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# When do luminance changes capture attention?

**Branka Spehar · Caleb Owens**

**Abstract** In two experiments, we examined the ability of task-irrelevant changes in luminance to capture attention in an irrelevant singleton search. By using uniform increment and decrement arrays, we were able to create changes of the same absolute magnitude, but resulting in a singleton with either higher or lower contrast magnitude, relative to other elements in the search array. A condition where a singleton changed contrast polarity without a concomitant change in the overall contrast magnitude was also included. It was found that only luminance changes resulting in a singleton having increased contrast (or saliency) were effective in capturing attention. In addition, no attentional capture was observed when the irrelevant singleton was characterized by the equivalent amount of static luminance differences, suggesting a unique attentional prioritization of luminance changes that increase singleton saliency.

**Keywords** Attentional capture · Visual search · Attention: Selective

The ability to focus on a particular aspect of a visual scene while disregarding others is essential for successful interaction with complex environments. It has been well established that many featural differences between individual objects, such as a unique color, luminance, or size, are effective in guiding attention when such properties are relevant to the current task (Bacon & Egeth, 1994; Folk, Remington, & Wright, 1994; Wolfe, 1994; Wolfe, Butcher, Lee, & Hyle, 2003). Although it has often been assumed that these salient properties possess a general ability to direct attention and establish processing priority, irrespective of the observer's goals, Yantis and Jonides (1984) were among the first to differentiate between efficient visual detection of salient features and obligatory attentional capture by those features. By now, there is a large body of evidence suggesting that suddenly appearing new elements are effective in capturing attention even when task irrelevant, whereas otherwise salient but static color and brightness differences fail to attract attention under such circumstances (Cole, Kuhn, Heywood, & Kentridge, 2009; Folk & Annett, 1994; Jonides & Yantis, 1988; Mounts, 2000; Rauschenberger, 2003; Yantis, 1993; Yantis & Egeth, 1999; Yantis & Jonides, 1984). However, the mechanisms by which the attentional prioritization of sudden onsets is accomplished continue to be the subject of much research and debate (Burnham, 2007; Pashler, Johnston, & Ruthruff, 2001; Rauschenberger, 2003; Theeuwes & Godjin, 2002; Yantis, 1993).

## Attentional capture by sudden onsets: Spatiotemporal transients or new objects?

Although the superiority of attentional capture by sudden onsets was initially attributed to the large luminance transients accompanying them (Yantis & Jonides, 1984), their ability to capture attention even in the absence of large luminance changes has led to an influential hypothesis that sudden onsets attain a high attentional priority because they represent the appearance of a new object (Yantis, 1993; Yantis & Hillstrom, 1994; Yantis & Jonides, 1996; see also Rauschenberger & Yantis, 2001). However, the role of sensory change in attentional capture by sudden onsets continues to be revisited, and it is still debated whether such stimuli capture attention

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because of the visual system's special sensitivity to new objects (Cole & Kuhn, 2009; Cole, Kuhn, & Liversedge, 2007; Cole & Liversedge, 2006; Davoli, Suszko, & Abrams, 2007) or because of their intrinsic association with luminance or motion transients (Franconeri & Simons, 2003; Franconeri, Hollingworth, & Simons, 2005; Gellatly, Cole, & Blurton, 1999; Hollingworth, Simons, & Franconeri, 2010; Martin-Emerson & Kramer, 1997; Miller, 1989; Theeuwes, 1995).

Contentious theoretical interpretations aside, the accumulated empirical evidence suggests that luminance transients are necessary for attentional capture by sudden onsets. However, although necessary, the detection of luminance transients per se might not be sufficient for attentional capture, and the extent to which luminance changes alone are capable of capturing attention remains an important, but somewhat neglected, aspect of this debate. Despite the long-standing assumption that any unexpected luminance transients are sufficient to automatically trigger attentional shifts to their spatial location (Breitmeyer & Ganz, 1976; Nakayama & Mackeban, 1989; Posner, 1980 and Steinman, Steinman & Lemkuhle, 1997), the evidence that unexpected luminance changes capture attention even when their occurrence is unrelated to the appearance of new objects is equivocal.

