Electrophysiological correlates of feature analysis during visual search

STEVEN J. LUCK AND STEVEN A. HILLYARD
Department of Neurosciences, University of California-San Diego, La Jolla

Abstract
Event-related brain potentials (ERPs) were recorded from normal young adults during visual search tasks in which the stimulus arrays contained either eight identical items (homogeneous arrays) or seven identical items and one deviant item (pop-out arrays). Four experiments were conducted in which different classes of stimulus arrays were designated targets and the remaining stimulus arrays were designated nontargets. In Experiments 1 and 2, both target and nontarget pop-out stimuli elicited an enhanced anterior N2 wave and a contralaterally larger posterior P1 wave, but Experiments 3 and 4 demonstrated that these components do not reflect fully automatic pop-out detection processes. In all four experiments, target pop-outs elicited enlarged anterior P2, posterior N2, occipital P3, and parietal P3 waves. The target-elicited posterior N2 wave contained a contralateral subcomponent (N2pc) that exhibited a focus over occipital cortex in maps of current source density. The overall pattern of results was consistent with guided search models in which preattentive stimulus information is used to guide attention to task-relevant stimuli.


Most electrophysiological studies of visual attention and perception have employed simple, discrete stimuli presented at a small number of predictable locations. In contrast, a large part of natural visual processing involves the discrimination of items that are placed in unpredictable locations and must be localized and identified within complex arrays of potentially distracting, irrelevant elements. Over the past two decades, visual search tasks have been increasingly utilized in studies of attention and perception, partly because they capture these qualities of visual scenes. In these tasks, arrays containing multiple stimulus items are presented and subjects must indicate whether or not a predefined target item is present among the nontarget distractor items. Performance is then measured in terms of reaction time (e.g., Treisman & Souther, 1985) or accuracy (e.g., Bergen & Julesz, 1983). The purpose of the present study is to characterize the event-related potential (ERP) components that are elicited during visual search and to consider what implications they may have for models of visual attention and perception.

There are two main classes of visual search tasks, one in which target detection is effortless and occurs in parallel and one in which target detection is effortful and appears to require a serial search of the stimulus array (Julesz, 1984; Treisman & Gelade, 1980). Effortless, parallel target detection usually occurs when the target item contains a simple feature that is absent from the distractors, causing it to "pop out" from the background. In contrast, serial processing is typically required when the target is defined by a conjunction of features or by the absence of some feature (for a discussion of counterexamples, however, see Treisman & Sato, 1990, and Wolfe, Cave, &Franzel, 1989). In a previous study (Luck & Hillyard, 1990a), we showed that the amplitude and latency of the P3 component can differentiate between these two classes of search tasks, supporting the parallel/serial distinction that is important in many models of visual search performance. The present study examines the parallel search case more closely in an attempt to characterize the processes underlying the effortless and parallel detection of simple pop-out targets.

There have been several attempts to explain the parallel detection of simple feature targets. Early versions of feature integration theory (e.g., Treisman & Gelade, 1980; Treisman & Souther, 1985) proposed that attention is needed only for localizing and conjoining features and that subjects can determine...

1 Recent evidence suggests that parallel and serial search patterns are actually opposite ends of a continuum rather than separate categories (e.g., Duncan & Humphreys, 1989; Treisman & Gormican, 1988). However, the extreme cases may be useful in revealing the nature of the underlying cognitive processes.
the presence or absence of targets possessing a unique feature by polling the relevant feature map directly, bypassing the use of a limited-capacity spatial attention mechanism (see also Braun & Sagi, 1990). However, more recent revisions of this theory have suggested that spatial attention may be necessary for the detection of any type of stimulus, whether defined by features or by conjunctions, and that parallel search performance is possible because a pop-out item can "call attention" to its location (Treisman, 1988, p. 205). This hypothesis is similar to Julesz's texton theory (Julesz, 1984), which proposes that differences in texton (feature) densities are automatically detected and can be used to guide attention.

These hypotheses lead naturally to the issue of automaticity. The phenomenological experience of pop-out stimuli is that they automatically grab attention and force themselves into awareness, hence appearing to pop out. Empirical support for automaticity was provided by Pashler (1988), who demonstrated that the presence of an irrelevant pop-out item will interfere with the processing of a relevant pop-out item, presumably because the irrelevant pop-out automatically attracts attention away from the relevant pop-out. One might therefore suspect that the difference between parallel and serial search performance depends on the presence or absence of automatic attentional orienting. However, Wolfe et al. (1989) showed that search performance can be parallel for triple conjunction targets, which possess no unique features that could automatically attract attention. The parallel search performance for triple conjunction targets, according to these authors, is the result of the use of preattentive feature information by top-down processes to guide attention to stimuli containing relevant features. Because triple conjunction targets possess relevant features in three stimulus dimensions, this process is even more effective than it is for the more typical double conjunction targets (see also Hoffman, 1979; Treisman & Sato, 1990). Thus, although some stimuli may attract attention automatically via bottom-up processes, parallel search performance can also be achieved by means of top-down processes that do not require automatic allocation of attention to the target. In addition, Jonides and Yantis (1988) showed that subjects trying to discriminate a target letter in an array of characters are not any faster when the target letter is presented in a unique color, even though the unique color might be expected to attract attention automatically. Thus, the ability of pop-out stimuli to attract attention in an automatic fashion has not yet been determined conclusively.

These issues—the necessity of attention for pop-out detection and the automaticity of attentional allocation to pop-outs—can also be addressed using electrophysiological methods. To use ERPs to assess the role of attention in pop-out detection, however, it is necessary to determine the relationship between the visual ERP components and attention. Unfortunately, there have been few electrophysiological studies employing visual search tasks (e.g., Hoffman, Simons, & Houck, 1983; Luck & Hillyard, 1990a; Wijers et al., 1987), and there is little information about the ERP components that are elicited during this task. However, several potentially relevant components have been observed in other paradigms.

When stimuli are presented individually in attended and unattended channels, the attention-sensitive ERP components differ according to the stimulus dimension that defines the attended channel. When a particular location is attended, the exogenous P1 and N1 waves elicited by stimuli presented in that location are enlarged (Hillyard & Munte, 1984; Mangun & Hillyard, 1988, 1990), an effect that has been interpreted as a sign of attentional modulation of sensory processing in the visual pathways (Mangun, Hillyard, & Luck, 1993). Enlargement of these exogenous components has been found only when location is the relevant attentional dimension; when other features such as color or spatial frequency are attended, the typical response to attended stimuli includes a broad selection negativity (Harter, Aine, & Schroeder, 1982; Prevè & Harter, 1982). In addition, attended features may also elicit a frontocentral positivity in the P2 latency range (Harter & Guido, 1980; Hillyard & Munte, 1984; Mangun, Mangun, & Hillyard, 1990; Wijers, Mulder, Okita, Mulder, & Scheffers, 1989) and/or an occipitally maximal positivity in the P3 latency range (Luck & Hillyard, 1990a; Mangun et al., 1990). These distinctive electrophysiological indices of attention appear to reflect the distinction between spatial and nonspatial features that is fundamental to feature integration theory and related models.

An ERP component that may be particularly relevant for visual search performance has been observed in recent studies at scalp sites overlying cortical visual areas contralateral to the position of an object that is being identified. We will call this component N2pc to denote its latency range (N2) and its distinctive scalp distribution (posterior contralateral). The N2pc component has been observed primarily when an item must be identified in the presence of simultaneous distractor items (Heinze, Luck, Mangun, & Hillyard, 1990; Luck, Heinze, Mangun, & Hillyard, 1990; Luck & Hillyard, 1990a) and may reflect an attentional process that is used during visual search. In particular, Luck and Hillyard (in press-a) found that this component is present when a target item is discriminated in the presence of competing distractor items but is absent when the distractors are eliminated, when the distractors do not conflict with the target, or when the distractors provide task-relevant information; these results led to the conclusion that the N2pc component reflects an attentional filtering process that is used to suppress the processing of competing or irrelevant information during object identification.

The following experiments were designed to determine which of the ERP components discussed above are actually present during pop-out detection and to provide a groundwork for using psychophysiological measures to examine the theoretical issues surrounding visual search. When considering the relationships between ERP components and psychological processes, however, it is crucial to note that only a small fraction of psychological and physiological processes may be reflected in scalp-recorded ERPs. For example, even if pop-outs were automatically detected at an early stage of processing, there is no guarantee that this process would produce an ERP signal at the scalp. Therefore, the existence of an ERP component that is correlated with some hypothetical cognitive process is usually more revealing than the absence of such a component.

