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New Objects Dominate Luminance Transients in Setting Attentional Priority

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Both the sudden appearance of an object and sudden changes in existing object features influence priority in visual search. However, direct comparisons of these influences have not been made under controlled conditions. In 5 visual search experiments, new object onsets were compared directly with changes in the luminance of old objects. Factors included the luminance contrast of items against the background, the magnitude of luminance change, and the probability that these changes were associated with the target item. New objects were consistently more effective in guiding search, such that a new item with very low luminance contrast was equivalent to an old item undergoing a large change in luminance. An important exception was an old item changing in contrast and polarity, which was as effective as the appearance of a new object. This indicates that search priority is biased toward object rather than situational changes.

The human visual system is confronted with a bewildering array of choices each time a new scene is encountered. Which features, objects, and relations among objects should be processed first? The answer to this question depends on complex interactions between the behavioral goals of the observer (Folk & Annett, 1994; Folk, Remington, & Johnston, 1992; Yantis & Egeth, 1999) and the neural machinery available to process visual input (Callaghan, Lasaga, & Garner, 1986; He & Nakayama, 1992; Rensink & Enns, 1998; Theeuwes, 1991, 1992). Visual attention refers to all the processes involved in the establishment of processing priority.

This article concerns itself with determinants of attentional priority under conditions where the behavioral goals of the observer are well defined. Namely, observers perform a speeded search task to determine which one of a prespecified pair of visual shapes is present in a display. A powerful influence on search priority under these conditions is the sudden appearance of a new object (Yantis, 1993a; Yantis & Jonides, 1984). In a typical experiment designed to measure this effect (see lower two panels in Figure 1), each trial begins with a display of figure-eight placeholders like those seen on a digital clock. After 1 s, two of the line segments in each placeholder are removed to reveal a letter. These *no-onset* letters (so called because no abrupt onset accompanies their appearance) are perceptually old because their segments have been present, though camouflaged, prior to their appearance. At the same time that the no-onset letters are revealed, an *onset* letter appears abruptly in a previously blank location. Each display contains one of two possible target letters, and observers are required to indicate which is present by pressing a corresponding button as quickly as possible. The design ensures that there is no predictive relation between the location of the onset letter and the target, thus avoiding any incentive for observers to deliberately attend to the onset item.

The results indicate that when the target is the onset letter, response time (RT) is rapid and influenced little by the number of letters in the array. However, if the target is one of the no-onset letters, RT increases linearly with display size, yielding RT slopes of 20–30 ms per item. These results indicate that the onset letter enjoys high priority in visual search despite the fact that it is not predictive of the target. As such, it exemplifies a strong form of attentional capture (Egeth & Yantis, 1997).

But why do new objects exert such a powerful influence? One possible reason is that new objects present the visual system with a bundle of new feature values, including luminance, color, and orientation (Thomas & Luck, 2000).[1] The greater the number of new features that co-occur in a particular location, and the larger the magnitude of the change involved, the stronger will be the influence on the priority for inspection of that location. According to this view, no special privilege is asserted for any particular kind of feature change. Each feature change simply contributes activation to the priority map on the basis of the strength and speed of the pathways signaling that kind of information. Luminance transients, for example, may be processed more quickly and given slightly

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[1] The ideas we refer to as the *new feature* hypothesis were first presented in a paper by Thomas and Luck (2000) that is yet to be published. We are grateful to the authors for their clear presentation of this account of the influences of display changes on visual search.

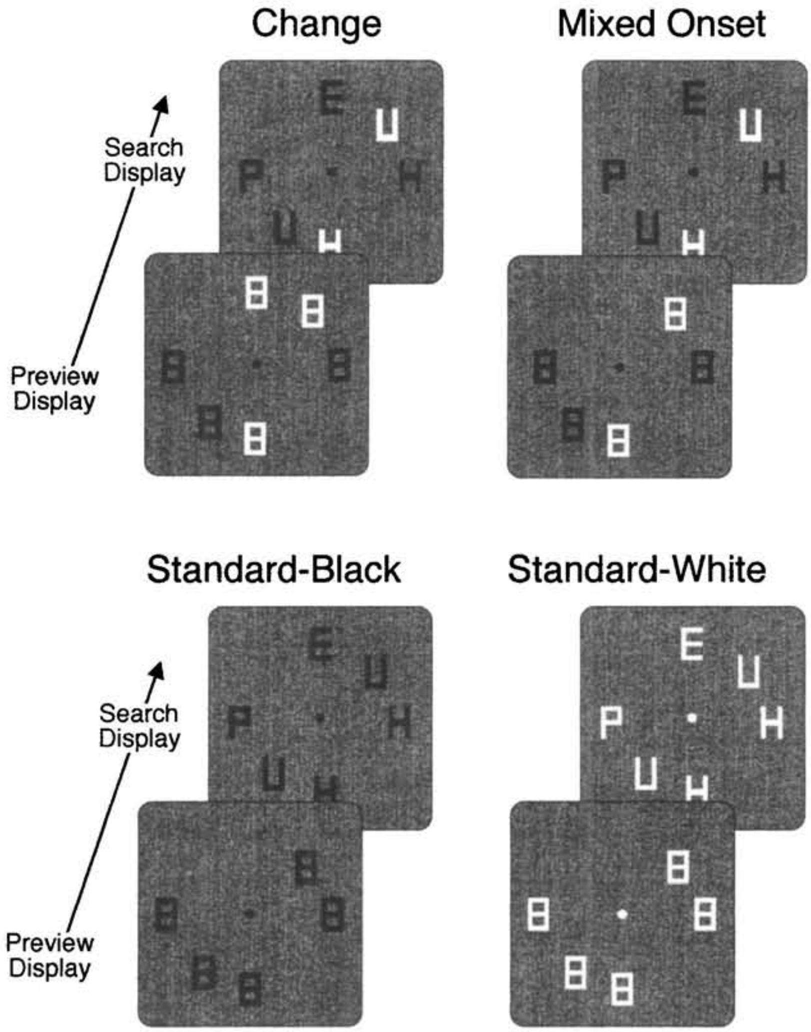

Figure 1. Examples of the four search conditions in Experiment 1. Although the display size shown is six, trials were evenly divided between display sizes of two, four, and six. The item that changed or the onset in the search display was not predictive of the target.

larger weight than color transients because of the inherent differences in neural signal properties between the magnocellular (rapid, luminance- and motion-based) and parvocellular (slower, form- and color-sensitive) visual pathways. We refer to this as the *new feature* hypothesis.

An alternative reason for attentional capture by new objects is that they require the obligatory establishment of a new visual object representation (Yantis, 1998; Yantis & Hillstrom, 1994; Yantis & Jonides, 1996), sometimes referred to as a temporary *object file* (Kahneman & Treisman, 1984). This view conveys a special status to new visual features over feature changes to existing objects. Only new features indicate that an object is present where none was present before. Feature changes in an existing object, such as a change in color, luminance, or position, often occur in the natural world because of relatively superficial changes in lighting (shadows, color of illumination changes), viewpoint, or motion of the viewer. The view that new objects dominate other stimulus changes in setting attentional priority is termed the *new object* hypothesis.

Evidence for the new object hypothesis comes from studies in which new items are shown to influence attentional priority even though the letters are not defined by luminance (Gellatly, Cole, & Blurton, 1999, Experiment 2; Thomas & Luck, 2000, Experiment 4; Yantis & Hillstrom, 1994). Onset letters that are rendered using only discontinuities in binocular disparity, texture, motion, or equiluminant color nonetheless influence attention. These findings are bolstered by studies showing that spatially unique luminance transients and changes in motion, in the absence of a new item, are themselves not sufficient to yield the pattern of visual search associated with attentional capture (Hillstrom & Yantis, 1994; Yantis & Egeth, 1999). The conclusion prompted by this work is that feature transients associated with an old item are neither necessary nor sufficient for influencing attentional priority in search (Yantis, 1993b). Other recent work demonstrates that goal-directed eye movements made toward uniquely colored targets are disrupted by the sudden appearance of a new but task-irrelevant object (Theeuwes, Kramer, Hahn, & Irwin, 1998). Taken together, these studies point to the existence of involuntary perceptual operations that are elicited by the sudden appearance of a new object.

However, any position based exclusively on the new object hypothesis must be tempered by other evidence that feature transients do sometimes influence perception even when they are not associated with the onset of a new item. For example, there have been many reports in the past two decades involving visual detection and discrimination tasks, in which a nonpredictive brief luminance transient of an existing object (e.g., an outline box or location markers) results in a benefit to RT or accuracy in responding to a subsequent target in the same location (e.g., Bashinski & Bacharach, 1980; Jonides, 1980; Posner, Snyder, & Davidson, 1980). Recently, Thomas and Luck (2000, Experiments 1 and 2) reported that even nonpredictive color and motion changes in preexisting location markers increased detection accuracy for targets that appeared in those locations after 300 ms. Related to this argument, Gellatly et al. (1999, Experiment 1), using a procedure similar to that of Yantis and Jonides (1984), found that a brief luminance transient in all the placeholders just prior to the onset of the letters disrupted the usual pattern of RT. Others have disrupted search by varying the onsets and offsets of letter segments in all preview item locations (Martin-Emerson & Kramer, 1997; Miller, 1989; Watson & Humphreys, 1995).

