drawn in red on 75% of target-present trials and would be drawn in violet on 25% of target-present trials; for this participant, we call red the *C_{75} color* and violet the *C_{25} color*.

If search occurs in serial, these probabilities should bias the observers to search the C_{75} item first and then shift to the C_{25} item (on the majority of trials). If search occurs in parallel, observers should simply allocate more resources to the C_{75} item and fewer resources to the C_{25} item. Thus, serial models predict that the N2pc component should initially appear over the hemisphere contralateral to the C_{75} item and then shift to the hemisphere contralateral to the C_{25} item. In contrast, parallel models predict that the N2pc component should simply be larger over the hemisphere contralateral to the C_{75} item than the hemisphere contralateral to the C_{25} item, with no rapid change in allocation over time.[3]

Figure 3B shows the results that were obtained for target-absent trials on which the two possible targets were in opposite visual fields. The N2pc component was more negative contralateral to the C_{75} item from approximately 200–300 ms poststimulus, and it was more negative contralateral to the C_{25} item from approximately 300–400 ms poststimulus. This indicates that attention shifted from the C_{75} item to the C_{25} item after approximately 100 ms. This is somewhat slower than the 50-ms-per-item search rate often obtained with tasks that would be expected to involve serial search (for a review, see Wolfe, 1996). However, to minimize the use of preattentive information in performing the target discrimination, this experiment used a very difficult gap localization task, and slower shifts of attention would therefore be expected. Indeed, RTs on target-present trials were 76 ms longer when the target was the C_{25} item than when it was the C_{75} item. Thus, the time course of the N2pc reversal was consistent with the RT results.

It might be argued that the design of this experiment biased the participants to scan in an unnatural manner, inducing them to search in serial even though search normally occurs in parallel. Even if this were true, this experiment would still provide evidence that rapid shifts of attention are possible. Nonetheless, it is desirable to know whether observers spontaneously perform visual search in serial. An additional experiment was therefore conducted in which a different method was used for predicting the search order. This experiment took advantage of the fact that observers will spontaneously assign priority to items near the fixation point, detecting targets near to fixation at shorter latencies than they detect targets far from fixation (even when the objects are scaled according to the cortical magnification factor; see Carrasco, Evert, Change, & Katz, 1995; Wolfe, O'Neill, & Bennett, 1998).

As illustrated in Figure 3C, each array contained 2 red items and approximately 40 black items. One red item was near the fixation point and the other was far from it, but both were equally likely to be the target. The size of each item was scaled according to the cortical magnification factor to equalize the perceptual difficulty of the near and far items. If search is serial, the participants would be expected to search the near item first and then shift attention to the far item; if search is parallel, the participants would be expected to allocate more resources to the near item than to the far item, with no rapid changes in allocation over time. As shown in Figure 3D, the ERP recordings were consistent with a serial search. The N2pc component was more negative contralateral to the near red item from approximately 200–300 ms and was more negative contralateral to the far red item from approximately 300–400 ms. RTs were an average of 78 ms shorter for targets at near than at far locations, which is comparable to the timing of the N2pc polarity reversal.

To test whether this pattern simply reflected generally slower processing for the far items, this study also included trials with a single red item, either near or far from fixation. These trials were used to determine whether RTs would be longer and the N2pc later for a single potential target item when it was far from fixation than when it was near fixation. We found that RTs and N2pc latency were both similar for near and far items on these trials, indicating that the results from the trials with two red items reflected the sequential operation of attention rather than intrinsic differences in the time course of processing for near and far items.

Although these results appear to provide evidence in favor of serial models of visual search, there are two problems with these experiments. The first is straightforward: In the experiment shown in Figure 3C, there was a low-level sensory difference between the two sides of the displays (i.e., the red item was farther from fixation on one side than on the other), and this may have distorted the ERP data in the time range of the N2pc wave. This problem was addressed in Experiment 1 of the present study.

The second problem arises in the interpretation of both experiments shown in Figure 3. Specifically, the N2pc component is measured as the difference in amplitude between the contralateral and ipsilateral waveforms, and it therefore reflects the difference in attentional allocation between the LVF and RVF rather than the absolute amount of attention allocated to a given item. It is therefore possible that attention was allocated to items in both the LVF and RVF simultaneously, and only the difference in alloca-

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[3] Because the class of parallel models is large, other predictions are also possible. Some of these alternatives are considered later.