**Experiment 1: Responses to Target and Nontarget Pop-Outs**

Three models of pop-out detection are contrasted in this study, one in which preattentive feature maps are polled for activity (e.g., Treisman & Souther, 1985), one in which unique features are automatically detected and subsequently identified via attention (e.g., Julesz, 1984; Treisman, 1988), and one in which preattentive information about feature identity is used to guide attention to the locations of probable targets (e.g., Treisman &
Sato, 1990; Wolfe et al., 1989). To examine these models, Experiment 1 compared three types of stimuli: homogeneous arrays, arrays containing a target pop-out item, and arrays containing a nontarget pop-out item (i.e., an item that is deviant in a different feature dimension from the target). If the target is detected by checking a map of the relevant features directly, without the use of attention, then the target pop-out arrays should be differentiated from both the nontarget pop-outs and the homogeneous arrays at the same initial stage. Alternatively, if the presence and location of a pop-out item are determined first, followed by the application of attention to determine the pop-out's identity, then the initial task-sensitive ERP components should differentiate between homogeneous arrays and arrays containing pop-outs but should not differentiate between target and nontarget pop-outs. In addition, if attention is used in the discrimination of pop-outs but can be guided by preattentive feature information, then the attention-related N2pc component should be present for target pop-outs but not for irrelevant pop-outs.

**Methods**

**Subjects**

The subjects in all experiments reported here were right-handed, neurologically normal college student volunteers between 18 and 29 years old who were paid for their participation. All subjects had normal or corrected-to-normal visual acuity and reported normal color vision. Twelve subjects participated in Experiment 1.

**Stimuli and Task**

The stimuli consisted of arrays of eight colored bars presented on a microcomputer-controlled video display at a distance of 100 cm (see Figure 1 for stimulus dimensions). On 50% of trials, all eight bars were small, blue, and vertical. On the remaining trials, one of the bars was horizontal ($p = .17$), green ($p = .17$), or large ($p = .17$) and clearly popped out from the array. The four array types were presented in random order, and the positions of the bars within each array also varied randomly. Each array was presented for 750 ms, with a variable-duration blank interval of 600-900 ms between arrays. A fixation point was continuously present in the center of the display.

At the beginning of each trial block, one of the three pop-out types was designated the target, and subjects were required to press a button with one hand for target-present trials and another button with the other hand for target-absent trials. The two nontarget pop-out types were therefore grouped into the same response class as the homogeneous arrays. Each subject received 18 trial blocks, with each of the three pop-out types serving as target, and each block consisted of 96 stimulus presentations. Half of the subjects used the right hand for target-present trials and half used the left hand. Subjects were instructed to maintain fixation at all times, to minimize blinking, and to respond as quickly as possible without making errors.

**Recording and Analysis**

The electroencephalogram (EEG) was recorded from nonpolarizable electrodes mounted in an elastic cap (ElectroCap International) and located at standard left and right hemisphere positions spanning much of the surface of the scalp (International 10/20 System names: F3, F4, C3, C4, P3, P4, O1, O2, T5, T6). These sites and the right mastoid were measured relative to a left mastoid reference electrode, and the ERP waveforms were algebraically rereferenced to the average of the left and right mastoids after averaging. The horizontal electrooculogram (EOG) was recorded as the voltage between a pair of electrodes located 1 cm lateral to each eye, and an electrode beneath the left eye was used to monitor eyeblinks. These signals were amplified by a Grass Model 12 polygraph with a bandpass of 0.01-100 Hz and then digitized at 256 Hz by a minicomputer. The digitized data were averaged offline; trials with blinks, eye movements, or incorrect behavioral responses were automatically excluded from the averages.

The amplitude of each ERP component was quantified as the mean voltage within a specified latency window, relative to the mean prestimulus voltage, and the latency was quantified as the time point of the maximum peak within a slightly wider window. The measurement sites and windows are summarized for each component in Table 1. To differentiate between temporally overlapping components, the N2 wave was measured separately at anterior and posterior scalp sites. The P1 and posterior N2 components were measured separately for trials with left and right visual field pop-outs; these are the only components that have exhibited position sensitivity across a large number of visual search and selective attention experiments. To measure the latencies of the experimental effects without distortion from the overlapping exogenous components, latencies were measured from difference waves in which the ERPs elicited by the homogeneous arrays were subtracted from the ERPs elicited by the pop-out arrays. The latencies of the components elicited by homogeneous arrays did not vary across conditions, justifying the use of this procedure.

The ERP measurements were analyzed in repeated-measures analyses of variance (ANOVA), using the Greenhouse–Geisser correction for nonsphericity (Jennings & Wood, 1976). For each component, an omnibus ANOVA was performed using four factors: target pop-out dimension (orientation, color, or size),

![Figure 1. Examples of the homogeneous, orientation pop-out, color pop-out, and size pop-out stimulus arrays. The stimulus items were placed at random locations within an imaginary rectangle that subtended 9.2 x 6.9 degrees of visual angle and that was centered about a continuously visible fixation point. Each individual bar subtended 0.3 x 0.9 degrees, except for the bar used to create the size pop-out stimulus, which subtended 0.9 x 0.9 degrees. Solid bars = blue; stippled bars = green.](image-url)
Table 1. ERP Component Measurement Windows and Electrode Locations

<table>
<thead>
<tr>
<th>Component</th>
<th>Peak latency search window (ms)</th>
<th>Mean amplitude integration window (ms)</th>
<th>Measurement electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>50-150</td>
<td>75-125</td>
<td>P3, P4, O1, O2, T5, T6</td>
</tr>
<tr>
<td>P2</td>
<td>150-300</td>
<td>175-250</td>
<td>F3, F4, C3, C4, P3, P4</td>
</tr>
<tr>
<td>Anterior N2</td>
<td>200-350</td>
<td>250-325</td>
<td>F3, F4, C3, C4, P3, P4</td>
</tr>
<tr>
<td>Posterior N2</td>
<td>175-300</td>
<td>200-275</td>
<td>P3, P4, O1, O2, T5, T6</td>
</tr>
<tr>
<td>P3</td>
<td>300-700</td>
<td>350-550</td>
<td>all scalp sites</td>
</tr>
</tbody>
</table>

stimulus class (homogeneous array, target pop-out, or nontarget pop-out), electrode location (in the anterior–posterior dimension, as listed in Table 1), and hemisphere (left or right). Because the latencies were measured from difference waves, the homogeneous arrays were excluded from the latency ANOVAs. The homogeneous arrays were also excluded when the P1 and N2pc components were analyzed on the basis of pop-out position, and the following factors were used: target pop-out dimension (orientation, color, or size), stimulus class (target or nontarget pop-out), electrode location (parietal, occipital, or temporal), hemisphere (left or right), and contralaterality (ipsilateral or contralateral pop-out relative to the electrode location). Planned pairwise comparisons were conducted to assess the specific differences between homogeneous, nontarget pop-out, and target pop-out arrays.

Results

Behavioral Performance

Response accuracy and reaction time are summarized for all experiments in Table 2. In Experiment 1, color was clearly the most discriminable pop-out dimension: for both target and nontarget stimuli, accuracy was greater and responses were faster when color was the target feature. When the data were collapsed across physical stimulus dimensions, reaction times were slowest for the targets, fastest for the homogeneous arrays, and intermediate for the nontarget pop-out arrays. A statistical analysis of the reaction times yielded significant main effects of pop-out dimension ($F[2,22] = 65.82, p < .001, \epsilon = 0.9743$) and stimulus class ($F[2,22] = 91.15, p < .001, \epsilon = 0.5299$) and a significant interaction between these variables ($F[4,44] = 13.89, p < .001, \epsilon = 0.6792$). Planned pairwise comparisons showed that mean reaction times for target pop-outs, nontarget pop-outs, and homogeneous arrays were all significantly different from each other ($p < .001$). An analysis of accuracy produced only a significant main effect of stimulus class ($F[2,22] = 41.73, p < .001, \epsilon = 0.8471$).

N2 Components

The ERPs elicited by the three task-defined stimulus classes are displayed in Figure 2. Target and nontarget pop-out arrays both elicited an enhanced anterior N2 component relative to the homogeneous arrays, but at posterior sites only the target pop-outs elicited an enhanced N2.² The N2 enhancement also had

²This effect may or may not reflect an increase in amplitude for the same set of neural generator sources that produces the N2 component for the homogeneous arrays. The term enhancement is used here simply to denote a change in amplitude in the latency range of a basic ERP component.