We are left, therefore, both with evidence favoring the new object hypothesis and with evidence that certain feature changes (e.g., luminance transients) do influence target processing and cannot always be ignored. Together, this shows that new objects and feature changes in old objects must both play some role in the setting of attentional priority, ruling out the extreme possibilities that new objects alone or feature changes alone are responsible for determining the bottom-up contribution to attentional priority setting. However, the relative contributions of new objects versus changes to features in existing objects remains an open question. For example, if the range of luminance change in an existing object is small relative to the luminance changes brought about by a new object (e.g., Hillstrom & Yantis, 1994), it would undermine the conclusions that new objects, and not luminance changes, dominate priority setting. Alternatively, studies reporting failures of attentional influence by items in equiluminant colors (Theeuwes, 1995; Thomas & Luck, 2000, Experiment 4) or motion (Gellatly et al., 1999, Experiment 3) may have used weak objects (i.e., stimuli that were relatively difficult to segment from their background), which would yield misleading evidence against the new object hypothesis.

We set out to make direct comparisons of this kind in the present study by treating the question of new objects versus feature change as an instance of the more general problem of comparing the visual discriminability of two classes of stimuli. In order to make such a comparison, one must first establish a metric of discriminability for one class of stimuli, preferably the more easily or reliably defined of the two. The second class can then be evaluated against the first, using the discrimination performance of observers as the common currency. The discriminability of the second, less well-defined class of stimuli can then be expressed in terms of the units used to assess the first class. Consistent with these general principles, previous studies of visual search have shown that RT slope (as a function of display size) decreases monotonically as the contrast of the items is increased with respect to the background (Palmer, 1995). This provided us with an objective basis for systematically varying the signal strength of both old and new visual items.

Overview of the Present Study

As is often the case in exploratory research, several preliminary experiments were conducted before we were prepared, both conceptually and methodologically, to make direct comparisons between new items and luminance change in old items. As we describe below, each of these experiments gave rise to surprising results. This forced us to reevaluate some of our initial assumptions and required us to collect data in important control conditions.

We began very simply in Experiment 1 by comparing the sudden appearance of a new item in a visual search task with a sudden change in the luminance of a single old item. It should be emphasized that we held constant the goal-directed aspects of search priority across conditions by (a) having observers search for the same items in each condition, (b) using identical search displays in each condition, and (c) making the singletons not predictive of the target letter. Conditions, therefore, differed only in the events that preceded the search display during the 1-s preview. We also opted to begin with a comparison that favored the luminance change singleton as much as possible. We tested an item change that was the maximum possible luminance difference we could implement on our display screens. In addition, we biased the comparison in favor of luminance change by making it concomitant with a reversal in the contrast polarity of the item. Previous studies of the role of polarity reversals in visual search indicated that this was a highly effective way to segregate visual search items from one another (Enns & Kingstone, 1995; Theeuwes & Kooi, 1994).

The surprise of this experiment, and of a subsequent one that compared new onset and luminance change items simultaneously within a search display (Experiment 2), was how ineffectual this nonpredictive luminance change was in influencing search. This led us to question one of our assumptions in Experiment 3, namely, whether a large luminance change of this magnitude was even capable of guiding search when it was predictive of the target letter. We found that it was to some extent, but again relatively little in comparison to the effectiveness of a predictive new onset. Therefore, this result was evidence against a strong form of the new feature hypothesis.

In Experiment 4 we systematically explored the relative discriminability of new and old search items by varying their luminance contrast with respect to the background. This comparison showed an advantage in search for new over old targets at even the smallest levels of item contrast, with the advantage growing as a direct function of item contrast. Therefore, these data established that the effectiveness of a sudden onset to modify search priority increases directly with contrast magnitude.

In Experiment 5 we extended this approach by comparing (a) the effectiveness of luminance changes versus new onsets at varying levels of item contrast and (b) the relative effectiveness of separable aspects of a change in luminance. We found that a new onset item with only a small contrast was equivalent in its influence to an old item that underwent a very large luminance change. Furthermore, when we isolated the relative contributions of luminance change from changes in contrast and reversals in contrast polarity, we found that only one combination of feature changes (contrast and polarity reversal) was similar in its effectiveness to that of a new onset of similar background contrast. These data suggest that there is at least one combination of feature changes in an old item that can alter search priority with similar effectiveness to a new onset. As such, it has implications for both the new feature and new object hypotheses.

Experiment 1: Maximum Luminance Transient Versus Sudden Onset

In this experiment we compared four different search conditions involving luminance-defined letters: change, a large luminance change occurred in one of the items at the same time that the figure eights turned to letters; mixed onset, a letter suddenly appeared in an unoccupied location among other letters of mixed polarity; standard onset-black, a black letter suddenly appeared in an unoccupied location among other black letters; and standard onset-white, identical to the previous condition with the exception that all letters were white. Example displays of each kind are illustrated in Figure 1.

Our main question was how a very large luminance change (the largest we could effect on our display screen) would compare in its influence on search to the sudden onset of a letter (a letter with equal contrast and polarity as the changed item). According to the feature change hypothesis (Thomas & Luck, 2000), a luminance change of this kind should have a strong effect on search priority because the signal strength associated with a target in the change condition is actually twice that of the target in the onset conditions. This is because a change item would switch from black to white (or vice versa) against a gray background, whereas a new item would be merely black (or white) on the same background. Note that in addition, an item in the change condition, but not in the onset conditions, would undergo a change in polarity with respect to the background.

We expected that a polarity reversal would increase the signal strength of the singleton because several lines of research indicate that contrast polarity is used by the visual system to segregate the image in visual search (Enns & Kingstone, 1995; Theeuwes & Kooi, 1994) and texture segregation (Sutter, Beck, & Graham, 1989). At a physiological level, reversals in contrast polarity activate separate visual streams within retinal ganglion cells and the lateral geniculate nucleus (for a review, see Fiorentini, Baumgartner, Magnussen, Schiller, & Thomas, 1990). Behavioral evidence suggests that this separation is maintained to some extent even in the visual cortex because visual segregation based on polarity reversal is evident in studies of contour detection (Dresp, 1999), vernier acuity (Victor & Conte, 1999), selective adaptation (Burton, Nagshineh, & Ruddock, 1977), metacontrast masking (Breitmeyer, 1978), spatial attention (Kooi, Toet, Tripathy, & Levi, 1994), and apparent motion (Dawson, Nevin-Meadows, & Wright, 1994; Mather & Murdoch, 1999; Pantle & Picciano, 1976). Of course, there are also tasks for which the visual system seems insensitive to polarity reversal, including some involving foveal visual detection (Chen & Tyler, 1999; Yu & Levi, 1998), apparent motion (Solomon & Sperling, 1994), subjective contours (He & Ooi, 1998), and stereodepth perception (Pope, Edwards, & Schor, 1999). A complete account of the role of contrast polarity in perception therefore awaits further empirical and theoretical development. However, because the previous studies most similar to the present one had shown sensitivity to polarity reversal, it was reasonable to expect that it would be an important factor here, too.

According to the new feature hypothesis, then, both the large magnitude of the luminance change and the accompanying polarity reversal should favor the change condition over the onset condition in modifying search priority. In contrast to this prediction, the new object hypothesis (Yantis, 1998) pointed to the onset conditions as the ones most likely to influence search because only in these conditions did an item appear where none had been displayed in the preview.

The purpose of including both mixed and standard onset conditions was to ensure that any differences found between the change and onset conditions could not be attributed to the presence of items of mixed polarity or luminance values in the change displays. Among the standard onset conditions, some observers searched through all black letters whereas others searched through all white letters to determine whether there were baseline differences in search for letters of one polarity over the other.

Method

Participants. A total of 62 observers were recruited from the undergraduate subject pool of the University of British Columbia to participate in return for partial course credit in one 50-min session. All were naive to the purpose of the experiment, and all indicated that they had normal or corrected-to-normal vision. Sixteen observers were tested in the change condition, 16 in the mixed onset, 15 in the standard onset-black, and 15 in the standard onset-white conditions.

Apparatus. Displays were generated on a 17″ AppleVision (Sony) monitor controlled by a Macintosh computer. The display was viewed from a distance of 60 cm, with a chin rest used to fix head position. Responses were made with the index finger of each hand on a standard computer keyboard. The *Z* key was covered with a sticker overwritten with *E* (left finger) and the / key was marked with an *S* (right finger).

Stimuli. Display items consisted of five uppercase English letters (*E, S, H, P, U*), with *E* and *S* serving as the two targets. Each letter was composed of a subset of the line segments in a digital clock figure eight, which permitted each letter to be camouflaged by a figure eight in the preview display (see Figure 1). The transition from figure eight to letter was achieved by the removal of two line segments.

Each display item could occur in either black or white, yielding a luminance value below that of the gray background in the one case and above in the other. The mean luminance of the white items, measured by a photometer over 5–10 occasions, was 54.7 cd/m^2, the mean luminance of the black items 6.9 cd/m^2, and the mean luminance of the gray background 17.7 cd/m^2. Items measured approximately 0.5° × 1.0° visual angle and were centered on the circumference of an imaginary circle of radius 3.0°. Items could occupy any of 8 equally spaced positions on the circle, with each location chosen randomly on each trial. A central black symbol presented in the intertrial interval, 0.2° in size, served both as a fixation point and as error feedback from the previous trial (plus sign for correct, minus for incorrect).