## Attentional capture by luminance transients that are not associated with new objects

A number of studies have shown that luminance transients created by removing or adding line segments to the old objects in the search display interfere with, or completely eliminate, the attentional capture by suddenly appearing new objects (Atchley, Kramer, & Hilstrom, 2000; Donk, Agter, & Pratt, 2009; Gellatly et al., 1999; Martin-Emerson & Kramer, 1997; Miller, 1989; Pratt, Theeuwes, & Donk, 2007; Theeuwes, 1995; Watson & Humphreys, 1995, 2002). Although these findings suggest that prioritized selection for new objects is mediated by a mechanism sensitive to the presence of luminance transients, the luminance transients created by the additions and deletions of contour segments also resemble aspects of objects' appearance and disappearance. Hence, their ability to compete for attentional prioritization might be effective predominantly, if not solely, because they trigger the same mechanisms that mediate the formation and updating of object files (Watson & Humphreys, 2002).

The luminance transients associated with irrelevant contour onsets and offsets are qualitatively different from changes in overall luminance that are typically associated with changes in the material properties of an object (such as variations in reflectance or illumination). Several studies that directly investigated attentional capture by the latter type of change found little or no attentional capture (Enns, Austen, DiLollo, Rauschenberger, & Yantis, 2001; Yantis & Hillstrom, 1994). Somewhat more pronounced levels of attentional capture were reported only when the luminance changes were large (Rauschenberg, 2003) or task relevant (Atchley et al., 2000; Irwin, Colcombe, Kramer, & Hahn, 2000).

Yantis and Hillstrom (1994) assessed the ability of irrelevant luminance change singletons to capture attention by having one of the search elements undergo a sudden and short-lived brightening in luminance (see Fig. 1a). The luminance of the search element was increased for a period of 50 ms and then returned to the luminance level of placeholders and other search elements. The search slopes for temporarily brightened targets and no-change targets did not differ, suggesting the failure of luminance change to capture attention.

A subsequent study by Enns et al. (2001) directly compared the ability of irrelevant luminance transients to capture attention under conditions in which they represented dynamic luminance changes to an existing object and those in which they were associated with the sudden appearance of a new object in a search array. Figure 1b shows a schematic depiction of stimulus arrays used to investigate the effect of the maximum possible luminance change to an existing object. Although the luminance changes to existing objects were twice as large in magnitude when compared with suddenly appearing elements in locations previously unoccupied by any of the placeholders, Enns et al. found an advantage for onsets over luminance changes to old items. An old item needed to undergo a very large luminance change in order to equal the ability of a new onset item, even with only a small contrast to capture attention.

While it remains plausible, as was suggested by Enns et al. (2001), that transient luminance singletons lacking an association with a new object are ineffective in recruiting peripheral spatiotemporal detection mechanisms, here we explore one additional possibility: Namely, in both the Yantis and Hillstrom (1994) and Enns et al. studies, the luminance change did not result in the prolonged distinctiveness of a singleton element that was virtually indistinguishable from other items in the array, either before or after this change was completed.

In Yantis and Hillstrom (1994), all elements in the search array were of the same luminance, both before and after a brief 50-ms change to one of the elements was completed. On the other hand, Enns et al. (2001) used heterogeneous arrays comprising either a mixture of black and white elements (as in Fig. 1b) or a mixture of white, light gray, dark gray, and black elements. The heterogeneous arrays, used to presumably maximize the amount of available luminance changes, inadvertently masked the conspicuity of singletons associated with dynamic luminance changes and, thus, decreased their saliency.[1] Indeed, Enns et al. found the same ineffective detection of

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[1] The large variability in both luminance and contrast levels of individual display elements has quite possibly acted as a pedestal against which the superimposed luminance changes are generally harder to detect (Bex, Solomon, & Dakin, 2009; Freeman & Badcock, 1999; Spehar & Zaidi, 1997).