Table 2. Reaction Time (RT) and Percent Correct for Each Target Condition and Array Type

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Condition²</th>
<th>Homogeneous</th>
<th>Color</th>
<th>Orientation</th>
<th>Size</th>
<th>Pop-out</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RT (ms)</td>
<td>% correct</td>
<td>RT (ms)</td>
<td>% correct</td>
<td>RT (ms)</td>
<td>% correct</td>
</tr>
<tr>
<td>1</td>
<td>Color</td>
<td>350</td>
<td>100</td>
<td>458</td>
<td>92</td>
<td>363</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>395</td>
<td>100</td>
<td>414</td>
<td>100</td>
<td>498</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>388</td>
<td>100</td>
<td>406</td>
<td>100</td>
<td>420</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>378</td>
<td>100</td>
<td>427</td>
<td>97</td>
<td>426</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>Single (.50)</td>
<td>455</td>
<td>98</td>
<td>418</td>
<td>97</td>
<td>448</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>Multiple (.50)</td>
<td>490</td>
<td>97</td>
<td>458</td>
<td>96</td>
<td>481</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>Single (.17)</td>
<td>421</td>
<td>100</td>
<td>481</td>
<td>95</td>
<td>515</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Multiple (.17)</td>
<td>436</td>
<td>100</td>
<td>512</td>
<td>96</td>
<td>524</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>450</td>
<td>99</td>
<td>467</td>
<td>96</td>
<td>492</td>
<td>94</td>
</tr>
<tr>
<td>3</td>
<td>Array color</td>
<td>386</td>
<td>98</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pop-out</td>
<td>471</td>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>428</td>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Color</td>
<td>463</td>
<td>99</td>
<td>465</td>
<td>98</td>
<td>472</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>534</td>
<td>98</td>
<td>533</td>
<td>98</td>
<td>520</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>499</td>
<td>99</td>
<td>499</td>
<td>98</td>
<td>496</td>
<td>98</td>
</tr>
</tbody>
</table>

²Condition was defined by target identity in Experiment 1, 3, and 4, and by target variability and target probability in Experiment 2.
Figure 2. Grand average ERPs for homogeneous arrays, target pop-outs, and nontarget pop-outs recorded at frontal, central, parietal, occipital, and posterior temporal electrode sites. These waveforms were averaged over left and right hemisphere electrode pairs and over the three pop-out dimensions. Negative is plotted upward, and time zero represents stimulus onset.

an earlier onset latency at the posterior sites than at the anterior sites. These differences imply the existence of separate anterior and posterior N2 subcomponents.

Separate statistical analyses were performed on the N2 wave for anterior and posterior electrode locations (see Table 1). For both anterior and posterior sites, a significant stimulus class effect was obtained for N2 amplitude (anterior: $F[2,22] = 8.17, p < .02, \epsilon = 0.5195$; posterior: $F[2,22] = 3.91, p < .05, \epsilon = 0.9451$). Planned comparisons indicated that both target and nontarget pop-outs differed from the homogeneous arrays at anterior sites (target: $F[1,11] = 9.16, p < .02$; nontarget: $F[1,11] = 26.79, p < .001$), whereas only the target pop-outs differed significantly at the posterior sites (target: $F[1,11] = 19.68, p < .001$; nontarget: $F < 1$).

Figure 3. Grand average difference waves constructed by subtracting the ERPs elicited by homogeneous arrays from the ERPs elicited by target (left) and nontarget (right) pop-out arrays. The difference waves from the frontal (top) and occipital (bottom) electrode sites, averaged over left and right, are shown separately for each of the three pop-out dimensions.

Difference waves were computed in which the ERPs elicited by homogeneous arrays were subtracted from the ERPs elicited by pop-out stimuli, and these waveforms are displayed for each target condition in Figure 3. These waveforms show that the anterior and posterior N2 enhancements were larger for color targets than for orientation or size targets, but this difference was reduced for nontarget pop-outs, resulting in significant Pop-Out Dimension × Stimulus Class interactions (anterior: $F[4,44] = 12.34, p < .001, \epsilon = 0.5453$; posterior: $F[4,44] = 15.46, p < .001, \epsilon = 0.6032$). Like reaction time, the latency of the anterior N2 wave was shorter for color pop-outs (268 ms) than for orientation (288 ms) and size pop-outs (303 ms), and this effect was evident for both target and nontarget pop-outs. However, the latency of the posterior N2 was unaffected by pop-out dimension. These results led to a significant pop-out dimension main effect for anterior N2 latency ($F[2,22] = 17.57, p < .001, \epsilon = 0.9857$), but no significant main effects or interactions involving pop-out dimension were obtained for posterior N2 latency ($p > .20$).

**P2 and P3 Components**

In addition to eliciting enhanced anterior and posterior N2 components, target pop-outs also elicited an enhanced P2 at anterior scalp sites and a large P3 with a parietal maximum and broad distribution (see Figure 2). The P2 enhancement was maximal at the frontal electrodes and was largest for color pop-out targets, resulting in a significant Pop-Out Dimension × Stimulus Class × Electrode interaction ($F[8,88] = 4.30, p < .02, \epsilon = 0.3774$). The Stimulus Class × Electrode interaction was significant when target pop-out arrays were compared with homogeneous arrays ($F[2,22] = 5.19, p < .05, \epsilon = 0.5306$) and with nontarget pop-out arrays ($F[2,22] = 6.83, p < .05, \epsilon = 0.5304$) but not when nontarget pop-out arrays were compared with homogeneous arrays ($F < 1$). The peak latency of the P2 wave appeared to be shorter for color pop-outs than for orientation or size pop-outs, but this effect did not quite attain statistical significance ($p > .05$) and may have been due to the overlapping anterior N2 component.
Like the P2 component, the parietally maximal P3 wave was enhanced for target pop-outs, resulting in a significant stimulus class main effect \( (F[2,22] = 93.19, \ p < .001) \). Planned comparisons showed that the P3 was larger for target pop-outs than for either nontarget pop-outs \( (F[1,11] = 126.89, \ p < .001) \) or homogeneous arrays \( (F[1,11] = 110.38, \ p < .001) \), but the slight difference between homogeneous arrays and nontarget pop-outs did not reach significance \( (p > .05) \). The color targets produced shorter P3 latencies (409 ms) than did the orientation (439 ms) and size (446 ms) targets, resulting in a significant target dimension main effect in the latency ANOVA \( (F[1,11] = 12.66, \ p < .005) \).

**Laterized Components**

When trials were sorted as a function of pop-out location, as displayed in Figure 4, a negative-going component could be observed at contralateral relative to ipsilateral scalp sites from 200 to 300 ms, especially at temporal and occipital scalp sites. This difference between contralateral and ipsilateral activity in the N2 latency range will be used to define the presence of the N2pc component. The N2pc was much larger for target pop-outs than for nontarget pop-outs, resulting in a Stimulus Class \( \times \) Contralaterality interaction \( (F[1,11] = 52.25, \ p < .001) \); however, separate analyses of the target and nontarget waveforms showed that the small amount of contralaterality observed for nontarget pop-outs was statistically significant \( (F[1,11] = 14.14, \ p < .005) \), as was the large contralaterality observed for targets \( (F[1,11] = 51.74, \ p < .001) \).

In addition to the negativity observed at contralateral sites relative to ipsilateral sites, there was also an enlarged N2 at the ipsilateral sites relative to the ERPs elicited by homogeneous arrays. However, it is clear from these waveforms that the N2 at contralateral sites began to deviate from the homogeneous waveform before the N2 at ipsilateral sites. This result suggests that there are two posterior N2 components, one that is contralateral and begins early (i.e., the N2pc component) and another that is bilateral and begins later. The posterior bilateral N2 subcomponent will henceforth be denoted N2pb to indicate its latency range (N2) and scalp distribution (posterior bilateral).

The existence of two separate posterior N2 components was also supported by the effects of pop-out dimension: color targets produced a larger overall posterior N2, but this effect was not accompanied by an increase in the contralaterality of the posterior N2, as would be expected for a unitary, contralaterally larger component (see McCarthy & Wood, 1985). This additivity was reflected in significant main effects of pop-out dimension \( (F[2,22] = 17.83, \ p < .001, \ \eta = .8133) \) and contralaterality \( (F[1,11] = 41.28, \ p < .001) \) without a significant interaction between these factors \( (F < 1) \).

The P1 component was also significantly larger at sites contralateral to the position of the pop-out \( (F[1,11] = 4.57, \ p < .05) \), although the contralaterality was quite small (approximately 0.25 \mu V). This effect appeared to be somewhat larger for targets than for nontargets, but the stimulus class \( \times \) Contralaterality interaction was not significant \( (p > .25) \).

**Discussion**

This experiment demonstrated that different ERP components are elicited by homogeneous arrays of stimuli, arrays containing a nontarget pop-out item, and arrays containing a target pop-out item. Although the task did not explicitly require subjects to differentiate between nontarget pop-outs and homogeneous arrays, three separate results indicate that the nontarget pop-outs were indeed differentially processed: (a) reaction times were longer for nontarget pop-outs than for homogeneous.
arrays, (b) both target and nontarget pop-outs elicited an enhanced anterior N2 component, and (c) the P1 component was larger at scalp sites contralateral to the position of target and nontarget pop-out items. These results are consistent with previous results indicating that pop-outs are detected and attract attention even when such detection is unnecessary and may interfere with task performance (Pashler, 1988). These findings also accord with single-unit data recorded from anesthetized monkeys in areas V1 (Knierim & Van Essen, 1992) and V4 (Desimone & Schein, 1987) showing that some cells exhibit smaller responses when stimulated by a portion of a large homogeneous pattern rather than a single stimulus or a stimulus that is discontinuous with the background pattern. However, although these results are consistent with the automatic detection of pop-out stimuli, subjects were not strongly motivated to ignore the nontarget pop-outs in the present study, and these results therefore cannot be considered strong evidence for automaticity. This issue will be explored in more detail in Experiments 3 and 4, wherein the P1 effect was shown to be caused by physiological refractoriness rather than automatic attentional allocation.