Design. Observers completed a practice block of 20 trials, followed by six blocks of 80 trials, for a total number of 480 trials that were analyzed. Each search task consisted of three different display sizes (2, 4, 6), two target types (change vs. no change in the luminance change condition; onset vs. no onset in the onset conditions), two target colors (black, white), and two target letters (*E, S*), all randomly chosen on each trial. Within each display size (ds), the proportion of displays for which the target was an onset item was as nearly as possible 1/ds, as shown in Table 1. Thus, neither the changed letter nor the new letter provided any clue to target location (see Yantis, 1993a).

Table 1
Breakdown of Trial Types in Experiments 1 and 2

Experiment and condition	Display size	Number of trials	Onset target	Change target	Old target
Experiment 1					
Change	2	160		80	80
	4	160		40	120
	6	160		27	133
Onset	2	160	80		80
	4	160	40		120
	6	160	27		133
Experiment 2	4	320	80	80	160
	7	224	32	32	160
	10	200	20	20	160

The search conditions illustrated in Figure 1 differed as follows. In the change condition, the preview items were equally divided between white and black. In the transition to the search display, one of these items underwent a color change (randomly chosen to be black-to-white or white-to-black). The remaining search items retained their color from the preview. In the mixed onset condition, the search displays were identical, but there was always one fewer item in the preview than in the search display. This caused one of the letters to suddenly appear in an unoccupied location in the transition from preview to search displays. All the no onset items retained their color from the preview. The two standard onset conditions were identical to mixed onset with the exception that all items were the same color: all black items for one group of observers, and all white items for the other group.

Procedure. Observers indicated with a keypress whether the letter *E* or *S* was present in each display. The instructions were to respond as rapidly as possible while keeping errors to a minimum. Observers were also told to fixate at the center of the screen for the duration of each trial; eye movements were not monitored. The sequence of events on every trial was as follows: The preview display of figure eights was presented for 1,000 ms, followed by the search display, which remained on view until a response was made or 2,000 ms had passed. The response was followed by the feedback symbol, which remained on view for 500 ms, and then a 1.5-s period elapsed before the next preview display was presented. If participants made more than 10% errors on a given block, the computer screen displayed a warning to "Please make fewer errors." To prevent fatigue, participants were permitted to take short breaks between trial blocks.

Results and Discussion

The mean correct RT, shown in Figure 2, clearly shows an advantage for onset targets over change targets. Whereas the mean RT slope for the change target was 17 ms per item, the mean RT slope for the mixed onset target was 5 ms per item, and that for the standard onset targets was 11 ms (black) and 7 ms (white) per item. Indeed, the efficiency of search for change targets fell midway between that of the old targets (24 ms per item on average) and onset targets that involved only one-half the magnitude of change in luminance from preview to display (8 ms per item on average).

These observations were confirmed by statistical analysis. A mixed-design analysis of variance (ANOVA) examined search task (change, mixed, standard-black, standard-white) as a between-subjects factor and display size (2, 4, 6) and target type (change vs. no change, onset vs. no onset) as within-subject factors. Error rates for each condition are shown in Table 2. An ANOVA of the error data, based on the same factors as the RT analysis, indicated no significant effects, and there were no speed–accuracy trends to complicate the analysis of RT.

An ANOVA revealed that targets associated with change (luminance change or onset) were found more rapidly than old targets, $F(1, 58) = 170.57$, $p < .01$, and that RT increased with display size, $F(2, 116) = 138.79$, $p < .01$. A Target $\times$ Display Size interaction confirmed that RT slopes over display size were greater for no-change targets than for change targets, $F(2, 116) = 26.24$, $p < .01$, and a Task $\times$ Display Size interaction revealed that the RT slopes were greater in the change than in the onset tasks, $F(4, 116) = 2.48$, $p < .03$. More detailed comparisons among the tasks revealed that although there were no significant differences in the best-fitting linear RT slopes for no-change targets, $F(2, 58) = 1.13$, the RT slope for change targets was significantly greater than for the new targets in the onset tasks, $F(1, 58) = 7.03$, $p < .01$. The RT slopes for new targets did not vary between any of the mixed or standard onset conditions (all $Fs < 1$).

These results indicate that the largest luminance change that was possible on our display screen was less effective in influencing search priority than a new item whose luminance change was only half as large. Notably, this less effective luminance change item

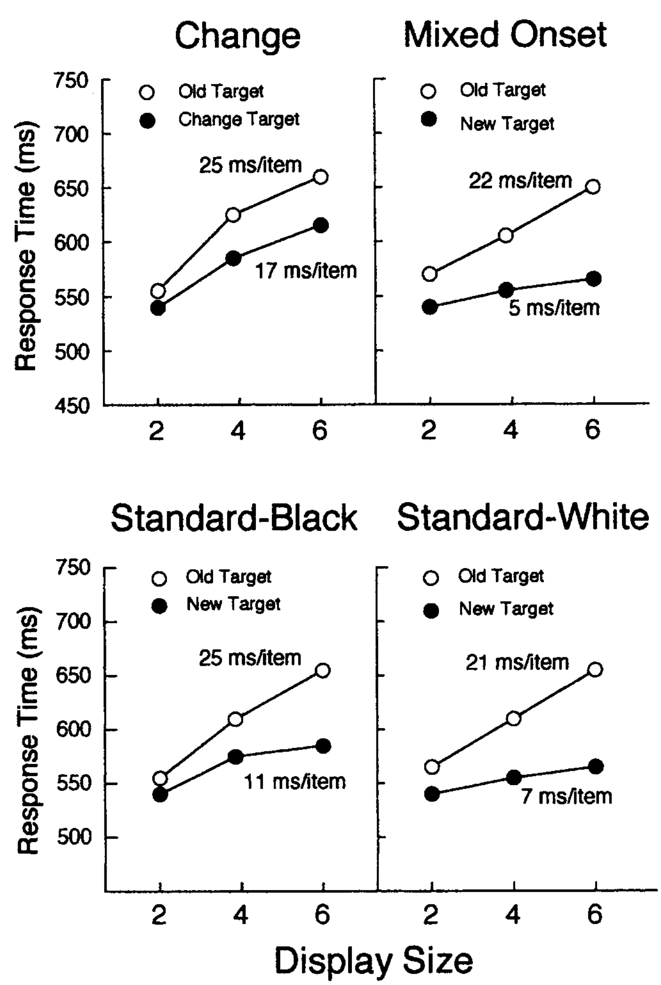

Figure 2. Mean correct response time (RT; in milliseconds) and mean RT slopes in the four search conditions of Experiment 1.

Table 2
Mean Percentages of Errors in Experiments 1–5

Experiment and condition	Target	Display size (ds)		
		ds-2	ds-4	ds-6
Experiment 1				
Change	Old	2.6	2.0	1.8
	Change	2.1	1.6	2.4
Mixed	Old	1.2	2.5	0.8
	New	3.1	2.0	2.0
Standard	Old	3.5	1.6	1.9
	New	2.9	2.1	2.0
		ds-4	ds-7	ds-10
Experiment 2				
	Old	2.2	1.9	2.7
	Change	1.8	1.5	2.2
	New	1.7	1.7	2.1
		ds-2	ds-4	ds-6
Experiment 3				
Change	Old	2.7	2.2	3.4
	Change	2.2	1.9	1.4
Onset	Old	3.0	3.0	3.7
	New	1.7	1.4	1.0
		ds-4	ds-8	
Experiment 4A				
Dim	Old	2.4	2.3	
	New	2.6	0.9	
Bright	Old	2.0	2.4	
	New	0.6	2.8	
		ds-4	ds-8	
Experiment 4B				
Dim	Old	3.8	3.2	
	New	3.9	5.5	
Bright	Old	0.8	2.5	
	New	1.2	4.0	
		ds-4	ds-8	
Experiment 5				
	Change	2.2	1.3	
	No change	1.9	2.4	

was also accompanied by a reversal in polarity. This latter point is noteworthy because of the research reviewed earlier indicating that polarity reversals are used by the visual system to segregate the visual image in space and time. If similar mechanisms of polarity-based segregation are relevant to attentional priority setting, they should have worked in the present experiment to create a salient signal. As can be seen, they did not. We return to this point in the experiments and discussion that follows.

For the moment, the most important result of this experiment is that the advantage for new targets over change targets runs counter to the new feature hypothesis (Thomas & Luck, 2000), which predicts that the number and strength of the features that change are the key determinants of attentional priority. Whereas the change target in this experiment consisted of a switch from white to black (or vice versa), the onset target consisted only of a change from gray to black (or white). Nonetheless, the onset target had the larger influence on search priority.

With respect to a secondary purpose of this experiment, to examine possible effects of including items of mixed polarity in a search display, the results showed that this had no influence on search efficiency. If anything, search was slightly more efficient in the mixed onset condition than in the standard onset condition, where all items were drawn in the same color. No baseline differences in search were found between the black and white versions of the standard onset condition.

Because these results were not intuitive, and because they were so counter to the new feature hypothesis, it was important to see if they could be replicated and generalized. The next experiment was designed as an even stronger test of the new object hypothesis.

Experiment 2: Direct Competition Between Change and Onset

In this experiment the effects of luminance change and sudden onset items were examined in the context of the same trial. Every display contained two items that underwent a change from preview to search display. One of the figure-eight items underwent a luminance change at the same time that another item appeared in a previously unoccupied location.