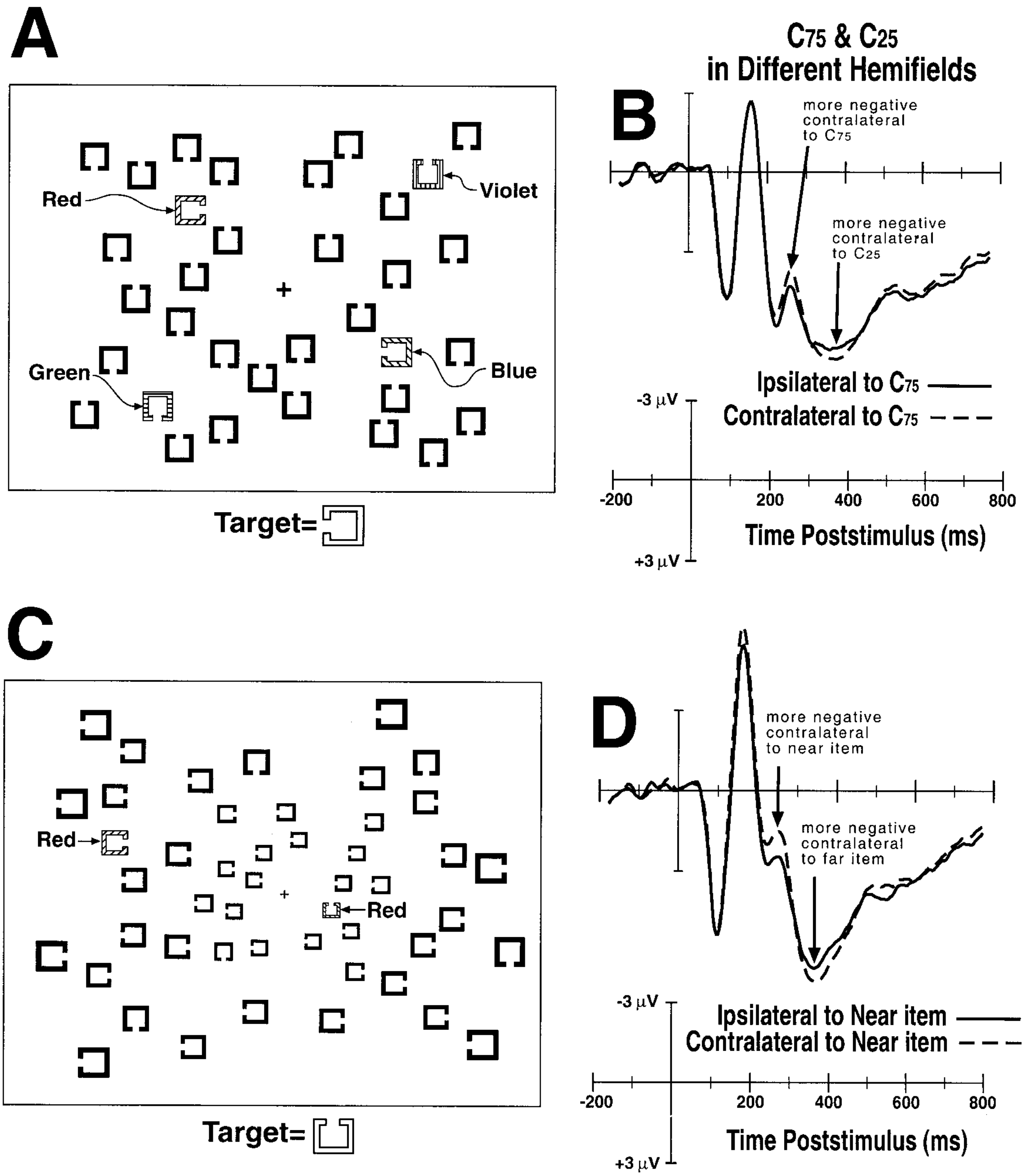

Figure 3. Stimuli and grand average event-related potential data from two previous experiments (Woodman & Luck, 1999). A: Example stimuli from an experiment in which a probability manipulation was used to manipulate search order. B: Waveforms from target-absent trials in which the two possible targets were in opposite hemifields. Voltages were recorded from lateral occipital electrode sites. The dashed line represents the voltage at the site contralateral to the most likely target color, and the solid line represents the voltage at the site ipsilateral to the most likely target color. The labels C_{75} and C_{25} refer to the colors that are, respectively, 75% and 25% likely to be the target. C: Example stimuli from an experiment in which eccentricity was used to manipulate search order. D: Waveforms from target-absent trials in which the two red items were in opposite hemifields (recorded from lateral occipital electrode sites).

tion shifted rapidly. Imagine, for example, that attention was initially allocated to both the near and far items, with more attention initially allocated to the near item. This should lead to rapid identification of the near item, and if attention was withdrawn from the near item as soon as it was identified, the relative allocation of attention to the far item would then be expected to increase. Some parallel models would therefore be consistent with the results of these experiments. Experiment 2 of the present study addressed this possibility by providing a method for measuring the N2pc component separately for the near and far items.

It should also be noted that the search tasks used in these experiments were somewhat different from those used in typical behavioral experiments, in that most of the items in each search array could be rejected preattentively on the basis of color (which was necessary because of the constraints of the N2pc component). If, however, observers can shift attention in serial in these somewhat unusual tasks, there is every reason to believe that they can also shift attention in serial in more conventional tasks.

Experiment 1

The purpose of this experiment was to rule out the possibility that sensory differences between the near and far red items contaminated the ERP recordings in the experiment of Woodman and Luck (1999; see Figure 3C). To solve this problem, we used stimulus arrays in which the sensory stimulation was identical in the two hemifields, and we included instructional manipulations to direct attention to a near item in one hemifield and a far item in the other hemifield.

Each stimulus array in this experiment contained two green items and two red items, along with many black distractor items. As illustrated in Figure 4, one red item and one green item were near fixation, but in opposite hemifields, and the other red and green items were far from fixation and again in opposite hemifields. Consequently, each hemifield contained one near item and one far item. The participants were instructed to search the red items in some trial blocks and to search the green items in other trial blocks, because the target would always appear in the attended color. Thus, a given stimulus array might contain a near attended item in the LVF and a far attended item in the RVF when the participants searched for red but would contain a near attended item in the RVF and a far attended item in the LVF when the participants searched for green. In this manner, sensory factors were completely controlled, making it possible to determine whether the previously observed changes in ERP lateralization reflected shifts of attention. As in our previous experiment, the items were scaled according to the cortical magnification factor.

To test for intrinsic differences in the time course of processing for near and far items, we also included trials with one red item and one green item, both near or both far from fixation. On these trials, we expected the time course of the N2pc component to be similar regardless of whether the attended item was near or far from fixation.

In this experiment, targets were present on 50% of trials and were equally likely to be near or far from fixation. Different N2pc

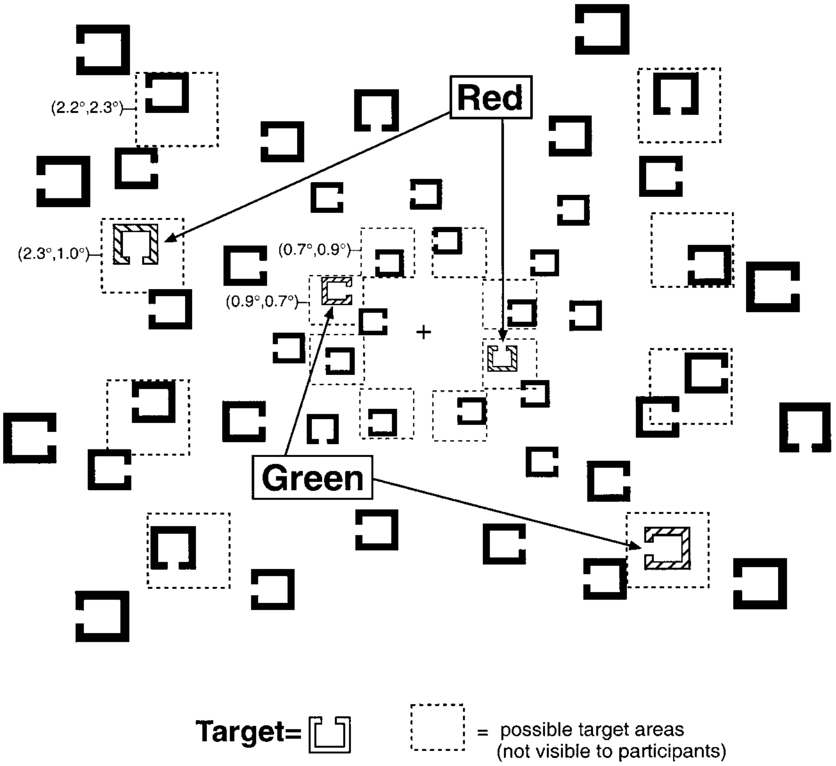

Figure 4. Example of a target-present stimulus array from Experiment 1. Participants searched either the red or green items for a square with a gap on its top. The colored items were presented within square regions, shown here as regions enclosed by broken lines. There were eight near regions and eight far regions. The near regions were 0.4° × 0.4° in size, and the far regions were 0.9° × 0.9° in size. The center of each region in the upper left quadrant is indicated in the figure by an (*x*, *y*) pair next to each region indicating degrees along the *x*- and *y*-axes from the fixation point. The possible target regions, the coordinates, and the color labels were not visible in the actual displays.

patterns would be predicted for target-present trials depending on whether the target was near or far, but dividing the trials in this manner led to an unacceptably low signal-to-noise ratio. Consequently, we focus here only on the target-absent trials. We have previously examined the switching of attention on target-present trials using a slightly different paradigm (Experiment 2 in Woodman & Luck, 1999); the results for target-present trials in that experiment were consistent with the results for target-absent trials in the present experiment.