Although the above results indicate that some processing occurs nonselectively for both target and nontarget pop-outs, other results from this experiment indicate that pop-out identity was extracted fairly rapidly. The P2, N2pb, and N2pc effects were observed primarily for target pop-outs, indicating that top-down information about stimulus classification affected pop-out processing within 175 ms of stimulus onset. Thus, it is not yet clear whether attention is directed to all feature discontinuities before target identification begins or whether identification processes are applied selectively to target features. In addition, to the extent that the N2pc component reflects spatial selective attention (Luck & Hillyard, in press-a), the presence of the N2pc component in this experiment suggests that pop-out identity is discriminated by means of attentional processing rather than the direct polling of feature map activity.

ERP components associated with pop-out dimensions, orientation, color, and size pop-outs all elicited qualitatively similar electrophysiological responses. These stimulus properties are all processed primarily in the parvocellular pathway that courses through the ventral portion of visual cortex (Hubel & Livingstone, 1987), and the present results suggest that common mechanisms are available for processing different features within this pathway (cf. Cavanagh, Arguin, & Treisman, 1990).

**Experiment 2: Effects of Probability and Predictability**

Experiment 1 provided support for the hypothesis that all pop-outs attract attention automatically but also provided support for the competing hypothesis that attention is applied only to items that possess relevant features. In Experiment 2, we examined these hypotheses in a different manner by examining the timing rather than the presence or absence of the various ERP components and by examining the effects of prior knowledge of pop-out identity on these components.

If pop-outs are identified by first localizing texture discontinuities nonselectively in a completely stimulus-driven fashion and subsequently using attention to identify the items producing the discontinuities (Julesz, 1984), then pop-out detection should not depend on prior knowledge of the pop-out's identity. However, if preattentive processes can be controlled by top-down information about which features are task relevant, then prior knowledge of pop-out identity should facilitate pop-out detection. Treisman (1988) described an experiment supporting this latter hypothesis. In one condition of this experiment, the identity of the pop-out item was constant across stimulus presentations; in another condition, the target could be an orientation, color, or size pop-out, and subjects were unable to predict pop-out identity before stimulus onset. Reaction times were approximately 90 ms longer in the unpredictable condition than in the predictable condition, supporting the hypothesis that top-down information plays an important role in pop-out detection.

Although these results suggest that top-down information can affect the efficiency of pop-out detection, there are alternative interpretations of these results. For example, the presence of multiple target types may have increased the memory load imposed by the task, thus producing the observed difference in reaction times. The present experiment attempts to determine which stage of processing is affected in this type of task by using the temporal information contained in the ERP waveforms. If prior knowledge of target identity facilitates response speed by influencing early perceptual processes, then latencies for all of the target-sensitive ERP components should be shorter in the predictable condition than in the unpredictable condition. However, if the reaction time effect is due to changes in postperceptual processing, then only the longer latency components should be affected. The present experiment tested these hypotheses by using two conditions, one in which the same pop-out feature was used throughout a block of trials (e.g., always an orientation pop-out) and one in which the pop-out feature varied at random across successive stimulus presentations. All pop-outs were targets in both conditions so that the subjects could predict the identity of the target for each stimulus array in the former condition but not in the latter.

This experiment also explored the relationship between target probability and the ERP correlates of pop-out detection. Probability was manipulated for three reasons. First, some ERP components become small when highly probable targets are used, reducing the precision of the latency measurements required for the present experiment. Second, probability-related differences between components may be useful in separating functionally different components and determining their psychological correlates. Third, different experimental designs often require different target probabilities, and a systematic exploration of this variable may facilitate comparisons across different studies of visual search.

**Methods**

**Subjects**

Sixteen subjects participated in this experiment and were randomly divided into two groups of 8, as discussed below.

**Stimuli and Task**

The pop-out types and stimulation parameters were identical to those used in Experiment 1, except as noted below. There were two conditions, constant target and variable target. In both conditions, arrays containing a pop-out were designated targets (irrespective of the feature distinguishing the pop-out item from the distractors) and homogeneous arrays were designated non-targets. As in Experiment 1, subjects pressed one thumb button
for target-present arrays and another for target-absent arrays. In the constant-target condition, a single pop-out feature was used within a given block, and in the variable-target condition, all three types of pop-outs (orientation, color, and size) were presented unpredictably within each block.

For one group of subjects (the target-17 group), 17% of the stimuli were targets and 83% were homogeneous arrays; for the other group (target-50), 50% of the stimuli were targets and 50% were homogeneous arrays. In the variable-target condition, each of the three pop-out types comprising the set of possible targets was therefore 6% probable for the target-17 group and 17% probable for the target-50 group. Each subject received 24 trial blocks, 12 in each condition, and each block consisted of 96 stimulus presentations.

Data Collection and Analysis
The data collection, averaging, and measurement procedures were identical to those used in Experiment 1. For the measurement of latencies, difference waves were again constructed in which the ERPs elicited by the homogeneous arrays were subtracted from the ERPs elicited by the pop-out arrays. This subtraction reveals the differential processing of the pop-out and homogeneous arrays, independent of the neural activity shared by both types of arrays. To disentangle the N2pb and N2pc waves, the N2pb was measured from difference waves in which the ERPs elicited by homogeneous arrays were subtracted from the ERPs elicited by ipsilateral pop-outs, and the N2pc was measured from difference waves created by subtracting ipsilateral waveforms from contralateral waveforms. However, although these difference waves should primarily reflect N2pb and N2pc activity, respectively, they may not provide completely isolated and independent measures of these two components. Latencies were also measured for the nontarget waveforms and analyzed separately.

To assess the effects of response class (i.e., pop-out arrays versus homogeneous arrays) and the effects of pop-out dimension (orientation, color, or size), two mixed-model ANOVAs were conducted for each measurement: one analysis compared the homogeneous arrays with the average of the three pop-out dimensions in each condition, and the second analysis excluded the homogeneous arrays and compared the three different pop-out dimensions with each other. The variables in the first set of ANOVAs were target predictability (constant or variable target), target probability (target-17 or target-50), response class (target or nontarget stimulus), electrode location (in the anterior-posterior direction, as listed in Table 1), and hemisphere (left or right). The second set of ANOVAs substituted a pop-out dimension variable (orientation, color, or size) for the response class variable.

Results
Behavioral Performance
Response accuracy and reaction time are summarized in Table 2. Reaction times were faster in the constant-target condition than in the variable-target condition; the difference was 36 ms for the target-50 group and 20 ms for the target-17 group. These results led to significant target predictability \((F[1, 14] = 47.69, p < .001)\) and Target Probability \(\times\) Probability \((F[1, 14] = 5.23, p < .05)\) effects. The longer reaction times for the variable-target condition qualitatively replicated the results of Treisman (1988), but the effects were smaller than the 90 ms difference reported in that study. Accuracy for the target-50 group was also slightly lower in the variable-target condition, resulting in a significant Target Predictability \(\times\) Probability interaction \((F[1, 14] = 4.61, p < .05)\). Target predictability had approximately equal effects for all three pop-out dimensions, and there were no significant interactions involving target predictability and pop-out dimension for either reaction time or accuracy.

As in Experiment 1, color was clearly the most discriminable pop-out dimension: responses were faster and more accurate for color pop-outs than for orientation or size pop-outs. This resulted in a significant main effect of pop-out dimension for both accuracy \((F[2, 28] = 10.32, p < .001, \eta = 0.7687)\) and reaction time \((F[2, 28] = 22.50, p < .001, \eta = 0.9026)\).

ERP Component
Figure 5 displays the ERPs elicited by pop-out and homogeneous arrays for the target-17 and target-50 groups, averaged over pop-out dimension and target predictability. As in Experiment 1, targets in the target-17 group elicited a sequence of several components including P2, anterior N2, N2pb, N2pc, and P3. The P2, N2pb, and P3 components for targets were much smaller in the target-50 group than in the target-17 group, but the anterior N2 and N2pc components were relatively unaffected by target probability.