This is a more direct test of the new feature hypothesis (Thomas & Luck, 2000) because it permits the effects of sudden onsets and luminance change to be resolved dynamically during the same task. As such, it eliminates strategic biases that may have contributed to the differences between conditions in Experiment 1. If the critical predictor of attentional priority is the number and strength of feature changes that occur simultaneously in a given location, then the change item, which undergoes a much larger luminance change and larger color change than the onset item, should have a greater influence on search. Alternatively, if new objects are critical (Yantis, 1998), then the larger degree of feature change in the change items should be inconsequential in the face of the simultaneously appearing onset item. But this design also creates a potential perceptual conflict because there will be two large visual transients on each trial: one associated with the new onset and the other with the changed item. Observers were informed that these two types of changes would be occurring on each trial and that neither type of change predicted the target letter. This gave observers every opportunity to set their expectations as optimally as possible for the detection of the target letters, independent of other display characteristics.

Method

Participants. Sixteen observers were recruited from the undergraduate subject pool of Johns Hopkins University. All were naive to the purpose of the experiment, and all indicated that they had normal or corrected-to-normal vision.

Apparatus. Displays were generated on a Taxan UV1150 21-inch color monitor controlled by an Artist Graphics XJS-1280 graphics board in a 386-based computer. The display was viewed from a distance of 54 cm with a chin rest to fix head position. Responses were made on a custom-built button box that was marked *U* on the left and *H* on the right.

Stimuli. Display items consisted of six uppercase English letters (*U, H, S, E, A,* and *P*) with *U* and *H* serving as the two targets. The mean luminance of the white items, measured by a photometer, was 65.6 cd/m^2, the mean luminance of the black items was 0.02 cd/m^2, and the mean luminance of the gray background was 38.3 cd/m^2. Items could occupy any of 12 equally spaced positions on a circle of radius 3.75°. Other details were similar to Experiment 1.

Design. Observers completed a practice block of 20 trials, followed by four blocks of 186 trials, for a total number of 744 trials that were analyzed. The experiment consisted of three different display sizes (4, 7, 10), three target types (change, onset, no change), two target colors (black, white), and two target letters (*U, H*), all randomly chosen on each trial. Within each display size (ds), the proportion of times the target was an onset, change, or no change item was 1/ds, 1/ds, and (ds − 2)/ds, respectively, as shown in Table 1. There were an equal number of trials on which the change item switched from black to white and vice versa. Whether the change item switched to the color of the abrupt onset item or not was also equal and randomly determined. All of these design features were critical to ensuring that the display events did not provide any information about target location (see Yantis, 1993a).

Procedure. Except as noted, the procedure was identical to Experiment 1. The sequence of events on every trial included a blank-screen interval of 1,000 ms; a fixation cross was then displayed in the center of ds-1 figure eights. After 1,000 ms, the letters of the search display were revealed by the removal of line segments from the figure eights. At the same time, one of the items changed in luminance (change item), and an additional letter appeared in a previously blank position (onset item). The search display remained on view until a response was issued or 2,000 ms had passed. Error feedback was provided by two successive 150-ms, 256-Hz tones, and the participant was penalized with a time-out of 2 s.

Feedback following each block included a display of the mean RT, the error percentage, and the number of blocks remaining. If participants made more than 5% errors on a given block, they were additionally cautioned to "Please slow down and make fewer errors." Observers were given a 5-min break after completing Blocks 1 and 3.

Results and Discussion

As can be seen in Figure 3, new targets enjoyed a sizeable advantage in search efficiency over both luminance change and no-change targets. Whereas the mean RT slope for the onset targets was 16 ms per item, the mean for change targets was 25 ms per item and that for old targets was 29 ms per item.

Statistical analysis confirmed these observations. An ANOVA revealed significant main effects of target type, $F(2, 30) = 16.50$, $p < .0001$, and display size, $F(2, 30) = 75.20$, $p < .0001$, as well as an interaction between these factors, $F(4, 60) = 5.60$, $p < .001$. No effects involving target color were significant. An ANOVA performed on the best-fitting linear slopes for each target type revealed significant differences between the conditions, $F(2, 30) = 8.40$, $p < .001$. Onset RT slopes were significantly smaller than both change and no-change target slopes ($p < .02$), which did not differ significantly from one another ($F < 1$). No effects reached significance in a similar analysis of errors (all Fs < 1). The pattern of mean errors, shown in Table 2, were not consistent with a speed–accuracy trade-off. An ANOVA of the error data, examining the same factors as in the RT analysis, revealed no significant effects.

We also noted that the RT slopes for onset targets in this experiment were somewhat larger than in Experiment 1: vs. mixed onset, $F(1, 29) = 8.25$, $p < .05$; vs. standard onset, $F(1, 29) = 3.82$, $p < .01$, where onset items did not occur at the same time as luminance change items on each trial. This suggests that there might be some competition between these two kinds of change, which is resolved in favor of the onset item (Gellatly et al., 1999, Experiment 1). To evaluate this competition quantitatively, we examined the relation between these two target types at all points in the RT distributions, as shown in Figure 4. This analysis involved (a) rank ordering all RTs for each observer and condition (i.e., display size by onset, change, or neither), (b) computing the mean RT for the fastest x% (in steps of 5%) of the trials in each condition for each observer, (c) averaging across observers, and (d) computing the search slopes. This analysis shows conclusively that onset targets influence search priority more effectively than change targets at every point in the RT distribution.

In summary, these results indicate that new items dominate much larger luminance transients when both of these changes are placed in direct competition in a search display. They also confirm that the results of Experiment 1 were not caused by observers adopting different strategies in the change and onset conditions. The methodological differences between experiments also helped to generalize the main result beyond a particular preparation. These differences included (a) different letter sets used as targets and distractors, (b) a larger range of luminance values in Experiment 2, (c) a larger range of display sizes, (d) letters presented on a larger imaginary circle to accommodate all display sizes, (e) simultaneous presentation of luminance changes and abrupt onsets, and (f) an unequal number of trials in each display size in Experiment 2 (see Table 1). These procedural changes did not alter the main finding: Large luminance changes in an existing item are much less effective at drawing attention than are abrupt onsets of new items.

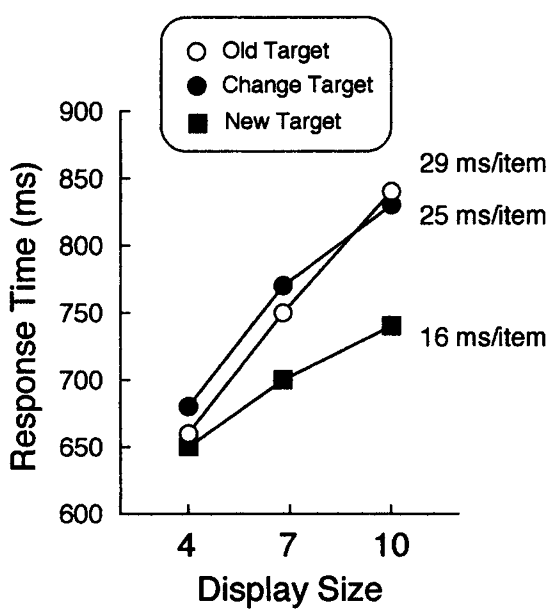

Figure 3. Mean correct response time (RT; in milliseconds) and mean RT slopes in Experiment 2.

Experiment 3: The Salience of a Predictable Luminance Change

Experiments 1 and 2 revealed, to our surprise, that an item undergoing a large but task-irrelevant luminance transient has a much smaller effect on visual search than the sudden appearance

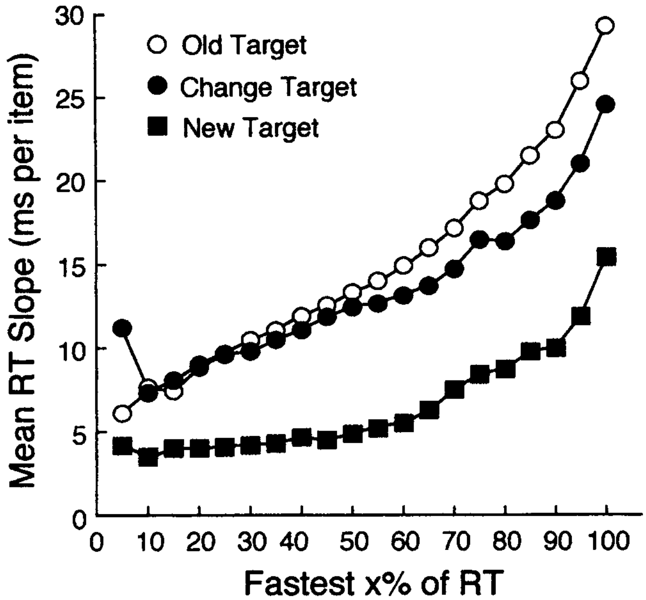

Figure 4. Mean response time (RT) slopes (in milliseconds per item) for the three target types in Experiment 2 as a function of the fastest *x*% of RT values.

of a new item. We next asked whether these transients could be used deliberately to guide search when they were predictive of the target letter. In Experiment 3, one item exhibited a large luminance transient (from white to black or vice versa) in a display containing both white and black elements. The target was the changing item on 80% of the trials. Observers were informed of this contingency and were encouraged to use it to guide their search of the display. The main objective was to assess the benefits of an informative luminance transient relative to a condition in which a sudden onset item was equally informative about target location. If luminance change is important in setting attentional priority, then this manipulation should maximize its contribution.