Method

Participants. Twelve neurologically normal volunteers between 18 and 35 years old were paid for their participation. All had normal or corrected-to-normal acuity and reported having normal color vision. Informed consent was obtained at the beginning of the experiment.

Stimuli. Stimuli were viewed from a distance of 100 cm on a video monitor with a gray background (9.99 cd/m^2) and a continuously visible fixation point. We measured stimulus chromaticity with a Tektronix J17 LumaColor chromaticity meter using the 1931 Commission International d'Eclairage chromaticity space.

Two types of stimulus arrays were used, *standard arrays* and *control arrays.* As illustrated in Figure 4, standard arrays were composed of 44 black squares, 2 red squares ($x = 0.648$, $y = 0.330$, 14.72 cd/m^2), and 2 green squares ($x = 0.330$, $y = 0.564$, 14.54 cd/m^2). Four near locations and four far locations were defined in each hemifield (see Figure 4 for details). In each stimulus array, one red item was placed at a randomly selected near location and one green item was placed at a randomly selected near location in the opposite hemifield. The other red item was placed at a randomly selected far location, and the other green item was placed at a randomly selected far location in the opposite hemifield. Thus, each hemifield contained a near red or green item and a far red or green item, and each array contained a near red item, a far red item, a near green item, and a far green item. The two colored items in a given hemifield were the same color on 50% of trials and different colors on the remaining trials. The black squares were randomly distributed over a 6.8° × 6.8° area, with the constraint that 22 black squares were present in each visual field.

Control arrays were identical to standard arrays except that they contained 46 black items, 1 red item, and 1 green item. The red and green items were always in opposite hemifields; both were at near locations on 50% of trials, and both were at far locations on the remaining trials.

Each square had a gap on one side that was 27% of the length of that side. The target square had a gap on the top, and the nontarget squares had a gap on the bottom, left, or right, selected at random. The squares were scaled according to the cortical magnification factor (Rovamo & Virsu, 1979). Squares between 0° and 1.0° from fixation measured 0.36°; squares between 1.0° and 1.56° from fixation measured 0.52°; squares between 1.56° and 2.44° from fixation measured 0.65°; and squares greater than 2.44° from fixation measured 0.78°. Minimum center-to-center distances between squares were similarly scaled and were 0.43°, 0.62°, 0.71°, and 0.88°, respectively, for these four eccentricity ranges.

Procedure. Each stimulus array was presented for 3,000 ms and was followed by a blank interval of 1,800–2,200 ms (rectangular distribution) during which only the fixation point was visible. At the beginning of each trial block, participants were told to attend either to the red squares or to the green squares. A target was present on 50% of trials, and, if present, it was equally likely to be the near or far square of the attended color. Participants were instructed to press a button with the index finger of their dominant hand if the target was present and to press a button with the middle finger of their dominant hand if the target was absent. Accuracy and speed of responses were equally stressed. Trials in which RTs were shorter than 200 ms or longer than 2,000 ms were excluded from further analysis.

Each participant performed 20–30 practice trials, followed by 12 blocks of 96 trials during which ERPs were recorded. All possible location combinations were equally likely within a given block. Sixty-seven percent of the arrays were standard arrays, and 33% were control arrays. Attend-red and attend-green blocks alternated; half of the participants began with attend-red and half with attend-green. The participants were instructed to maintain fixation throughout each trial, and feedback regarding eye movements was provided at the end of each block.

Recording and analysis. The EEG was recorded from tin electrodes in an elastic cap (Electrocap International); a subset of International 10/20 System sites was used (F3, F4, C3, C4, P3, P4, T3, T4, T5, T6, O1, and O2). Two nonstandard sites were also used: OL (halfway between O1 and T5) and OR (halfway between O2 and T6). These sites, along with a left-mastoid site, were recorded with a right-mastoid reference electrode, and the signals were re-referenced offline to the average of the left and right mastoids (Nunez, 1981). The horizontal electrooculogram (EOG), recorded as the voltage between electrodes placed 1 cm lateral to the external canthi, was used to measure horizontal eye movements. The vertical EOG was recorded from an electrode beneath the left eye, referenced to the right mastoid, and was used to detect blinks and vertical eye movements. The EEG and EOG were amplified by an SA Instrumentation amplifier with a gain of 20,000 and a bandpass of 0.01–80 Hz, and the amplified signals were digitized at 250 Hz by a PC-compatible computer and averaged offline. Trials involving incorrect behavioral responses or ocular artifacts were excluded from the averages.

Ocular artifacts (blinks and eye movements) were rejected by means of a two-step procedure. First, individual trials containing artifacts were eliminated by computing the cross covariance between the single-trial EOG waveform and a 100-ms step function and rejecting trials on which the maximum covariance exceeded a threshold. Visual inspection of the single-trial waveforms was used to determine, for each individual participant, a threshold value that would lead to the rejection of all clearly visible artifacts without also leading to the rejection of large numbers of artifact-free trials. Because of the limited signal-to-noise ratio of EOG recordings, trials with very small eye movements could not be reliably detected and rejected by the first step.

In the second step, we computed averaged horizontal EOG waveforms for left-target and right-target trials to assess the degree of residual eye movement activity. Any systematic eye movement toward the potential target items can be observed in these waveforms, which have an extremely high signal-to-noise ratio. Our standard procedure is to use the data only from participants whose residual EOG activity is less than 3 μV, which corresponds to an average eye movement of less than 0.2° and a propagated voltage of less than 0.1 μV at the posterior scalp sites (Lins, Picton, Berg, & Scherg, 1993). All participants in the present experiment met this criterion. We also routinely replace any participants for whom more than 25% of the trials are rejected owing to eye movements; 4 participants were replaced for this reason in the present experiment. Among the remaining participants, artifacts led to the rejection of an average of 15.3% of trials, with a single-participant maximum of 23.9%.

The N2pc component was measured during two different time windows, 200–300 ms and 300–400 ms poststimulus, at the O1, O2, OL, OR, T5, and T6 electrode sites. N2pc amplitude was measured as the mean amplitude during these time windows, relative to the mean amplitude during a 200-ms prestimulus baseline period. To isolate the N2pc component from other overlapping components, we quantified it as the average of the contralateral potentials (left hemisphere with right target and right hemisphere with left target) minus the average of the ipsilateral potentials (left hemisphere with left target and right hemisphere with right target).

Analysis of variance (ANOVA) was used for all statistical tests, and all probability values were adjusted with the Greenhouse–Geisser epsilon correction for nonsphericity (Jennings & Wood, 1976). The data were collapsed across attend-red and attend-green blocks to eliminate any possible sensory differences.

Results

Behavior. First, we consider the results from standard arrays (those with two items of the attended color). Accuracy for these arrays was above 93% for all participants and all stimulus conditions. Responses were more accurate when the target was absent ($M = 98.9\%$) than when the target was present at either near ($M = 96.4\%$) or far ($M = 97.1\%$) locations (ps $< .05$). However, accuracy did not differ significantly between near and far target-present trials ($p > .35$).