![Figure 5](image_url)

**Figure 5.** Grand average ERPs elicited by homogeneous and pop-out arrays in the target-17 (left) and target-50 (right) groups, averaged across left and right hemisphere electrode sites and constant- and variable-target conditions.
**Figure 6.** Grand average difference waves constructed by subtracting the ERPs elicited by homogeneous arrays from the ERPs elicited by pop-out arrays, averaged over left and right frontal electrode sites for the target-50 (top) and target-17 (bottom) groups. The left column displays separate waveforms for the orientation, color, and size pop-outs, averaged over the constant- and variable-target conditions; the right column displays separate waveforms for the constant- and variable-target conditions, averaged over the three pop-out dimensions.

**ERP Latency Effects**

The effects of pop-out dimension and target predictability are presented in Figures 6 and 7, and statistical analyses of these effects are summarized in Tables 3 and 4. Figure 6 displays pop-out minus homogeneous difference waves from frontal electrode sites: the left panel displays the waveforms for each of the three pop-out dimensions, collapsed over the constant- and variable-target conditions, and the right panel displays the waveforms for the constant- and variable-target conditions, averaged over the three pop-out dimensions. Similar waveforms are presented for posterior temporal electrodes in Figure 7, except that the N2pc was separated from the N2pb by computing two types of difference waves: contralateral minus ipsilateral difference waves are shown at the top, representing the amount of exclusively contralateral ERP activity; ipsilateral minus homogeneous difference waves are shown at the bottom, representing the amount of bilateral (or ipsilateral) ERP activity.

**Table 3. Summary of Latency ANOVAs for Each Component in Experiment 2**

<table>
<thead>
<tr>
<th>Component</th>
<th>P2</th>
<th>Anterior N2</th>
<th>N2pb</th>
<th>N2pc</th>
<th>Nontarget P3</th>
<th>Target P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target probability</td>
<td>n.s.</td>
<td>n.s.</td>
<td>.005</td>
<td>n.s.</td>
<td>n.s.</td>
<td>.001</td>
</tr>
<tr>
<td>Pop-out dimension</td>
<td>.001</td>
<td>.001</td>
<td>.02</td>
<td>.01</td>
<td>n.s.</td>
<td>.02</td>
</tr>
<tr>
<td>Target predictability</td>
<td>.005</td>
<td>.002</td>
<td>n.s.</td>
<td>.01</td>
<td>.001</td>
<td>.01</td>
</tr>
<tr>
<td>Probability × Dimension</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>.02</td>
</tr>
<tr>
<td>Probability × Predictability</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>.002</td>
<td>n.s.</td>
</tr>
<tr>
<td>Dimension × Predictability</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>.02</td>
</tr>
</tbody>
</table>
Figure 7. Grand average difference waves constructed by subtracting the ipsilateral pop-out ERPs from the contralateral pop-out ERPs (top) and by subtracting the homogeneous array ERPs from the ipsilateral pop-out ERPs (bottom). The left column shows waveforms for the three pop-out dimensions averaged over the constant- and variable-target conditions; the right column shows waveforms for the constant- and variable-target conditions averaged over the three pop-out dimensions.

appeared to be larger in the target-50 condition, in which the reaction time effects were also larger. In Experiment 1, all three pop-out dimensions produced equal latencies for the posterior N2 components. In the present experiment, however, size pop-outs produced significantly longer latencies for both the N2pb ($F[2,28] = 5.00, p < .02, \epsilon = 0.8040$) and the N2pc ($F[2,28] = 5.57, p < .01, \epsilon = 0.7908$). These effects were present primarily in the target-17 group, although the Probability x Pop-Out Dimension interaction did not reach significance for either measurement.

The ERP latency and reaction time results are summarized in Figure 8, which displays the change in latency observed between the constant- and variable-target conditions for each component. Two aspects of these results are especially notable. First, the effects of target predictability generally increased over the course of processing, from the P2 component through the final behavioral response. Second, although the Target Predictability x Probability interaction was significant only for the non-target P3 component, the target predictability effect was larger in the target-50 group than in the target-17 group for almost every component. The target-elicited P3 component appears to be an exception to this second generalization, but functionally different P3 components were probably being measured in the target-17 and target-50 groups.

Figure 8. Changes in reaction time and ERP peak latencies due to target variability in the target-17 (open bars) and target-50 (solid bars) groups. The changes were measured by subtracting the latency in the constant-target condition from the latency in the variable-target condition. The latencies were measured from the target minus nontarget difference waves for all of the ERP components except for the component labeled P3 N, which was measured from the nontarget waveforms directly. The latency measures were averaged over all of the sites at which each component was measured.

**ERP Amplitude Effects**

The major predictions for this experiment focused on latency measurements, but this experiment also provided an opportunity to examine the effects of probability and target predictability on the amplitude of the task-sensitive ERP components.

**P2 and P3 amplitude.** The P3 and anterior P2 components were much larger for targets than for nontargets in the target-17 group, but these differences were small in the target-50 group (see Figure 5). Moreover, the difference between the target and nontarget trials in the P3 latency range had an occipital maximum in the target-50 group, as opposed to the parietal maximum observed for the target-17 group. Because P3 amplitude would not be expected to differ between equiprobable classes of stimuli with similar response requirements and because the difference between pop-out and no-pop-out ERPs in the target-50 condition had an occipital maximum, the P3 wave in this condition is probably different from the parietally maximal P3 component typically observed for improbable targets.

The statistical analysis of target and nontarget P2 amplitudes, summarized in Table 4, yielded a significant main effect of response class ($F[1,14] = 23.85, p < .001$). Because the P2 effect was largest at the frontal electrode sites, a significant Response Class x Electrode Site interaction was also obtained ($F[2,28] = 4.79, p < .05, \epsilon = 0.5672$). The greater size of the P2 effect for the target-17 group resulted in a significant Probability x Response Class x Electrode Site interaction ($F[2,28] = 5.95, p < .02, \epsilon = 0.5672$).

Statistical analyses of the P3 wave also revealed significant response class ($F[1,14] = 185.01, p < .001$), Response Class x Electrode Site ($F[4,46] = 7.41, p < .02, \epsilon = 0.3499$), and Probability x Response Class x Electrode Site ($F[4,46] = 5.16, p < .02, \epsilon = 0.3499$) effects. The P3 effect was somewhat larger in the variable-target condition, resulting in a significant Target
Table 4. Summary of Amplitude ANOVAs for Each Component in Experiment 2

<table>
<thead>
<tr>
<th></th>
<th>P2</th>
<th>Anterior N2</th>
<th>N2pb</th>
<th>N2pc</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target probability</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Response class</td>
<td>.001&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.</td>
<td>n.s.&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.001&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Target predictability</td>
<td>.005&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.</td>
</tr>
<tr>
<td>Probability \times Response Class</td>
<td>n.s.&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Probability \times Predictability</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Response Class \times Predictability</td>
<td>.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.</td>
<td>.001&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n.s.</td>
<td>.001</td>
</tr>
</tbody>
</table>

Note: These ANOVAs included the response class variable but not the pop-out dimension variable. The response class variable was not used in the N2pc analysis.

<sup>a</sup>Significant interaction with electrode site.

Predictability \times Response Class interaction ($F[1,14] = 22.42$, $p < .001$). In addition, there was a long-lasting right hemispheric positivity overlapping the P3 component, as in Experiment 1 (see footnote 3), resulting in a significant hemisphere main effect ($F[1,14] = 13.54$, $p < .005$).

**N2 amplitude.** As in Experiment 1, the targets elicited enhanced anterior and posterior N2 components relative to the homogeneous arrays. The anterior N2 effect appeared to be smaller for the target-17 group, but this may be an artifact due to the overlapping P2 and P3 waves, which were larger for this group. The enhanced anterior N2 for target stimuli and the greater size of this effect for the target-50 group resulted in significant Response Class \times Electrode Site ($F[2,28] = 8.38$, $p < .01$, $\epsilon = 0.7627$) and Probability \times Response Class \times Electrode Site ($F[2,28] = 8.08$, $p < .01$, $\epsilon = 0.7627$) interactions. Like the P2 and P3 effects, the N2pb effect was robust for the target-17 group but virtually absent for the target-50 group, resulting in a significant Probability \times Response Class interaction ($F[1,14] = 20.50$, $p < .002$).

The amplitude of the anterior N2 (Figure 6) was not significantly different in the constant- and variable-target conditions ($p > .25$), but the N2pb enhancement (Figure 7, bottom) was larger in the constant-target condition than in the variable-target condition, resulting in a significant Target Predictability \times Response Class interaction for the N2pb ($F[1,14] = 18.33$, $p < .001$). Thus, although the N2pb became larger when the target response class was made less probable, its amplitude decreased when there were multiple stimulus classes comprising the target class.