Method

Fifteen undergraduate students participated in the luminance change condition; a different group of 15 participated in the predictive onset condition. The procedure was identical to that in Experiment 1, except that on 80% of the trials the target was the item undergoing change (either luminance or onset). On the remaining 20% of trials, the target item underwent no change (no luminance change or onset).

Results and Discussion

Figure 5 shows the results for the predictive luminance change and predictive onset conditions, respectively. The RT slope for the predictive change targets was 16 ms per item faster than that for old targets. This compared with a smaller difference of 8 ms per item for nonpredictive changes in Experiment 1, $F(1, 29) = 7.55$, $p < .01$, indicating that making the luminance change predictive led to a significant benefit in search.

The RT slope for the predictive onset targets in Experiment 3 was 15 ms per item faster than that for the old targets, compared with a similar difference of 17 ms per item for nonpredictive onsets in Experiment 1, $F(1, 29) < 1$, indicating no additional benefits for making onset targets predictive.

A direct comparison of change and onset targets in Experiment 3 revealed significantly steeper RT slopes for the change targets than the onset targets, $F(1, 28) = 12.11, p < .01$, but no significant interaction between target type and task ($F < 1$). The errors, shown in Table 2, indicated no speed–accuracy trading relations, and the ANOVA of errors revealed no significant effects.

Experiment 3 therefore demonstrates that a luminance change accompanied by a polarity reversal influences the priority of search to a greater degree when it is predictive than when it is not. However, the same manipulation applied to onset targets does not influence them in the same way. This is probably because of a floor effect, reflecting the high priority given to onset items even when they are not predictive of the target.

Given the relative difficulty observers had using the predictive luminance change to guide their target search in this experiment, it is perhaps less surprising that they had such a weak influence on search when they were nonpredictive in Experiments 1 and 2. However, both results are essential for understanding the role of luminance changes in setting search priority. Without the results from the nonpredictive conditions, one could question the generality of the present result in one of two ways. First, nonpredictive changes might have been even less effective than we found them to be, and second, intentional search strategies in the predictive condition may have been interfering with the workings of a low-level system that is tuned to large luminance changes and therefore would be evident when nonpredictive changes were used.

Experiment 4: The Role of Item Contrast in Setting Attentional Priority

Earlier, we emphasized the importance of a common metric for assessing the relative contributions of various stimulus features. We argued that it was important to be able to compare directly the influence of luminance change with the onset of new items. However, in our first three experiments, we failed in making this comparison because we were unable to observe any condition in which a large luminance change even approached the strong influence of onset items. In Experiment 4, we tried to bridge this gap by measuring the efficiency of visual search for nonpredictive onset items using items with much smaller luminance contrasts relative to the background.

Two predictions can be made about the relation between item contrast and the efficiency of visual search. First, as the luminance contrast of a search item is decreased, it should become both less visible against the background and less discriminable from other items. Therefore, both overall mean RT and search slopes should increase because more time will be needed to locate each target and more time will be devoted to each item to extract the information required to determine whether it is the target. This prediction holds for both new (onset) and old (no onset) target items because it is merely the application of a general principle of visual discriminability.

The second prediction is specific to new targets: As the contrast of the onset item is decreased, we would expect its ability to draw attention to become weaker. We expected, therefore, to observe a continuum of decreasing attentional priority for onsets as the luminance contrast of the target items was decreased. This out-

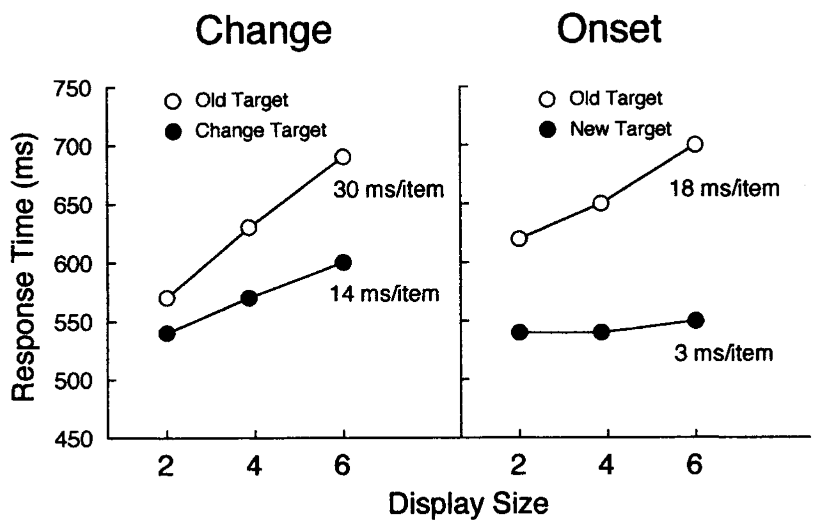

Figure 5. Mean correct response time (RT; in milliseconds) and mean RT slopes in Experiment 3.

come would be observed most directly in a more rapid reduction in search slopes for new targets relative to old targets as the luminance contrast of the target was increased.

It should be emphasized that this approach to the quantification of attentional priority, using item contrast to manipulate search speed, is at odds with an earlier view premised on the idea that preattentive vision is an encapsulated processing module that performs certain visual operations in an all-or-none fashion (e.g., Treisman & Gelade, 1980). Rather, the emerging view in several different attention literatures is that all visual processes are potentially influenced by the higher level goals of the organism (Egeth & Yantis, 1997; Folk, Remington, & Johnston, 1992; Rensink, O'Regan, & Clark, 1997; Theeuwes, Kramer, & Atchley, 1999; Yantis & Egeth, 1999). As such, it is no longer tenable to define *capture* by such arbitrary criteria as search slopes of 0 or even 10 ms per item. As is now well documented, search slopes in a wide variety of tasks vary smoothly from shallow to steep, depending on the discriminability of the search item from the background and from other nontarget items (Duncan & Humphreys, 1989; Palmer, 1995; Wolfe, 1998).

Experiment 4 was conducted in two steps because, as it turned out, our first attempt to use search items that were low in contrast did not greatly reduce the attentional priority of new targets. We, therefore, refer to Experiments 4A and 4B in what follows; the only difference between experiments concerns the luminance values selected for the items.

Method

Twelve undergraduate students participated in Experiment 4A; a different group of 12 participated in Experiment 4B. The procedure was otherwise similar to the previous experiments, with the exception that only two display sizes were tested (4 and 8 items) and the luminance values of the items in the display were systematically varied. Observers completed a practice block of 10 trials, followed by eight blocks of 60 trials, for a total number of 480 trials that were analyzed.

All reported luminance measurements are averages taken over six or more photometer readings. The mean luminance values were then used to define the item contrast of each search item in terms of Michelson units, $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L = the mean luminance value expressed in cd/m^2. As illustrated in Figure 6, the items were presented on a medium gray background (17.68 cd/m^2). In Experiment 4A, the figure eights in the preview displays and all letters appeared in one of four luminance values: (A) white (28.53 cd/m^2), (B) light gray (21.14 cd/m^2), (C) dark gray (14.69 cd/m^2), or (D) black (10.37 cd/m^2). In Experiment 4B, the equivalent values were (A) white (21.14 cd/m^2), (B) light gray (18.65 cd/m^2), (C) dark gray (16.55 cd/m^2), and (D) black (14.69 cd/m^2). In each case, the figure eights in the preview display always contained an equal number of each of the four possible luminance values. These luminance values were maintained when the figure eights turned into letters in the search display, with the luminance value of the new item being chosen

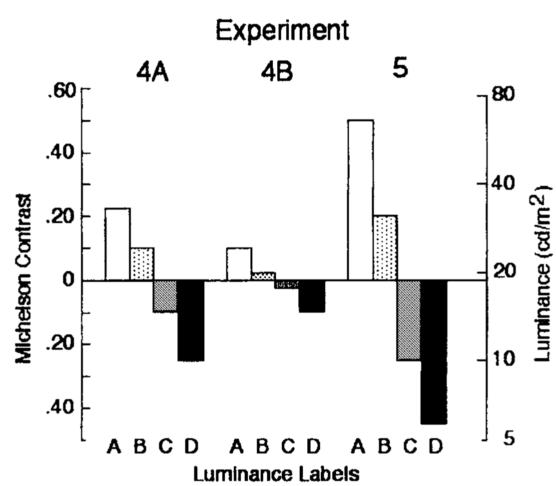

Figure 6. Luminance and contrast profiles for the search items used in Experiments 4 and 5. In Experiment 4, the low-contrast items (light gray and dark gray, or B and C) were selected to be one-half the screen intensity of the high-contrast items (white and black, or A and D). In Experiment 5, the low-contrast items (light gray and dark gray, B and C) were selected to be two-thirds the screen intensity of the high-contrast items (white and black, A and D), so that the transition from A to B was approximately equal in magnitude to the transition from B to C and C to D.

randomly on each trial and with the constraint that the four luminance values appeared equally often.

Results and Discussion

Figure 7 shows that both mean RT and RT slopes increased monotonically as the luminance contrast of the target item was decreased. For the highest contrast new targets in Experiment 4A, the mean RT was 606 ms, and the mean RT slope was 8 ms per item. For the lowest contrast new targets in Experiment 4B, the mean RT was 966 ms, and the mean RT slope was 29 ms per item. The pattern for old targets was similar, with the highest contrast old target yielding a mean RT of 688 ms and a mean RT slope of 21 ms per item and the lowest contrast old target yielding a mean RT of 998 ms and a mean RT slope of 41 ms per item.