RTs are summarized in Table 1. RTs were faster for targets at near locations ($M = 737$ ms) than for targets at far locations ($M = 831$ ms), producing a significant difference of 94 ms, $F(1, 11) = 25.06$, $p < .001$. This RT pattern is consistent with the assumption that the participants usually searched the near item before the far item. Near target-present responses were significantly faster than target-absent responses ($M = 853$ ms), $F(1, 11) = 107.59$, $p < .001$, but far target-present RTs did not significantly differ from target-absent RTs ($p > .30$). RTs were slightly longer when the attended items were in the same hemifield than when they were in different hemifields, an effect that approached significance, $F(1, 11) = 4.51$, $p = .057$. At this point, it is unclear why we observed this trend toward longer RTs when both of the relevant items were in the same hemifield. For example, this pattern may have simply been due to noise, or it is possible that there was a greater amount of interference in this condition because the two items were nearer one another than in the different hemifield condition (Luck et al., 1997).

Mean accuracy for the control arrays (those with only one item of the attended color) was above 97% for all observers and all stimulus conditions. Response accuracy did not differ between target-present ($M = 98.7\%$) and target-absent ($M = 98.9\%$) responses ($p > .50$). In addition, response accuracy did not differ between near ($M = 98.8\%$) and far ($M = 99.1\%$) target-present trials ($p > .50$). RTs were significantly shorter on target-present trials ($M = 664$ ms) than on target-absent trials ($M = 749$ ms), $F(1, 11) = 49.57$, $p < .001$, but did not differ for targets presented at near ($M = 667$ ms) versus far ($M = 661$ ms) locations ($p > .60$). These data are consistent with the assumptions that attention can select far targets just as efficiently as near targets and that there was no inherent difference in the processing of individual items at near versus far locations.

N2pc for standard arrays. Figure 5 shows the ERP waveforms from lateral occipital scalp sites on target-absent trials for the standard arrays, averaged across participants and across the attend-red and attend-green conditions. When the two possible target items were in opposite hemifields, the ERP waveform was more negative contralateral to the near possible target from approximately 200–300 ms poststimulus (Figure 5A). The waveform then became more negative contralateral to the far possible target from approximately 300–475 ms poststimulus. This hemispheric reversal of the N2pc wave was not present when both the near and far possible target items were in the same hemifield (Figure 5B). Instead, the negativity began at approximately 200 ms and continued until the end of the recording epoch.

The N2pc measurements on target-absent trials for the standard arrays were analyzed in a three-way repeated measures ANOVA in which the factors were stimulus configuration (near and far attended items in the same vs. opposite hemifields), measurement window (200–300 ms vs. 300–400 ms poststimulus), and within-hemisphere electrode position (occipital, lateral occipital, or temporal). The finding of a reversal of N2pc polarity between the early and late measurement windows when the possible targets were in opposite hemifields, but not when they were in the same hemifield, led to a significant interaction between measurement window and stimulus configuration, $F(1, 11) = 10.86$, $p < .01$. The main effects of measurement window, stimulus configuration, and within-hemisphere electrode position were also significant, $F(1, 11) = 8.03$, $p < .05$; $F(1, 11) = 10.45$, $p < .001$; and $F(2, 22) = 4.85$, $p < .05$, respectively. These effects reflect a larger overall N2pc in the late measurement window than in the early measurement window, a larger overall N2pc when the possible targets were in the same hemifield than when they were in opposite hemifields, and a larger overall N2pc component at the lateral occipital electrode sites than at the other sites.

A set of planned comparisons was conducted to decompose the interaction between measurement window and stimulus configuration. First, separate two-way ANOVAs with measurement window and within-hemisphere electrode position as factors were conducted for each of the two stimulus configurations. The main effect of measurement window was found to be significant when the near and far items were in opposite hemifields, $F(1, 11) = 23.55$, $p < .001$, but this effect was not significant when the near and far items were in the same hemifield, $F(1, 11) = 1.51$, $p > .25$. This reflects the fact that the N2pc component switched polarity over time only when the two possible targets were in opposite hemifields. Further planned analyses of each measurement window for the two stimulus configurations showed that a significant N2pc component was present in both the early and late measurement windows for both configurations (all ps $< .05$).

N2pc for control arrays. Figure 6 shows the nontarget waveforms from the control arrays, in which only near or only far items were present. These arrays were used to determine whether there were any intrinsic differences in N2pc timing for near versus far items. The N2pc component was slightly larger when the possible target item was near than when it was far, but the timing of the N2pc component was virtually identical in both cases. Most important, there was no substantial N2pc activity during the late measurement window (300–400 ms).

The data from the control arrays were first analyzed in a three-

Table 1
Mean Reaction Times (RTs; in Milliseconds): Experiment 1

Type of array	Mean RT
Standard	
Absent: same hemifield	868
Absent: different hemifields	839
Present near: same hemifield	758
Present near: different hemifields	718
Present far: same hemifield	826
Present far: different hemifields	837
Single-item control	
Absent: near	753
Absent: far	746
Present: near	668
Present: far	661

Note. The 95% within-subject confidence intervals, as described by Loftus and Loftus (1988), were ±17 ms for the standard arrays and ±10 ms for the single-item control arrays.

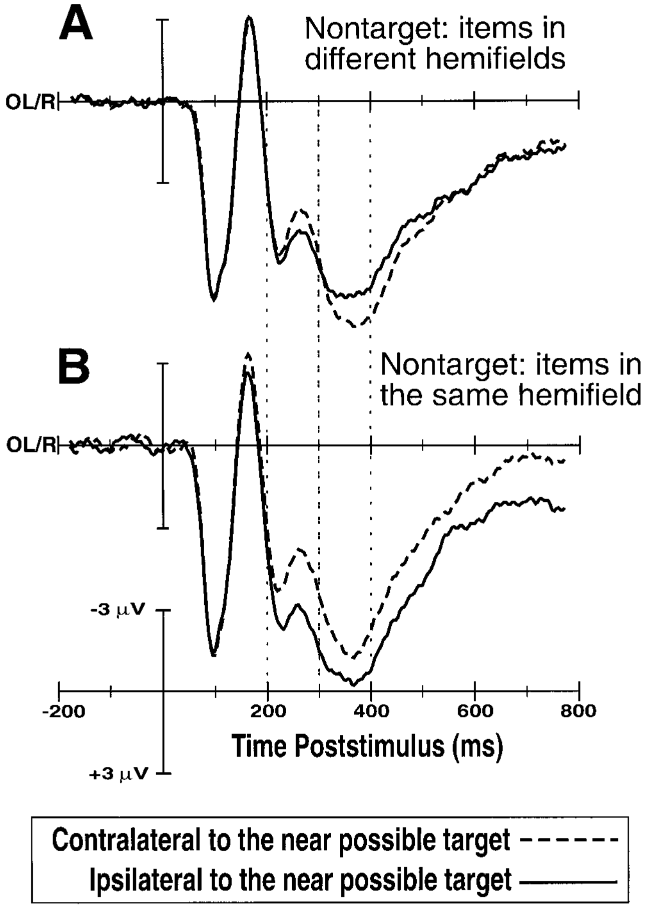

Figure 5. Grand average waveforms from Experiment 1. A: Waveforms elicited by target-absent arrays in which the two possible target items were in opposite hemifields. B: Waveforms elicited by target-absent trials in which the two possible target items were in the same hemifield. The dashed lines indicate the N2pc measurement windows. OL/R = average of lateral occipital electrode sites.