**Contralaterality.** The contralateral minus ipsilateral difference waves displayed in Figure 7 (top) show a robust N2pc component, which resulted in significant contralaterality ($F[1,14] = 46.43$, $p < .001$) and Contralaterality \times Electrode ($F[2,28] = 5.81$, $p < .01$, $\epsilon = 0.9691$) effects. Although the N2pb was significantly larger for the target-17 group than for the target-50 group (Figure 7, bottom) and was larger in the constant-target condition than in the variable-target condition, neither of these factors significantly affected N2pc amplitude ($F < 1$ for Probability \times Contralaterality and $p > .2$ for Target Predictability \times Contralaterality). In addition, although the color pop-out produced a larger N2pb, the size pop-out produced a significantly larger N2pc ($F[2,28] = 6.45$, $p < .01$, $\epsilon = 0.8201$, for Pop-Out Dimension \times Contralaterality). These results provide additional evidence for the existence of separable N2pb and N2pc subcomponents.

The P1 was also larger at scalp sites contralateral to the position of the pop-out, producing a significant contralaterality main effect ($F[1,14] = 6.24$, $p < .05$). This effect appeared to be larger in the constant-target condition than in the variable-target condition, but this difference was not statistically reliable ($p > .1$).

**Discussion**

The ERP results from this experiment indicate that prior knowledge of pop-out identity speeds pop-out identification at several stages. As processing proceeded, foreknowledge of pop-out identity led to greater and greater effects, from 7-10 ms for the P2 component to 20-36 ms for the behavioral response. This progressive increase may reflect a "snowball" effect in the variable-target condition, whereby each processing stage received delayed information from the preceding stage and then added an additional delay before passing the information forward to the next stage. The existence of these effects for almost every ERP component after 175 ms suggests that top-down information about pop-out identity can influence the speed of processing at both early and late stages. These effects are consistent with guided search models proposing that bottom-up feature information can be combined with top-down task information to guide attention to the locations of likely targets (e.g., Treisman & Sato, 1990; Wolfe et al., 1989) but are also consistent with the task-controlled polling of feature maps (Treisman & Gelade, 1980).

The results of this experiment also provide information about the availability of preattentive feature information to higher level cognitive processes. In this experiment, the presence of a texture discontinuity was sufficient to indicate target presence, whereas Experiment 1 required subjects to identify the feature that created the discontinuity. Could subjects therefore perform the task without attention by simply detecting the presence or absence of a texture discontinuity? Because approximately

---

<sup>6</sup>CLOSE INSPECTION OF THE CONTRALATERAL MINUS IPSILATERAL DIFFERENCE WAVES IN FIGURE 7 INDICATES THAT THE CONTRALATERAL RESPONSE IS ACTUALLY TRI-PHASIC, CONSISTING OF A NEGATIVITY PEAKING AT 225 MS, A RETURN TO BASELINE OR POSITIVITY AROUND 300 MS, AND A SUBSEQUENT LONG-LASTING NEGATIVITY. THE LATER TWO PHASES ARE ESPECIALLY EVIDENT FOR THE TARGET-17 GROUP AND CAN ALSO BE OBSERVED IN THE ERPS FROM EXPERIMENT 1 (SEE FIGURE 4). THIS NEGATIVE-POSITIVE-NEGATIVE SEQUENCE COULD ARISE FROM ANY OF SEVERAL POSSIBLE GENERATOR CONFIGURATIONS, SUCH AS A SINGLE POLARITY-INVERTING SOURCE, A LONG-LASTING NEGATIVE COMPONENT DIVIDED BY A POSITIVE COMPONENT, TWO SEPARATE COMPONENTS AND A POSITIVE COMPONENT, ETC.
equivalent reaction times and similar ERP components were observed in both experiments, it appears that subjects do not have fast and direct access to the presence of feature discontinuities per se and must use the same detection processes for both tasks.

A second goal of Experiment 2 was to determine the effects of target probability on the ERP components observed in Experiment 1, and this manipulation clarified the existence of multiple separable components in the N2 and P3 latency ranges. For example, the anterior N2 became slightly smaller when the targets were made improbable, whereas the N2pb was much larger for improbable targets, indicating that the anterior and posterior N2 components reflect different cognitive processes (functional differences between anterior and posterior N2 components for visual stimuli have also been described by Breton, Ritter, Simson, & Vaughan, 1988). Moreover, although probability had a strong effect on the N2pb, the N2pc component was unaffected by probability, providing additional evidence that the N2pc and N2pb components reflect separable processes. Additional evidence for this separability was provided by the effects of pop-out dimension and target predictability, which were different for the N2pb and N2pc.

In addition to differentiating between the anterior N2, N2pb, and N2pc components, the probability manipulation also allowed two different components to be distinguished in the P3 latency range. When the target class was improbable, targets elicited a large, parietalesl maximal P3 wave. When the target and non-target classes were equiprobable, however, there was an occipitally maximal difference between the target and non-target ERPs in the P3 latency range. This finding replicates and extends the results of Luck and Hillyard (1990a), who observed a similar occipital P3 in a visual search task when the target was defined by the presence of a simple feature, as in the present study. However, although the P3 effect was parietalesl maximal in the target-17 condition, the occipitally maximal P3 effect may have also been present in this condition but may have been masked by the larger parietalesl P3 component.

Experiments 3 and 4: Automaticity of Pop-Out Detection

Experiments 1 and 2 provided support for the hypothesis that parallel visual search is accomplished by the use of top-down information to restrict processing to task-relevant features. However, this model is difficult to reconcile with the apparently automatic detection of pop-outs that was suggested by the finding of an enhanced anterior N2 and a contralaterally larger P1 for both target and non-target pop-outs in Experiment 1. The purpose of Experiments 3 and 4 was to determine if these effects truly reflect automatic pop-out detection.

Experiment 3 used a very simple manipulation to test for automatic pop-out detection: a pop-out detection condition was compared with a condition in which pop-out detection was not required. If the anterior N2 and contralateral P1 effects reflect automatic pop-out detection, then they should be observed even when pop-out detection is not required. Alternatively, if the allocation of processing resources to pop-out stimuli is controlled by top-down processes, then these effects should be absent when subjects are not motivated to identify pop-outs. Experiment 3 also eliminated a potential confound that was present in the previous experiments. In Experiments 1 and 2, the pop-out items were physically different from the distractors, and such physical differences are known to affect the P1 component. For example, the green bars used as color pop-outs may have been brighter than the blue bars used as distractors, thus producing a larger P1 component at scalp sites contralateral to the position of the pop-out. To mitigate these effects, the identities of the pop-out and distractor items were reversed on half of the runs in Experiment 3.

After Experiment 3 was conducted, it was discovered that the contralateral P1 enhancement observed for pop-outs in the previous experiments might have been caused by physiological refractoriness rather than being an automatic response to the pop-outs. This potential confound derives from the assumption that the P1 component reflects the summed activity of a large population of neurons, each of which has been stimulated more or less recently and is therefore in a particular state of refractoriness. In the preceding experiments, the neurons that responded to the small blue vertical bars used as distractors were activated frequently and were thus in a highly refractory state. The neurons that responded to a particular pop-out item, however, were activated primarily when that item was presented within their receptive fields, which happened infrequently. Accordingly, these neurons would have been in a less refractory state on the average and should have produced larger responses than the more refractory neurons that responded to the distractor items. Because the P1 is usually largest in the hemisphere contralateral to the position of the item that elicits it, these refractoriness effects would lead to a larger P1 at sites contralateral to the pop-out item.

Experiment 4 eliminated this confound by reversing the identities of the pop-out and distractor items at random within runs of stimuli. For example, the first stimulus might contain a green pop-out item among blue distractors and the second might contain a blue pop-out item among green distractors. The order of these arrays was randomized, so neurons that respond differentially to the pop-out and distractor items would be activated equally often and would therefore be made equally refractory.

Although Experiments 3 and 4 were primarily designed to assess the automaticity of the anterior N2 and contralateral P1 effects, we also used these experiments as an opportunity to examine the scalp distribution of the N2pc component more carefully so that the location of its neural generator source could be estimated. As discussed previously, the N2pc component appears to be related to attentional processing, and determining the location of the N2pc's generator would provide information about important questions about attention. At the psychological level, it would indicate whether the attentional process reflected by this component operates at an early stage or a late stage. At the physiological level, it would suggest hypotheses about which areas of cortex can be modified by top-down information, presumably mediated by the extensive backward connections of the visual system. Previous single-unit recordings from monkeys have indicated that inferotemporal cortex and extrastriate area V4 can be modulated by spatial selective attention, but that primary visual cortex is not affected by task requirements in a spatially specific manner (Moran & Desimone, 1985).

Methods

Subjects

Eight subjects participated in Experiment 3, and 12 subjects participated in Experiment 4.

---

We are grateful to Marty Woldorff for pointing out this possibility.
ERPs during visual search

Stimuli and Procedure

The stimuli in Experiment 3 consisted of homogeneous arrays ($p = .5$) and arrays with an orientation pop-out ($p = .5$); the distractor items were vertical in half of the runs and horizontal in the other half, and the pop-out items were perpendicular to these distractors. Half of the arrays were entirely blue and half were entirely green. Array color and pop-out presence or absence varied randomly and independently within each run. Two conditions were used: in the pop-out condition, subjects were required to press one button upon detecting the pop-out bar and to press another button for homogeneous arrays; in the array color condition, subjects were told to ignore the pop-out and press one button for blue arrays and another for green arrays. Half of the subjects experienced the pop-out condition first and half experienced the array color condition first. The assignment of responses to the left and right hands varied randomly across subjects.