The ANOVA for Experiment 4A indicated that all main effects were significant: target, $F(1, 11) = 47.14, p < .01$; contrast, $F(1, 11) = 23.44, p < .01$; display size, $F(1, 11) = 88.64, p < .01$. Most importantly, Target × Display Size was significant, $F(1, 11) = 20.30, p < .01$, indicating that new items were given search priority over old items. Contrast × Display Size was also significant, $F(1, 11) = 4.81, p < .05$, reflecting that high contrast targets yielded smaller RT slopes than low contrast targets. No other interactions were significant.

The ANOVA for Experiment 4B revealed a very similar pattern, albeit with much slower RTs and larger RT slopes. The main effects were all significant: target, $F(1, 11) = 18.02, p < .01$; contrast, $F(1, 11) = 50.49, p < .01$; and display size, $F(1, 11) = 90.76, p < .01$; as were the interactions of Contrast × Display Size, $F(1, 11) = 12.28, p < .01$, and Target × Contrast, $F(1, 11) = 5.17, p < .05$. The error data for both Experiments 4A and 4B, shown in Table 2, again indicated no speed–accuracy trading relations, and the ANOVAs of errors revealed no significant effects.

These results, along with those from the onset conditions in Experiment 1, are summarized in Figure 8. The data points in the top panel (Figure 8A) are the mean RT slopes for both old and new targets, plotted as a function of the contrast of the items. Three important results are clearly evident in this graph. First, as the contrast of the search items is reduced, search becomes increasingly inefficient, as evidenced by the increase in RT slope, for targets that are both new and old items. This is the expected influence of item discriminability on search speed (Palmer, 1995). Second, there is a sizable advantage in search for new targets over old targets at every level of item contrast. Even items that were barely visible against the background (Michelson contrast = 0.03) showed a marked search advantage when these items appeared suddenly rather than having their camouflage removed. This result is strongly at odds with the new features hypothesis (Thomas & Luck, 2000). Third, attentional priority is not set in an all-or-none fashion. The relative advantage of an onset target is clearly smaller for weak objects (i.e., items that were difficult to segment from the background because of low contrast) than for stronger ones (i.e., items of high contrast).

The advantage of new over old items is summarized compactly in Figure 8B, where we have used the ratio of old target RT slope to new target RT slope as a convenient index of search efficiency for new targets. A slope ratio of 1.0 indicates no search benefit for a new item; slope ratios larger than 1.0 quantify the priority given to a suddenly appearing target item. As can be seen, slope ratios in this study were always greater than 1.0, even for items of very low

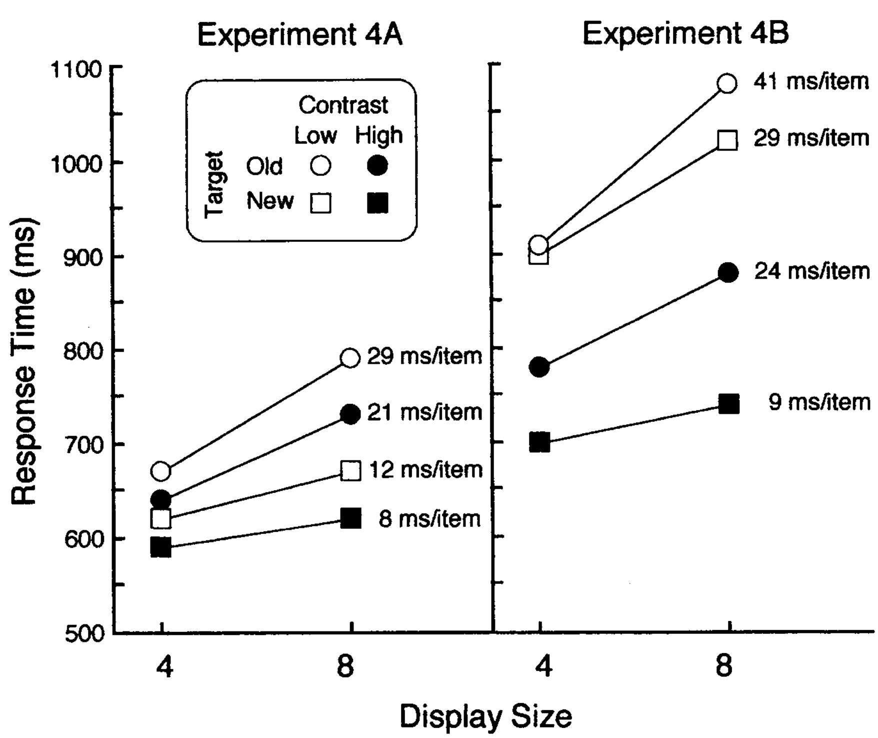

Figure 7. Mean correct response time (RT; in milliseconds) and mean RT slopes in Experiment 4.

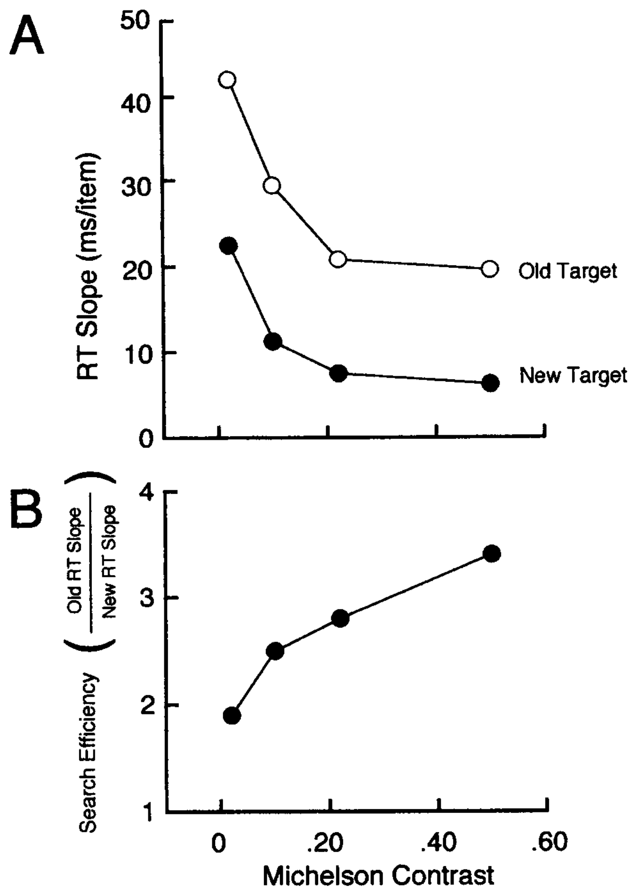

Figure 8. A: Mean response time (RT) slopes (in milliseconds per item) for old and new targets, plotted as a function of item contrast against the background. The data points for the smallest three contrast values are taken from Experiment 3; data points for the largest contrast value are from Experiment 1. B: The ratio of old target RT slope to new target RT slope in Panel A is a convenient index of search efficiency for new targets. This search efficiency index is used as a standard in Experiment 5 (Figure 9), in which the influence of luminance changes in existing items is examined.

contrast, indicating that the sudden appearance of these items still produced a visual signal with more salience than that of old items. This index of search efficiency was used as a standard in the next experiment, where we examined how luminance changes of different kinds influence search priority.

Experiment 5: Luminance Change and Item Contrast

This experiment had the same design as Experiment 4, with the exception that the changed search item always involved a luminance change from a preceding figure eight in the preview. Four different kinds of luminance change were studied in an attempt to pinpoint those with the greatest influence on search priority: (a) magnitude of luminance change, (b) change in contrast without a polarity reversal, (c) polarity reversal without a change in contrast, and (d) combined polarity reversal and contrast change. What led to this decomposition was the surprising result that large luminance changes were relatively weak signals for the attraction (Experiments 1–2) and guidance (Experiment 3) of attention. We reasoned that these changes may have had little effect because, although they involved polarity reversal, they did not involve any change in contrast. Although this possibility runs counter to the findings of previous work on polarity reversals and visual search in static displays (Enns & Kingstone, 1995; Theeuwes & Kooi, 1994), if correct for dynamic displays, it would explain why the luminance changes we had tested so far were relatively ineffectual.

On every trial in Experiment 5, one of the items underwent a luminance change in the transition from preview to search display. As before, this luminance change was not predictive of the target letter. However, because there were four possible luminance values for each of the items, as shown in Figure 6, there were 12 different types of luminance change in all (four different possible preview colors combined with three different display color possibilities). In what follows, we have averaged the changes that involved the same luminance values in different orders (e.g., A → B, B → A) because the direction of the change had no measurable influence on performance.

The resulting six types of change were classified according to how they involved the different aspects of luminance change, as shown in Table 3: *luminance change* (small, medium, and large changes from preview to display), *contrast change* (changes in item contrast from preview to display versus no such change), and *polarity reversal* (changes in luminance that cross the background gray level vs. those that do not). For example, to examine the influence of luminance change, small changes (involving B and C in Figure 6) were compared with large changes (A and D in Figure 6). Notably, each condition in this comparison involved a change in polarity but not a change in contrast. The separate influences of contrast change (A and B, C and D) and polarity reversal (B and C) were examined using similar logic. In these comparisons, we controlled the magnitude of the change by restricting the analysis to transitions involving small luminance changes. Finally, to test for a synergy between changes in polarity and contrast, transitions involving both of these features were considered. These involved transitions between A and C, and B and D in Figure 6.