way ANOVA that paralleled the ANOVA used for the standard arrays, except that the stimulus configuration factor was replaced by an eccentricity factor (near vs. far). This ANOVA yielded a significant main effect of measurement window, $F(1, 11) = 7.69$, $p < .05$, reflecting the presence of the N2pc component during the early window and the absence of this component during the late window. However, the interaction between eccentricity and measurement window did not approach significance, $F(1, 11) = 1.55$, $p > .20$, indicating that similar N2pc components were elicited by near and far items. Planned comparisons verified that the N2pc was significant during the early window (200–300 ms) in both eccentricity conditions (i.e., near and far; *p*s < .05). In contrast, the N2pc was not significant during the late window (300–400 ms) in either the near or the far condition (*p*s > .75). Thus, the N2pc time course observed for the near and far items presented alone cannot explain the N2pc time course observed when they were presented together.

Discussion

In this experiment, we replicated our previous finding that the N2pc component shifts between hemispheres during visual search and also ruled out a low-level sensory confound. The ERP waveform was more negative contralateral to the near item from approximately 200–300 ms and then became more negative contralateral to the far item, consistent with serial models of visual search.

The time course of the N2pc component provides an approximate measure of the time course of attention shifting, suggesting that attention was first allocated to the near item approximately 200 ms after the onset of the search array and then shifted to the far item approximately 100 ms later. It is important to note, however, that this timing estimate is based on averaged waveforms and may not perfectly reflect the time course of processing on individual trials. For example, it is likely that the onset and duration of the allocation of attention to the near item varied from trial to trial, with an onset at 200–250 ms and a duration of 50–150 ms. The time course shown in Figure 5 should not, therefore, be treated as the time course of processing on a single trial. Moreover, the time course of the N2pc component may not be directly comparable to the difference in mean RT between near and far targets, because averaged ERP waveforms reflect the entire frequency distribution of trials, whereas mean RTs reflect only one

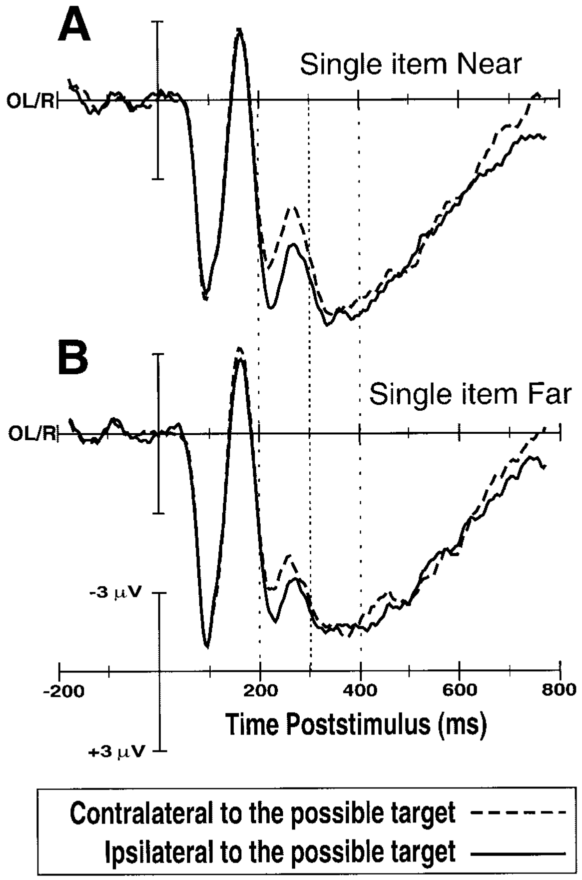

Figure 6. Grand average waveforms from the control arrays of Experiment 1. A: Waveforms elicited by target-absent arrays in which the possible target was at a near location. B: Waveforms elicited by target-absent arrays in which the possible target was at a far location. The dashed lines indicate the N2pc measurement windows. OL/R = average of lateral occipital scalp sites.

parameter of the frequency distribution. Nonetheless, the time course shown in Figure 5 provides a ballpark estimate of the timing of the shifts of attention, and the estimate of a 100-ms attentional dwell time corresponds very well with the 94-ms difference in RT observed between near-target and far-target trials with the standard arrays. In contrast, there was no significant slowing of RT or N2pc latency for far-target trials relative to near-target control trials, for which the arrays contained only one potential target item.

One substantial dissociation between RT and the N2pc component was observed. Specifically, RTs were shorter for near targets in the control arrays than in the standard arrays, whereas the onset of the N2pc component was essentially identical for both types of arrays. The shorter RTs for the control arrays might lead one to conclude that the far potential target item in the standard arrays was processed in parallel with the near potential target item, increasing RTs when the near item was a target and the far item was a nontarget relative to control trials on which a near target was present without a far potential target item.

However, there are many other possible explanations for this RT effect. For example, observers may have occasionally searched the far item before searching the near item in the standard arrays, leading to longer mean RTs for near-target standard arrays than for near-target control arrays. This is entirely plausible, because the observers had no extrinsic motivation to search the near item before the far item. Similarly, it is possible that observers sometimes shifted attention to the far item after they had searched the near item, even when the near item was a target (perhaps because the system responsible for shifting attention did not immediately receive the signal that a target had been detected).

It is important to note that the lateralization in the present waveforms reflects the *relative* allocation of attention to the near and far items rather than the *absolute* allocation of attention. Consequently, the time course in Figure 5 is consistent with a parallel model of attentional deployment in which attention is withdrawn from an item as soon as it is identified. In such a model, attention might initially be allocated to both the near and far items, with greater allocation to the near item and hence a more negative waveform contralateral to the near item. Because of its greater share of attention, the near item would be identified more quickly than the far item, leading to a rapid decrease in attention to the near item. As the allocation of attention to the near item decreased, the remaining allocation of attention to the far item would become visible as a more negative waveform contralateral to the far item.[4] Experiment 2 was designed to distinguish between serial search and this parallel account.

Experiment 2

In Experiment 2, we used a procedure in which the allocation of attention to one item could be measured independently of the allocation of attention to the other items. This procedure takes advantage of the fact that the N2pc component is measured as a difference between contralateral and ipsilateral waveforms and that, as a result, no net N2pc activity is observed when attention is allocated to an item on the vertical meridian. That is, when attention is allocated to an item on the vertical meridian, the concepts of ipsilateral and contralateral do not apply, and the N2pc is effectively invisible.