In both experiments, the colored bars used to create the stimulus arrays were green-vertical, green-horizontal, blue-vertical, or blue-horizontal. In Experiment 4, each stimulus array was composed of eight instances of one of these items ($p = .33$) or seven instances of that item and one instance of an item that differed in orientation ($p = .33$) or color ($p = .33$) but not both (e.g., when green-vertical was the distractor, either green-horizontal or blue-vertical could be the pop-out, but not blue-horizontal). All of the possible stimulus combinations were presented in random order within each trial block. On half of the blocks, subjects were instructed to press one button whenever they detected any type of orientation pop-out — whether it was a horizontal bar among vertical distractors or vice versa — and to press another button whenever there was no orientation pop-out. On the remaining blocks, color pop-outs were the target instead of orientation pop-outs. Each subject received 16 trial blocks, each consisting of 150 stimulus presentations.

Recording and Analysis

To provide a more accurate estimate of ERP generator sources, the EEG was recorded from customized electrode caps with 28 electrodes placed in a regular grid over the posterior half of the head (see Figure 11) and 2 anterior electrodes situated approximately 1.5 cm lateral to F3 and F4. The reference and EOG electrodes, amplifiers, filters, digitization, and averaging procedures were identical to those used in the preceding experiments. The same latency windows were used for measuring the ERP components, and these components were measured from the electrode sites closest to the sites used in Experiments 1 and 2.

To estimate the locus of the N2pc's generator, topographic maps of the N2pc's voltage distribution over the scalp were computed and converted into current source density (CSD). CSD is the second spatial derivative of the voltage gradient over the scalp and provides a reference-free estimate of the flow of current perpendicular to the scalp at each electrode location (Perrier, Perrin, & Bertrand, 1988). CSD maps emphasize superficial generator sources and reduce the effects of the spatial smearing caused by the resistance of the skull, thereby increasing the probability that the location of a component's CSD focus lies near the neural generator of the component. The topographic CSD maps from this experiment were plotted using the spherical spline interpolation technique described by Perrin, Perrier, Bertrand, and Echallier (1989). To reduce contamination from overlapping components in the N2pc latency range, the topographic maps were derived from difference waves in which the ERPs elicited by homogeneous arrays (Experiment 3) or non-target pop-out arrays (Experiment 4) were subtracted from the ERPs elicited by target pop-out arrays.

Results

Behavioral Performance

Subjects were significantly faster ($F[1,7] = 67.44, p < .001$) and more accurate ($F[1,7] = 23.76, p < .002$) for the array color discrimination than for the pop-out discrimination in Experiment 3 (see Table 2). However, accuracy and reaction time were essentially equivalent for pop-out arrays and homogeneous arrays within these conditions ($p > .25$ for reaction time; $F < 1$ for accuracy). In Experiment 4, reaction times were significantly faster when color was the target feature ($F[1,11] = 403.31, p < .001$); there were no other significant effects for either reaction time or accuracy.

Experiment 3 ERP Waveforms

Figure 9 (top) displays the ERP waveforms from anterior electrode sites in Experiment 3. When pop-outs were targets, they elicited enhanced P2 and anterior N2 components, but these enhancements were virtually eliminated in the array color condition, resulting in significant Stimulus Class x Target Type x Electrode Site interactions (P2: $F[2,14] = 5.48, p < .05, \epsilon = 0.6550$; anterior N2: $F[2,14] = 31.60, p < .001, \epsilon = 0.6919$). Separate analyses of the pop-out and array color conditions showed that significant P2 and N2 effects were present only in the pop-out condition (P2: $F[2,14] = 6.45, p < .05, \epsilon = 0.7164$; ante-

![Figure 9](image-url)

Figure 9. Grand average ERP waveforms from the pop-out detection (left) and array color discrimination (right) conditions of Experiment 3, averaged over the two array colors. The waveforms at the top were averaged over the frontal scalp sites, and the ERPs elicited by homogeneous and pop-out arrays are plotted separately. The bottom traces show the ERPs elicited by pop-out stimuli at posterior temporal scalp sites ipsilateral and contralateral to the position of the pop-out item.
rior N2: $F[2,14] = 33.74, P < .001, \epsilon = 0.6362$) and were absent in the array color condition ($p > .15$). Thus, although irrelevant pop-outs in Experiment 1 elicited an enhanced anterior N2 component when subjects were required to detect relevant pop-outs, this component was not observed when the task did not require the detection of any pop-outs.

The ERPs from contralateral and ipsilateral posterior temporal electrode sites are shown at the bottom of Figure 9. The N2pc component was present for pop-outs when they were task relevant but was absent when subjects were required to discriminate array color, resulting in a significant Contralaterality x Task interaction ($F[1,7] = 32.65, p < .001$). There was no observable N2pc component for target arrays compared with nontarget arrays in the present experiment, presumably because target probability was 50%, comparable to the target-50 group in Experiment 2.

As in the preceding experiments, the P1 component was slightly larger at posterior contralateral sites, resulting in a Contralaterality x Electrode Site interaction ($F[1,14] = 4.23, p < .05, \epsilon = 0.2068$). This small ($0.2 \mu V$) effect did not depend on whether subjects were discriminating pop-out presence or array color ($F < 1$) or whether the pop-out item was horizontal or vertical ($F < 1$) and again appeared to be an automatic response to the pop-out items.

**Experiment 4 ERP Waveforms**

In contrast with Experiments 1, 2, and 3, the P1 component was not significantly larger at contralateral sites in Experiment 4 (for both contralaterality and Contrastnterality x Electrode Site), presumably because the refractoriness confound was eliminated. Because the P1 contralaterality is typically quite small, however, it is difficult to be certain that the elimination of the refractoriness confound was responsible for the lack of statistical significance. Accordingly, a sequential analysis was conducted to examine the effects of refractoriness more directly. Pop-out stimuli were sorted according to whether the distractors in the previous stimulus were the same as the current pop-out item or were the opposite feature. If refractoriness accounts for the P1 contralaterality observed in Experiments 1–3, then the contralaterality should be observed in Experiment 4 when the distractors from the previous stimulus differ from the pop-out in the current stimulus, but this effect should be absent when the preceding distractors are the same as the current pop-out. The ERPs from this sequential analysis are shown in Figure 10 and confirm this prediction: the P1 was contralaterally larger when preceded by opposite distractors but not when preceded by identical distractors, resulting in a significant Sequential Order x Contrastnterality x Electrode Site interaction ($F[2,22] = 5.26, p < .02, \epsilon = 0.8454$). Thus, it appears that the P1 contralaterality is not an automatic response to pop-outs per se but is instead a consequence of a refractoriness confound that is present in most pop-out detection paradigms.

**Current Source Density Analysis**

Current source density isocontour maps are plotted in Figure 11 for Experiments 3 and 4, showing CSD for the N2pc and P1 latency ranges. The N2pc data were plotted such that the right side of the schematic head represents the side contralateral to the position of the pop-out, and the data were taken from difference waves in which the ERPs elicited by homogeneous arrays (Experiment 3) or nontarget pop-out arrays (Experiment 4) were subtracted from the ERPs elicited by target pop-out arrays. The P1 plots were created directly from the ERPs elicited by homogeneous arrays, without the subtraction procedure used for the N2pc plots.

Although there are some differences between the two experiments in CSD topography for both the N2pc and P1 components, the CSD for both components is focused over the occipital lobe. In addition, these maps indicate that the CSD focus for the N2pc component is somewhat more posterior/medial than the CSD focus for the P1 component. This result is clearer for Experiment 4 than for Experiment 3, possibly because of the different subtraction procedures and/or experimental protocols employed for these experiments or the individual differences in cortical folding patterns among the subjects in these experiments. In any case, these maps suggest that the N2pc component is generated in the occipital lobe, perhaps at a location posterior to the generator of the P1 component.

**Discussion**

Experiments 3 and 4 have demonstrated that the anterior N2 enhancement and P1 contralaterality effects observed in Experiments 1 and 2 do not reflect automatic responses to pop-out stimuli; the anterior N2 enhancement was eliminated when subjects attended to the global color of the stimulus arrays and were not required to detect pop-outs, and the P1 contralaterality was eliminated when refractoriness was controlled. In addition, although reaction times for nontarget pop-outs were significantly slower than reaction times for homogeneous arrays in Experiment 1, indicating differential processing of the pop-out arrays, reaction times did not differ significantly between these stimulus classes in the array color condition of Experiment 3. Thus, these results accord with the behavioral results of Jonides and Yantis (1988) indicating that pop-out detection is not strongly automatic.