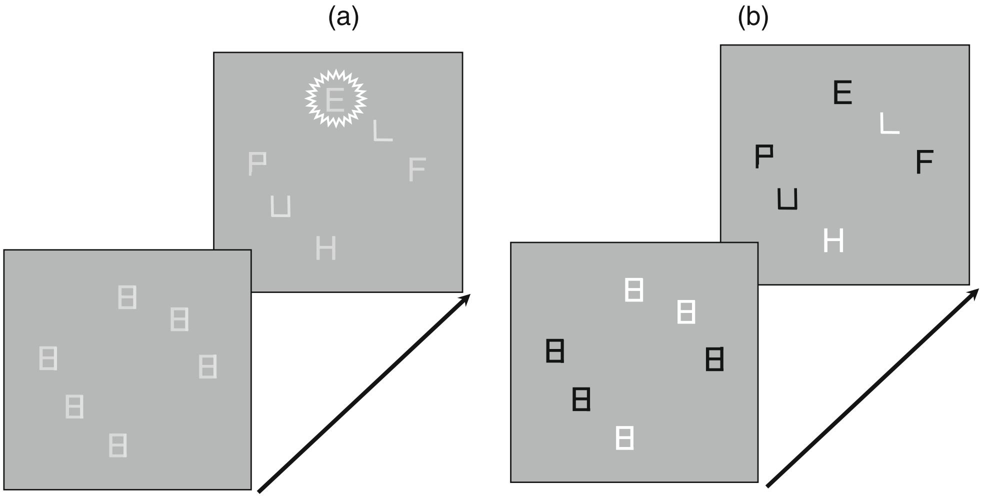

**Fig. 1** Schematic representation of stimulus configurations used in the Yantis & Hillstrom (1994) and Enns, Austen, Di Lollo, Rauschenberger & Yantis (2001) studies: (**a**) A short-lived temporary luminance change used in Yantis & Hilstrom (1994); (**b**) A maximum luminance chage to an old object used in Enns et al., (2001)

these changes even when they were highly predictive of target appearance.

Here, we revisit attentional capture by irrelevant luminance changes and argue that changes that are not associated with noticeable variations in a singleton's uniqueness are unlikely to capture attention. In order to more fully characterize the relationship between the nature of luminance transients and the attentional capture they afford, we compare the effect of luminance transients that lead to either an increased singleton contrast with their immediate background (high saliency) or a decreased singleton contrast with their immediate background (low saliency). We show that the end point saliency of an irrelevant luminance change is the key to efficient attentional capture, consistent with models of attentional allocation that emphasize the role of stimulus-driven levels of relative neural activity generated by display items (Cave & Wolfe, 1990; Itti & Koch, 2000; Koch & Ullman, 1985). This is also consistent with a considerable body of evidence suggesting that greater saliency leads to more pronounced attentional capture even with static luminance singletons (Lu & Han, 2009; Proulx & Egeth, 2006, 2008; Todd & Kramer, 1994; Yantis & Egeth, 1999). Indeed, in order to determine whether dynamic luminance changes result in any processing benefits that extend those that could be already afforded by static luminance differences, we make a direct comparison between attentional capture by static luminance differences and dynamic luminance transients that are matched in their magnitude.

## Experiment 1

In Experiment 1, we investigated attentional capture by a variety of task-irrelevant luminance changes of the same absolute magnitude but varying in saliency. To ensure the conspicuity of transient luminance singletons, we used uniform displays, typical of attentional capture studies, and used both all increment and all decrement displays (see Table 1). With the use of both increment and decrement search arrays, it was possible to decouple the effects of absolute increases or decreases in luminance from the associated increases or decreases in a singleton's contrast magnitude. The increases and decreases in luminance made one of the elements of the search display undergo simultaneous luminance and contrast magnitude change, resulting in either a higher contrast singleton than the surrounding items or a lower contrast singleton than the surrounding items (see Figs. 2, 3 and Table 1). By keeping the magnitude of the luminance change constant and varying the nature of the change, we were able to determine whether it was the absolute magnitude of the luminance change itself that captured attention or whether the end state