In this experiment, we used stimulus arrays in which one possible target was on the vertical meridian and the other was on the horizontal meridian. In such arrays, it is possible to observe the N2pc component elicited by the item on the horizontal meridian, uncontaminated by any ERP activity elicited by the allocation of attention to the item on the vertical meridian. When the near item is on the horizontal meridian and the far item is on the vertical meridian, the N2pc component—measured as the difference in voltage between electrode sites contralateral versus ipsilateral to the item on the horizontal meridian—will reflect the time course of the allocation of attention to the near item. That is, although attention will be allocated to the item on the vertical meridian for some period of time, this allocation will not lead to lateralized brain activity and will not influence the lateralized ERP responses elicited by the allocation of attention to the item on the horizontal meridian (except insofar as the allocation of attention to this item is influenced). Thus, when the near item is on the horizontal meridian and the far item is on the vertical meridian, the N2pc component will provide a pure measure of the time course of attentional allocation to the near item. Likewise, when the far item is on the horizontal meridian and the near item is on the vertical meridian, the N2pc component will provide a pure measure of the time course of attentional allocation to the far item.

Serial models predict that attention will be allocated solely to the near item for some period of time, followed by a period during which attention will be allocated solely to the far item. Parallel models, in contrast, predict that attention will initially be allocated to both items, with more attention allocated to the near item than to the far item.

In a perfectly serial system, the allocation of attention to the far item would not begin until attention has been completely withdrawn from the near item. However, if there is trial-to-trial variation in the onset or duration of the allocation of attention to the near item, then the offset of attentional allocation to the near item on some trials will be later than the onset of attentional allocation to the far item on other trials. Consequently, it is likely that the offset of the N2pc component for the near item will occur later than the onset of the N2pc component for the far item in the averaged ERP waveforms. However, if the search process is serial and the trial-to-trial variation in timing is not too large, then there should be a significant period of time during which the N2pc component is present for the near item and has not yet begun for the far item. In contrast, parallel models would predict that the N2pc component would onset at the same time for the near and far items, with a greater initial amplitude for the near item than for the far item.

Method

The method was identical to that of Experiment 1, except as noted. Twelve new volunteers from the same participant pool were recruited for this experiment. As illustrated in Figure 7, the sample arrays were composed of 48 outlined squares with a gap on one side. On each trial, 40 of these squares were black and placed at random locations on the same homogeneous gray background used in Experiment 1. Each array also contained 2 red squares ($x = 0.648$, $y = 0.330$, 14.72 cd/m^2), 2 green

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[4] We thank Shaun Vecera, Tom Spalding, and Gordon Logan for pointing out this possibility.

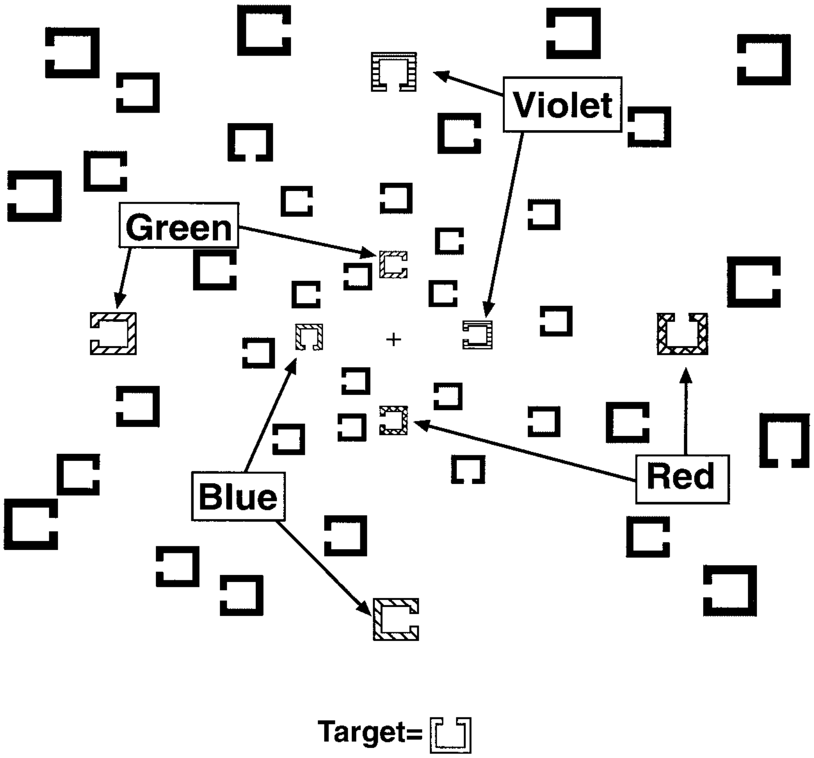

Figure 7. Example of a target-present stimulus array from Experiment 2. Participants searched the red, green, blue, or violet items in separate blocks of trials. The color labels were not present in actual displays. The colored items were always on either the vertical or horizontal meridian of the display. Near items were placed an average of 0.8° from fixation, with a random jitter of ±0.3°; far items were placed an average of 2.4° from fixation, with a random jitter of ±1.0°.

squares ($x = 0.330$, $y = 0.564$, 14.54 cd/m^2), 2 violet squares ($x = 0.320$, $y = 0.154$, 5.78 cd/m^2), and 2 blue squares ($x = 0.154$, $y = 0.065$, 5.65 cd/m^2). Four colors were used to control for sensory differences between conditions, ensuring that each meridian would contain two colored items on each side of the fixation point.

Each colored item was placed at one of eight predefined locations at a near (0.8 ± 0.3°) or a far (2.4 ± 1.0°) distance from fixation on the horizontal or vertical meridian (see Figure 7). One square of each color was presented at a near location, and the other was presented at a far location. Either the near or far square of a given color was presented on the horizontal meridian, and the other square of that color was presented on the vertical meridian. Figure 7 shows an example array in which the target color was red, the near possible target was on the vertical meridian, and the far possible target was on the horizontal meridian. With the exception of these constraints, the colored items were distributed at random among the eight locations. The near and far possible target locations were the same mean distance from fixation as the possible target locations used in Experiment 1. The black distractor items were distributed in the same way as in Experiment 1. The target was again a square with a gap at the top, and all squares were cortically scaled as in Experiment 1. Each of the four colors served as the attended color during two different trial blocks. Participants completed eight blocks of 96 trials, and a different randomized ordering of attended colors was used for each participant.

As in Experiment 1, trials involving incorrect behavioral responses or ocular artifacts were excluded from the averages. Five participants were replaced owing to excessive ocular artifacts (i.e., more than 25% of the trials were rejected as a result of eye movements). One participant was replaced owing to an inability to perform the task accurately (i.e., mean accuracy was below 75%). Among the remaining participants, artifacts led to the rejection of an average of 16.3% of trials in this experiment, with a single-participant maximum of 24.1%.

Results

Behavior. Accuracy was above 94% for all participants and all trial types. Accuracy was significantly higher for nontarget arrays ($M = 99.0\%$) than for near target-present arrays ($M = 97.2\%$), $F(1, 11) = 13.88$, $p < .01$. Performance on far target-present arrays was intermediate ($M = 98.2\%$), and this accuracy did not differ significantly from that for either the near target-present arrays or the target-absent arrays (ps $> .10$).