Method

Fifteen observers participated. The procedure was identical to the previous experiment with two notable exceptions. First, all of the search items were old in that they were preceded by a figure-eight placeholder. Second, a larger range of luminance values was used, as shown in Figure 6, to maximize the possibility of obtaining some overlap in search efficiency between the new items in Experiment 4 and the present items undergoing a luminance change. Figure eights and letters were therefore presented in

Table 3
Aspects of the Luminance Changes in Experiment 5

Change type	Luminance change	Contrast change	Polarity reversal
A ↔ B	small	yes	no
B ↔ C	small	no	yes
C ↔ D	small	yes	no
A ↔ C	medium	yes	yes
B ↔ D	medium	yes	yes
A ↔ D	large	no	yes

one of four luminance values: (A) white (54.70 cd/m^2), (B) light gray (27.10 cd/m^2), (C) dark gray (10.15 cd/m^2), and (D) black (6.90 cd/m^2). Once again, the one item undergoing luminance change on each trial offered no information about the location of the target letter. Observers completed a practice block of 10 trials, followed by eight blocks of 60 trials, for a total number of 480 trials that were analyzed.

Results and Discussion

A preliminary analysis indicated that luminance transients in existing items were generally not very effective in influencing search. In comparison with the old targets, which yielded an average RT slope of 33 ms per item, the change targets averaged 23 ms per item. An ANOVA revealed significant main effects of display size, $F(1, 14) = 102.51$, $p < .01$, and target type, $F(1, 14) = 10.89$, $p < .01$, but the interaction did not reach significance, $F(1, 14) = 4.13$, $p > .05$. The error data, shown in Table 2, indicated no speed–accuracy trading relations, and the ANOVA of errors revealed no significant effects.

The results for the more detailed analyses involving luminance change, polarity reversal, and contrast change are shown in Figure 9. The influence of each of these aspects is summarized using RT slope ratios as an index of search efficiency. As a context for each analysis, each aspect of luminance change has been plotted against the summary of search efficiency for new items in Experiment 4 (Figure 8B), which are shown as gray symbols and dashed lines in Figure 9. The ratio of old RT slope over change RT slope is used to index search efficiency, with the old item slope of 33 ms per item being used as the numerator in each ratio (fine-grained statistical tests looking for effects of new item luminance on old target search revealed no significant differences). The average contrast of the target item against the gray background was used to reference each condition in Figure 9 (black squares) to its appropriate comparison with new item search efficiency (gray circles and dashed lines).

The results for luminance change indicated that neither small nor large luminance changes came close to the search efficiency seen for new items at comparable levels of item contrast. The mean RT slope for small changes was 33 ms per item, that for large changes was 23 ms per item, and no-change targets were 33 ms per item. The ANOVA indicated significant main effects of display size, $F(1, 14) = 46.07$, $p < .01$, and change, $F(2, 28) = 13.01$, $p < .03$, but the differences in RT slope between small, large, and no-change targets were not significant, $F(2, 28) < 1$. The difference between search efficiency based on luminance change and the expected efficiency based on new items of the same contrast was

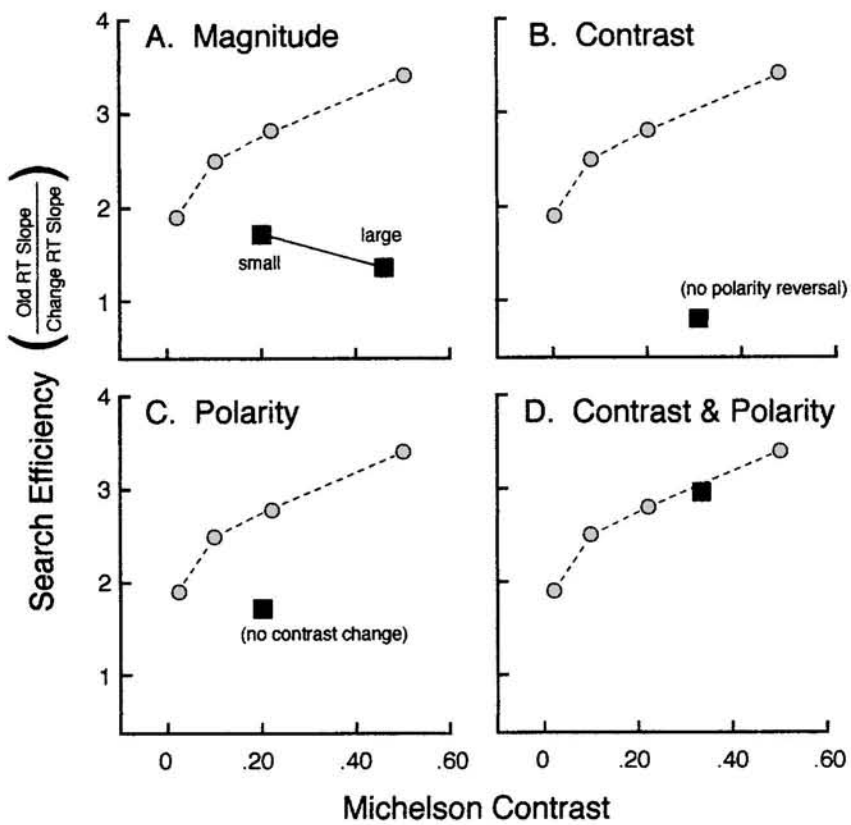

Figure 9. Search efficiency (ratio of old target response time [RT] slope to change target RT slope) in Experiment 5 as a function of item contrast (data points are black squares). Separate comparisons were made for the properties of luminance change (A), contrast change (B), polarity reversal (C), and contrast change and polarity reversal (D). The gray symbols and dashed lines are the data from abrupt onset search tasks shown in Figure 8B (Experiments 1 and 4).

significant for both small, $t(14) = 4.23$, $p < .01$, and large luminance changes, $t(14) = 8.10$, $p < .05$.

The results for polarity reversal and contrast change also indicated that these aspects of a luminance change did not result in search efficiency that was comparable to that for a new item at the same level of item contrast. The mean RT slope for a contrast change (without polarity reversal) was 41 ms per item, that for a polarity reversal (without contrast change) was 18 ms per item, and no-change targets were 27 ms per item. The ANOVA indicated significant main effects of display size, $F(1, 14) = 67.38$, $p < .01$, but the main effect of target type and the differences in RT slope between contrast, polarity, and no-change targets were not significant, $F(2, 28) = 2.66$ and $F(2, 28) = 2.62$, respectively. The difference between search efficiency based on these aspects of a luminance change and the expected efficiency based on new items of the same contrast was significant for contrast, $t(14) = 5.97$, $p < .01$, and marginally significant for polarity, $t(14) = 2.01$, $p < .10$.

It is important to be reminded in this context that these ineffective luminance changes in old items were actually larger changes than those in Experiment 4 that led to efficient search for new items. This can be seen in Figure 6 by comparing the magnitude of the luminance changes in Experiment 5 (e.g., A to B for a contrast change, B to C for a polarity change) to those in Experiment 4. In addition, these results establish that the weak effects of luminance change in Experiments 1–3 were not brought about by a failure to have changes in luminance associated with changes in contrast: Large changes in contrast within the same polarity in Experiment 5 still produced only weak influences on search.

The one type of change that did produce comparable search efficiency to new items involved a concurrent change in polarity and contrast. This is shown in Figure 9D. This included changes among the conditions labeled A and C, and among those labeled B and D, in Figure 6 and Table 3. Note that these changes involved a medium change in luminance but that the earlier analysis of luminance change had already shown that even larger changes were of little effect in guiding search. The mean RT slope for changes involving both polarity reversal and a contrast change was 11 ms per item; the slope for no-change targets was 33 ms per item. This is both significantly more efficient than search for an old target, $F(1, 14) = 28.81$, $p < .01$, and very comparable to the efficiency of search for a new item of similar item contrast (the dashed line in Figure 9D at the corresponding level of item contrast), $t(14) < 1$.

In summary, these results confirm the general ineffectiveness of luminance changes in old items to guide search in the new–old search paradigm (Yantis, 1993a; Yantis & Jonides, 1984). As shown for the analysis of luminance change in Figure 9A, a very large change in an existing item was approximately equal in its influence on search to a very weak onset in a new item. Similar analyses showed that polarity reversals and contrast changes, on their own, were also relatively ineffective in guiding search. We discuss the implications of the one exception to this general pattern, the results for concurrent contrast and polarity changes, in the next section.

General Discussion

We began this study by asking "What is the influence of a suddenly appearing new object on a visual search task relative to the influence of a large change in the luminance of an existing object?" According to the new feature hypothesis (Thomas & Luck, 2000), a new object should have no privileged influence on the setting of search priority, over and above the influence of the constituent features involved in its onset. On the other hand, the new object hypothesis (Yantis & Hillstrom, 1994) claims that the appearance of a new perceptual object is a change that contributes disproportionately to the priority of search. Changes to features of existing objects, although important in some tasks, are not as fundamentally important as the appearance of new objects, because feature changes can be appended to existing perceptual representations of objects. New perceptual objects, on the other hand, demand the establishment of representations where previously there were none. As such, the visual system is predisposed to accord especially high priority to new objects.