Based on the CSD maps from these experiments, it appears that the generator of the N2pc component is located in the occipital lobe. The focus of CSD for the P1 component lies approximately on the border between cortical areas 18 and 19, and Mangun, Hillyard, and Luck (1993) suggested that it is gener-
Experiment 3

200-250

N2pc

80-120

P1

Experiment 4

200-250

80-120

Figure 11. Isocontour maps of current source density. The top row maps were computed from the mean amplitude between 200 and 250 ms in difference waves created by subtracting the ERPs elicited by homogeneous arrays (Experiment 3) or nontarget pop-out arrays (Experiment 4) from the ERPs elicited by target pop-out arrays. The bottom row maps were computed from the mean amplitude between 80 and 120 ms in the homogeneous array ERPs. Light shading represents negative values (current sinks), and dark shading represents positive values (current sources). Each isocontour line represents a change of $2 \mu V/m^2$ for the N2pc maps, $10 \mu V/m^2$ for the P1 maps from Experiment 3, and $7 \mu V/m^2$ for the P1 maps from Experiment 4.

ated in lateral extrastriate cortex. The CSD focus of the N2pc appears to be at least as posterior as the focus of the P1, consistent with a generator located in striate or extrastriate cortex, although this proposal must be considered tentative until more evidence has been garnered. Thus, although the P1 component onsets 100 ms before the N2pc component, the N2pc may be generated at an anatomically similar level of visual cortex, presumably under the control of feedback projections from higher areas.

General Discussion

ERP Componentry

The main goals of this study were to describe the relationships between several ERP components and various aspects of visual search and to draw some preliminary conclusions about theories of visual attention based on the electrophysiological findings. Several components were sensitive to variables such as response class, target probability, and target variability, and many of these effects have been replicated, either across the four experiments presented here or in other studies of visual search (e.g., Hillyard, Mangun, Luck, & Heinze, 1990; Luck, Fan, & Hillyard, 1993; Luck & Hillyard, 1990a, 1990b, in press-a, in press-b).

Seven separable components were sensitive to various visual search parameters, and Table 5 provides a summary of the effects of the major experimental variables on each of these components. The anterior N2 component and the P1 contralaterality effect were elicited by both targets and nontargets (under some conditions), and the remaining five components were primarily present only for targets. Of the target-elicited components, the P2, parietal P3, and N2pb components were much larger when the targets were improbable, whereas the N2pc and occipital P3 components were largely unaffected by target probability. Donchin and colleagues (Donchin, 1980; Donchin & Coles, 1988) have accounted for the influence of probability on the parietal P3 by proposing that this component represents a process of context updating, which is minimized when targets are presented frequently. However, the P2 and N2pb components are probably related to the analysis of the stimuli rather than to postperceptual processing (Naätänen & Picton, 1986; Ritter, Simson, & Vaughan, 1983), and it is not clear why they should be affected by probability.

Enhanced anterior P2 components have previously been observed when subjects were required to attend to a particular color (Hillyard & Munte, 1984; Kenemans, Kok, & Smulders, 1993; Mangun et al., 1990; Wijers et al., 1989). The present study extends these results, showing that the P2 effect is present for the features of orientation and size as well as color and can occur when only one of several simultaneously presented objects contains the relevant feature. This component therefore appears to reflect a transdimensional feature detection process.

It is somewhat difficult to determine the relationship between the N2 components observed in the present study and N2 components observed in other paradigms. Comparing scalp distributions across paradigms may be misleading because the existence of separate anterior and posterior N2 components in the present study was only revealed in the comparison between the ERP's elicited by target and by nontarget pop-out stimuli; without this manipulation, the anterior and posterior N2 components would have appeared to be a single, broadly distributed component. The dependence of the N2pb on stimulus probability, however, suggests that N2pb may be related to the N2 components observed during visual classification tasks by several authors (e.g., Renault & Lesèvre, 1978; Ritter et al., 1983; Simon, Vaughan, & Ritter, 1976). The finding that the anterior N2 may be elicited by both targets and nontargets suggests that it may be related to the auditory mismatch negativity (Naätänen, Simpson, & Loveles, 1982). However, the mismatch negativ-
ity appears to be more strongly automatic than the anterior N2 (Woldorff, Hackley, & Hillyard, 1991), and Näätänen (1990) argued that the mismatch negativity can be elicited only by auditory stimuli (but see Woods, Alho, & Algazi, 1992). The anterior N2 also bears some resemblance to the NA component described by Ritter and colleagues (e.g., Ritter et al., 1983, 1988), which also has a somewhat anterior scalp distribution and is insensitive to target probability but typically onsets earlier than the anterior N2 effect observed in the present study.

**Implications for Visual Search Mechanisms**

Three models of pop-out detection have been contrasted in this study: one in which all texture discontinuities are automatically detected, followed by the application of attention to determine pop-out identity (e.g., Julesz, 1984; Treisman, 1988), one in which feature maps are polled directly, without spatially selective attentional processing (e.g., Treisman & Gelade, 1980), and one in which preattentive information is used to guide attention to the locations of items containing relevant features (e.g., Treisman & Sato, 1990; Wolfe et al., 1989). The present results provide evidence that top-down information about target identity influences pop-out detection at both early and late stages of processing, consistent with the feature map polling and guided search models. In contrast, no physiological index corresponding to the automatic detection of feature discontinuities was observed.

It is somewhat more difficult to differentiate between the feature map polling and guided search models on the basis of the present results. Experiment 1 demonstrated that the N2pc component accompanies the identification of target pop-outs, and other evidence (Luck & Hillyard, in press-a) suggests that this component reflects a process by which one item is selected for identification and the surrounding items are suppressed. This component has previously been observed during conjunction discrimination tasks (Luck et al., 1993), and its presence for simple feature targets in the present study suggests that a common attentional mechanism is used for both feature detection and conjunction discrimination (see also Luck & Hillyard, in press-b). Together, these results support the hypotheses of Wolfe et al. (1989) and others who have proposed that preattentive processes can be used to guide attention rapidly to the location of an object that contains relevant features, thus leading to the fast, set-size-insensitive reaction times that are observed during visual search for simple features. It must be stressed, however, that these conclusions depend on the assumption that the N2pc component reflects the application of spatial attention to the target item.

Although the anterior N2 enhancement and P1 contralaterality effects observed for nontarget pop-outs in Experiment 1 suggested that pop-outs are automatically detected regardless of identity, Experiments 3 and 4 demonstrated that these effects do not reflect fully automatic pop-out detection. In Experiment 3, the anterior N2 enhancement was eliminated for orientation pop-outs when subjects were required to discriminate the color of the entire stimulus array, suggesting that pop-out detection is suppressed when small-scale texture discontinuities are task irrelevant. However, although the anterior N2 effect is not fully automatic, the presence of this effect for nontarget pop-outs in Experiment 1 suggests that irrelevant pop-outs may be detected in a partially automatic manner when subjects search for pop-outs in another dimension. This conclusion complements Pashler's (1988) finding that irrelevant texture discontinuities interfere with target detection only when the discontinuities have the same spatial scale as the targets (see also Folk, Remington, & Johnston, 1992).

Unlike the anterior N2 effect, the P1 contralaterality was unaffected by the nature of the task in Experiment 3. However, Experiment 4 showed that the P1 contralaterality could be explained by the fact that when the same distractor features are used for every stimulus array neurons tuned to the pop-out feature are in a less refractory state than neurons tuned to the distractor feature. Thus, although the P1 contralaterality may be automatic when refractoriness is not controlled, it is not a response to the occurrence of a pop-out per se within the current stimulus array. The P1 contralaterality should not be dismissed as an irrelevant electrophysiological artifact, however, because the conditions that produced this effect have been present in a large number of pop-out detection experiments and may account for some of the behavioral results observed in such studies (psychophysical evidence for this proposal has been reported by Theeuwes & Lucassen, 1993).

**Generator Sources**

In the CSD maps from Experiments 3 and 4, the focus of the N2pc component was located over the occipital lobe, slightly posterior to the focus of the P1 component. Although it is difficult to localize an ERP component's generator on the basis of its voltage or CSD topography alone, these results strongly suggest that the generator of the N2pc is located in the occipital lobe and may be even more posterior than the generator of the P1 component. This result is somewhat surprising, because information typically flows through the visual system from posterior areas to anterior areas, and the longer latency of the N2pc would
therefore be expected to correspond to a more anterior component. In addition, the attention-related process indexed by the N2pc component is typically applied to targets but not nontargets (e.g., Experiment 1), so the posterior generator location of the N2pc suggests that subjects are able to use top-down information about the task to control the flow of information through the visual system, which again supports guided search models of attention (Treisman & Sato, 1990; Wolfe et al., 1989).

REFERENCES


(Received February 18, 1993; Accepted August 11, 1993)