Table 2 provides mean RTs from the various trial types. RTs were shorter for targets at near locations ($M = 729$ ms) than for targets at far locations ($M = 832$ ms), producing a significant difference of 103 ms, $F(1, 11) = 56.15$, $p < .001$. In addition, target-absent responses ($M = 846$ ms) were significantly slower than responses to targets near fixation, $F(1, 11) = 27.44$, $p < .001$, but target-absent RTs were not significantly different from far target-present RTs ($p > .5$). These results are consistent with the proposal that the participants searched the near location first and then searched the far location. RTs were slightly shorter for targets on the horizontal versus the vertical meridian, an effect that approached significance, $F(1, 11) = 3.65$, $p = .082$.

Table 2
Mean Reaction Times (RTs; in Milliseconds): Experiment 2

Target condition	Mean RT
Absent	847
Present near: horizontal meridian	723
Present near: vertical meridian	735
Present far: horizontal meridian	818
Present far: vertical meridian	846

Note. The 95% within-subject confidence intervals were ±17 ms for the target-absent condition and ±17 ms for the target-present conditions.

Electrophysiology. Figure 8 shows the average ERP waveforms for target-absent trials in the various stimulus configurations. As predicted by serial models, there was very little overlap between the N2pc elicited by the near and far items. The N2pc component elicited by near objects began at approximately 200 ms and continued until approximately 375 ms, whereas the N2pc component elicited by the far object did not begin until approximately 350 ms.

To evaluate this pattern of results statistically, we conducted an ANOVA in which the factors were stimulus configuration (i.e., near item on the horizontal meridian and far item on the vertical meridian vs. near item on the vertical meridian and far item on the horizontal meridian), N2pc measurement interval (200–375 ms vs. 375–550 ms), and within-hemisphere electrode position (O1/2, OL/R, or T5/6). This analysis yielded a significant interaction between stimulus configuration and measurement interval, $F(1, 9) = 112.86$, $p < .001$, corresponding to the appearance of the N2pc component in different time intervals when the item on the horizontal meridian was near versus far. No other main effects or interactions were significant.

Planned comparisons were conducted to decompose the interaction between stimulus configuration and measurement window. Specifically, separate two-way ANOVAs with the factors of measurement window and within-hemisphere electrode position were performed for each of the two stimulus configurations. When the near attended-color item was lateralized, there was a significant main effect of measurement window, $F(1, 11) = 27.20$, $p < .001$. Follow-up analyses indicated that this effect was due to a significant N2pc component in the early measurement window, $F(1, 11) = 21.38$, $p < .001$, but no significant N2pc component in the late measurement window, $F < 1$. When the far attended-color item was lateralized, there was again a significant main effect of measurement window, $F(1, 11) = 32.87$, $p < .001$, but this was due to the opposite temporal pattern. That is, follow-up ANOVAs for this stimulus configuration indicated that there was no significant N2pc in the early measurement window, $F < 1$, but there was a significant N2pc in the late measurement window, $F(1, 11) = 8.57$, $p < .05$.

Could this pattern be due to intrinsic differences in the time course of processing for near and far items? Because of signal-to-noise considerations, it was not possible to include control arrays with only a single attended-color item in the present experiment. However, the near and far attended-color items in the present experiment were at the same mean distance from fixation as the near and far attended-color items in Experiment 1, and the same search items and task were used in both experiments. Moreover, the RTs for near-target and far-target trials were nearly identical for the two experiments (737 vs. 831 ms in Experiment 1 and 729 vs. 832 ms in Experiment 2). Consequently, the absence of N2pc timing differences for near and far items in the control arrays of Experiment 1 is sufficient to rule out the possibility that the very large difference in timing between near and far items in the present experiment was due to intrinsic differences in the time course of processing near and far items.

Discussion

This experiment examined the essential difference between serial and parallel search, namely the extent to which multiple items are attended simultaneously versus sequentially. The results provided clear evidence that, in this particular search task, attention was focused on only one item for a considerable period of time and then switched to another item. The degree of temporal overlap between the N2pc components elicited by the near and far items was minimal, even though trial-by-trial timing variations could have led to the appearance of temporal overlap in the averaged ERP waveforms. Thus, the results of Experiment 2 provide strong support for serial models of attention and are difficult to reconcile with slowly evolving parallel models.

The N2pc component elicited by the far item began at approximately 350 ms poststimulus, which was approximately 150 ms

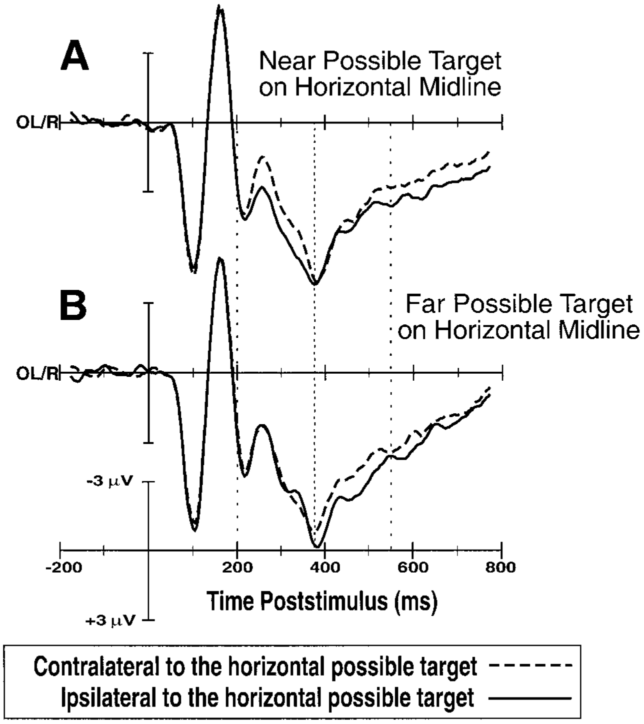

Figure 8. Grand average waveforms from Experiment 2. A: Waveforms elicited by target-absent arrays in which the near possible target was on the horizontal meridian and the far possible target was on the vertical meridian. B: Waveforms elicited by target-absent arrays in which the near possible target was on the vertical meridian and the far possible target was on the horizontal meridian. The dashed lines indicate the N2pc measurement windows. OL/R = average of lateral occipital scalp sites.

after the onset of the N2pc component elicited by the near item. This was substantially later than the N2pc polarity reversal observed in Experiment 1, which occurred at approximately 300 ms poststimulus (approximately 100 ms after the onset of the N2pc component). This may indicate that attention shifts from item to item every 150 ms, which would be relatively slow, even considering the difficulty of the target–nontarget discrimination. However, it is plausible that the relatively late onset of the N2pc component for the far item in the present experiment was a result of noise. We have conducted four previous experiments in which the N2pc component was used to track the time course of attention shifts, and the shifts appeared to occur after approximately 100 ms in all of these experiments (see, e.g., Figure 3). There is no reason to suppose that the time course of attention shifting should be later when estimated with the procedure used in the present experiment. In addition, onset and offset latencies are difficult to estimate precisely, because they are by nature time points at which the signal is small.