Our initial approach to this question involved making comparisons between a large luminance change in an existing visual search item with the sudden appearance of a new item (Experiments 1–2). These two search items were both singletons in the search display, by virtue of their changes with respect to the preview display. They both also had identical contrast with respect to the background. From the outset, this comparison was biased in favor of the change items, both in terms of the number and strength of the visual features involved. That is, change items underwent a reversal in polarity along with a very large luminance transient; onset items did not involve the reversal of polarity and consisted of a luminance transient of only one half the size. Nonetheless, we found that the change item was much less effective in capturing attention than the item that appeared suddenly.

This imbalance in the influence of change and onset items was still clearly apparent when we made the change (and the onset) highly predictive of the target item (Experiment 3). This indicates that not only is the priority-setting influence of large luminance transients weaker than that of new objects when the changes are task irrelevant, it remains so even when top-down guidance can be used to form expectations about the likely location of the target.

In Experiment 4 we systematically varied the luminance contrast of both old and new letters, allowing us to quantify the relationship between attentional priority and item discriminability. We found that the relative search efficiencies associated with these two kinds of items were equivalent only when the contrast of the old items was much higher than that of the new item. To illustrate, note that in Figure 8A the most efficient search slope for old targets is about 20 ms per item, and it is achieved only when the contrast is 0.20 Michelson units or larger. Similar search efficiency for new items is achieved when their contrast was 6–7 times smaller (0.03 Michelson units).

A similar experimental design in Experiment 5, applied to luminance changes in old items, revealed that the largest possible luminance change on our display screens resulted in search efficiency that was approximately equal to the onset of a new item that was barely visible. Similar analyses showed that polarity reversals and contrast changes, on their own, were also relatively ineffective in guiding search. These results were important in establishing that the weak effects of luminance change in Experiments 1–3 were not brought about by a failure to have changes in contrast associated with the changes in luminance: Large changes in contrast within the same polarity in Experiment 5 were still ineffectual.

The truly novel finding of Experiment 5 was that a concurrent change in contrast and polarity was as effective as a new item in guiding search, once item contrast had been equated. This finding is of interest for at least two reasons. First, this finding is akin to previous findings in visual search (Aks & Enns, 1992; Gilchrist, Humphreys, Riddoch, & Neumann, 1997) and texture segmentation (Sutter et al., 1989), which revealed an interaction between item contrast and polarity. In those studies, the visual system was shown to be much more sensitive to spatial differences in contrast when those differences also involved a reversal in polarity. In the present study, sensitivity to contrast was also enhanced when the differences involved polarity reversal, but in this case the contrast differences occurred over time. That is, item contrast changed from the preview display to the search display, and it was this temporal change that had an influence on search efficiency. This finding suggests, at a very general level, that the visual system has adopted similar rules for parsing the visual world in both space and time.

Second, this result prompts speculation on a possible ecological constraint that may be used by the visual system to help set priorities in search. The constraint concerns the important distinction between situation and object properties in perception (Coren, Ward, & Enns, 1999). Whereas situation properties refer to the highly variable characteristics of a visual image (e.g., the luminance intensity and contrast of various regions in the two-dimensional image), object properties refer to the unchanging attributes of the three-dimensional scene (e.g., the luminance reflectance profile of surfaces). As a general rule, the visual system may have evolved to signal changes in object properties because they reveal new information about the immediate visual environment and to ignore changes in situation properties because they are highly dependent on current lighting and viewpoint conditions. It is therefore very interesting that large changes in luminance and contrast in the present study do not strongly influence search priority because they correspond to changes in the image that are often due solely to changes in situation properties such as shadowing, lighting, and viewpoint. And, it is equally interesting that concurrent changes in contrast and polarity do influence search. Such concurrent changes do not typically occur as the result of changes in shadowing, partial transparency, or viewpoint. Future studies should test directly the possibility that attentional priority is directly related to the changes in object properties rather than changes in situation properties in the image.

Visual Objects as the Entry Level for Visual Selection

The main finding of the present study, that the sudden appearance of a new object dominates luminance changes in the establishment of search priority, is consistent with several lines of evidence indicating that visual selection operates at the level of object representations and not at the level of image feature representations. For example, Duncan (1984) reported that when observers reported on the identity of two attributes of spatially superimposed objects, they were more accurate in reporting the attributes when they were from the same object than when they belonged to different objects. He concluded that attention operates on objects, such that attention to an object permits perceptual access to all the object's features.

More recently, studies have shown that attending to only part of an object yields detection and discrimination benefits for other, more distant, parts of the same object (Behrmann, Zemel, & Mozer, 1998; Egly, Driver, & Rafal, 1994; Moore, Yantis, & Vaughan, 1998). These studies reveal that when part of an object is selected, other parts of the object are also selected, although there may be gradients of attentional strength in different parts of the object.

Other examples of the central role of object representations come from studies in which observers must search for targets defined by their retinal-image properties or their scene properties (e.g., Cavanagh, Arguin, & Treisman, 1990; He & Nakayama, 1992; Rensink & Enns, 1995, 1998). Rensink and Enns (1998) asked observers to search for a segmented disk or "pacman" in a background of complete disks and squares; search was very efficient. They then changed the displays slightly so that the pacman target was abutting a square so that it appeared to be a partly occluded complete disk. In this case, search was highly inefficient. This result shows that perceptual completion of the pacman occurred before selection; attention operates on the post-completion object-based representation. In other words, the shape of the object in the scene (a complete but partly occluded disk) preempts the shape of the object in the retinal image (a pacman). Rivest and Cavanagh (1996) showed that judgments concerning the location of a multiattribute contour are based on a representation in which the various attributes (luminance, color, motion, and texture) have been previously integrated at a common site.

Implications for Theories of Attentional Priority Setting

These results have important implications for both the new features and the new objects hypotheses. With respect to the new features view, these results certainly rule out a strong version in which the number and strength of the features involved in a change are used directly to predict the influence on search efficiency (Thomas & Luck, 2000). Yet, proponents of this view might be tempted to appeal for support to the findings of Experiment 5, where a concurrent change in contrast and polarity was as effective as a new object in influencing search. The obstacle encountered in doing so is that other combinations of feature changes were not as effective. For instance, large luminance changes concurrent with a reversal in polarity had no special consequences for search. Similarly, changes in luminance associated with changes in contrast had little effect (see A and B for Experiment 5 in Figure 6), even though these changes were considerably larger than the small luminance changes, which produced very efficient search for new items in Experiment 4.

A version of the new features hypothesis that seems more tenable, in light of these results, is a proposal involving a hierarchy of effective features. The present results show that the visual system is more sensitively tuned to one particular conjunction of luminance properties than an examination of each of the individual properties would suggest. This indicates that the salience of a visual item within the search array is not determined simply by first-order properties of the visual signal, such as the strength of the signal in the magnocellular pathway (luminance change) or a switch from ON- to OFF-ganglion cells (polarity reversal). Findings such as these are important in distinguishing those properties that are effective features for signaling change from those properties that some part of the visual system registers but that do not influence visual search. We take the question of what makes a feature effective in setting search priority to be far from closed. The answer can clearly not be predicted solely from an analysis of the magnitude and number of image changes. Further empirical work of this sort, along with theoretical frameworks such as the situation–object properties distinction (Coren et al., 1999), will be important in deciding the ultimate validity of the new features hypothesis.

The implications of the present results for the new objects view are equally important. Although most of the results favored new objects over feature changes, the finding for concurrent changes in contrast and polarity (Experiment 5) clearly poses a problem for a strong version of this hypothesis too. Because these were changes to an old item in the preview display, they were not predicted to influence search priority to the extent they did. Future studies will be needed to decide between the possible directions that this finding points toward. For instance, the new objects hypothesis will ultimately be strengthened if future studies indicate that this finding is illustrative of a small number of feature combinations that the visual system takes as evidence of a new object. Such an outcome would be consistent with the view that attentional selection in visual search indeed operates at the level of objects. On the other hand, if future studies reveal a large set of feature changes to old items (and feature change combinations) that strongly influence search, then the new objects view will have to become more explicit about the processes involved in making the attribution of object to a collection of visual features.

It should also be noted that the present findings may not apply to displays in which there is only a single spatially localized luminance change. It is important to be reminded that the present study was conducted in the same context that attentional capture has been studied for over 16 years (Yantis & Jonides, 1984), namely, with displays in which each of the items undergoes a small luminance change (because of line-segment deletion) in the transition from preview figure eight to search letter. It is possible that a solitary luminance transient in an otherwise stationary display is a much more effective determinant of search priority than it appears to be in this context. However, such a result would not negate the main finding of the present study. What it calls for instead is an analysis of how the observer's search set is determined by general characteristics of the displays (i.e., whether small transients occur at all item locations or not) over and above the contribution of the experimental instructions (e.g., to ignore transients because they are not predictive).

Whatever the outcome of future work in this area, the most important message of the present study is that attentional priority must be considered within the larger context of visual discriminability. Only by carefully controlling the discriminability of visual search items were we able to compare the influences of new onsets with those of feature changes to old items. We believe that extensions of the present approach to other features (color, motion, etc.) will help eventually to reveal whether the new objects hypothesis, the new features hypothesis, a hybrid hypothesis, or even an entirely different hypothesis holds most generally.

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