Thus, it seems plausible that the relatively late onset of the N2pc component for the far item in the present experiment was due to noise and that this experiment overestimated the amount of time required to shift attention from item to item. Moreover, even if 150 ms is required for attention to shift from one item to the next on a very difficult search task, the present experiment provides clear evidence that the items were processed in serial, with virtually no overlap in the processing of the near and far items. This result provides strong support for serial models and greatly constrains the set of possible parallel models.

General Discussion

The goal of this study was to distinguish between the modal serial and slowly evolving parallel subclasses of visual search models by determining whether search occurs in serial under at least some conditions. To accomplish this, we used the N2pc component to measure the time course of attentional allocation. In Experiment 1, the N2pc component switched from hemisphere to hemisphere when potential targets were in opposite hemifields, consistent with serial models. However, these results could be explained by a parallel model in which attention is redistributed across the possible target items as information accumulates about object identities. Experiment 2 was therefore designed to independently measure the allocation of attention to two potential target items, making it possible to determine whether attention was allocated to one object before being allocated to the next object. Very little temporal overlap in the allocation of attention to the two objects was observed. Instead, attention was initially allocated to one item and then shifted to the other item.

The results of Experiment 2 provide definitive support for the proposal that attention is deployed in a serial fashion during some demanding visual search tasks. It is possible that other demanding visual search tasks rely on parallel rather than serial processing, but the present results clearly rule out all parallel models in which attention cannot shift from one item to another within 100–150 ms (e.g., the model of Duncan, 1996). Moreover, the timing of the attention shifts as estimated from the N2pc data was similar to the timing as estimated from the RT data, consistent with the tenets of the modal serial subclass of search models.

Many serial models assume that attention can shift every 50 ms or even faster (Julesz, 1984; Treisman & Paterson, 1984; Wolfe, 1994), and the present results are not sufficient to demonstrate that attention can shift that quickly. It might be possible to combine the electrophysiological approach of the present study with stimuli that can be discriminated more quickly, but there are two problems that may make this approach difficult. First, if the time required to shift attention from one item to another is short and there is significant trial-to-trial variance in the onset or duration of the focusing of attention, then the averaged ERP waveforms may appear to indicate substantial overlap between the focusing of attention on multiple items even if there is little overlap on individual trials. Second, Wolfe, Alvarez, and Horowitz (2000) provided evidence that attention can shift much more rapidly when allowed to move randomly than when controlled in a top-down manner, and the present paradigm requires significant top-down control over attention. Thus, it is not clear whether the present approach will be able to demonstrate that attention can shift at speeds of greater than 100 ms per item, even if such shifts exist. Additional research involving this approach and other approaches will be necessary to assess the limits of serial shifts of attention.

The present results provide strong evidence that the attentional mechanism reflected by the N2pc component can operate in a manner consistent with serial models of visual search. It is always possible, however, that other attentional mechanisms may also operate during visual search and may be allocated in parallel rather than in serial. For example, once items are identified, decision processes may operate in parallel on object-identity representations. Nonetheless, the properties of the N2pc component match the properties of attention specified by most contemporary serial models of attention (e.g., the N2pc component is larger for conjunction targets than for feature targets), and the present findings are therefore consistent with the proposal that this variety of attention can operate in serial.

The N2pc component cannot be used to measure within-hemifield shifts of attention, and it is possible that the between-hemifield shifts of attention measured in the present study are different from within-hemifield shifts of attention. However, studies of search in normal individuals and in split-brain patients have shown that search rates among normal individuals are nearly identical whether the arrays are presented within a single hemifield or are divided between both hemifields (although split-brain patients can search bilateral arrays twice as fast as unilateral arrays; Luck et al., 1989; Luck, Hillyard, Mangun, & Gazzaniga, 1994). It is therefore likely that between-hemifield shifts of attention are not substantially different from within-hemifield shifts. For a more definitive conclusion, the present paradigm could be adapted for use with single-unit recordings from extrastriate cortex in monkeys, which would provide a more spatially detailed picture of the time course of attention shifts.

The search tasks used in this study were somewhat unusual because of the constraints of ERP recordings and the N2pc component, and it is important to consider how these results relate to more typical search tasks. In particular, each search array in the present study contained only two potential target items, clearly marked by their color, and the distractors served merely to provide competing visual information, which may be necessary to create the conditions under which serial processing is necessary (Cohen & Ivry, 1989, 1991). Despite this difference from typical search tasks, the present results demonstrate that observers can and do engage in serial processing under some conditions, providing a significant challenge to models that deny that observers can or do shift attention in serial.

Several previous studies have provided evidence of parallel processing in demanding search tasks, and it is important to consider why serial search was observed in the present study. Contemporary serial models are actually quite difficult to falsify, because they contain both a parallel stage and a serial stage. Consequently, evidence for parallel processing can often be explained away by proposing that it reflects the parallel stage of the model. The most obvious case of this is the exquisite evidence provided by Palmer and his colleagues that very difficult feature-based searches lead to nonzero slopes because of decision noise within a parallel, unlimited capacity system (Palmer, 1994, 1998; Palmer, Ames, & Lindsey, 1993; Palmer et al., 2000). These results are perfectly compatible with a model such as feature integration theory, in which feature processing is accomplished in parallel (e.g., Treisman, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Sato, 1990).

Other cases of parallel processing can be explained by two-stage models in which the parallel preattentive stage provides coarsely coded information about feature locations, as hypothesized by Cohen and Ivry (1989, 1991) and Luck et al. (1997). In these models, features are coded by areas such as V4, in which the receptive fields are moderately large, providing coarse information about feature location. This information can be used to discriminate conjunction stimuli when the spacing between items is large, but illusory conjunctions limit performance when the stimuli are packed too densely to be resolved by this coarse coding. According to this perspective, serial processing will be necessary when three conditions are met: (a) The task requires precise feature localization (as in conjunction tasks); (b) the search arrays are densely packed; and (c) highly accurate discriminations are required.

Previous demonstrations of parallel processing have not met all three of these conditions. For example, Mordkoff et al. (1990) used redundant targets to provide evidence of parallel processing of color–form conjunctions, but the stimuli were widely spaced, making it possible for the observers to obtain at least some information about the targets from the coarsely coded preattentive stage. Similarly, McElree and Carrasco (1999) used the response-signal speed–accuracy trade-off procedure to provide evidence of parallel processing in a conjunction search task, but the stimuli were sparsely distributed. Moreover, the stimulus arrays were presented for only 150 ms, leading to relatively poor asymptotic performance levels. Short display durations will naturally discourage serial search, and the low accuracy levels that were observed are exactly what would be expected if the observers based their responses on the information provided by the coarse preattentive stage. Thus, previous findings of parallel processing are consistent with two-stage serial models in which the preattentive stage can provide coarsely coded information about conjunctions.

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