**Table 1** Types of static and dynamic luminance singletons used in Experiment 1

| | Increment Displays | | Decrement Displays | | Mixed |
|---|---|---|---|---|---|
| | Luminance Decreases | Luminance Increases | Luminance Decreases | Luminance Increases | Luminance Decreases |
| Polarity change/difference | No | No | No | No | Yes |
| Contrast change/difference | Yes | Yes | Yes | Yes | No |
| Singleton contrast (saliency) | Low | High | High | Low | Low |

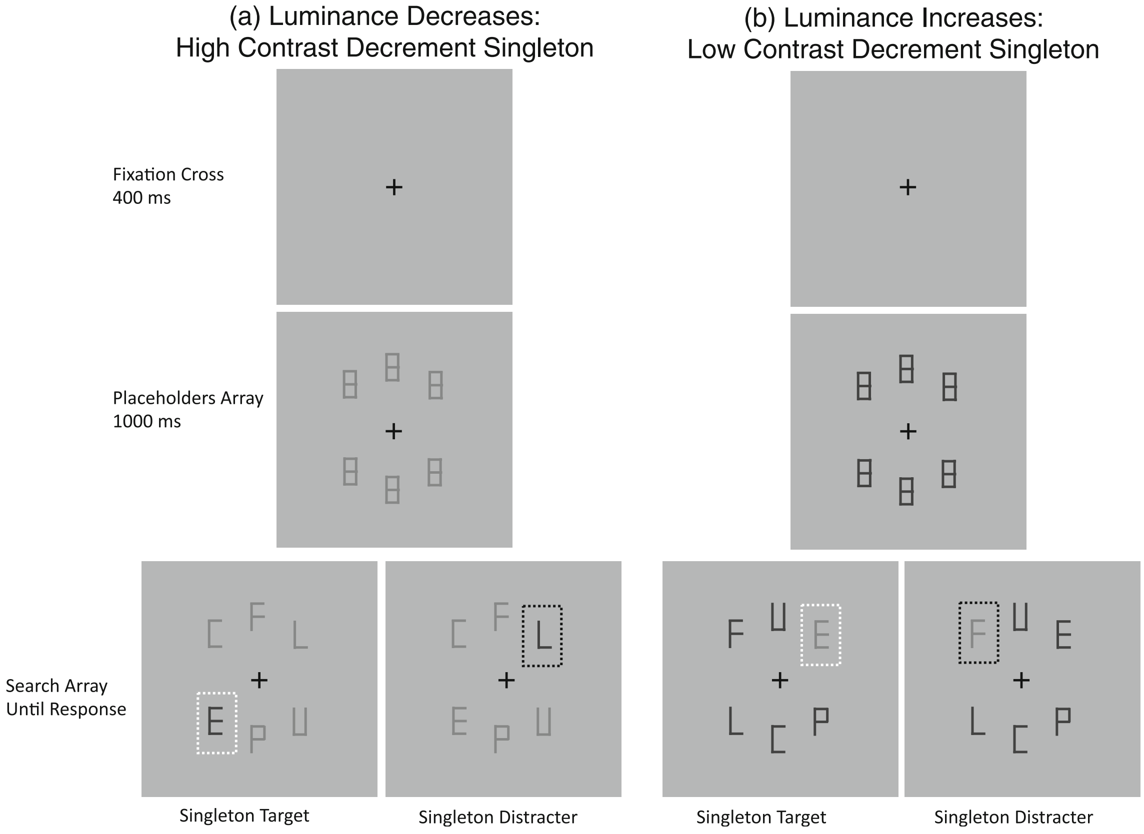

**Fig. 2** Experimental sequence for the luminance change singletons in decrement arrays: **a** Singleton decreases in luminance to become a high-contrast decrement; **b** singleton increases in luminance to become a low-contrast decrement. White and dark gray dashed schematic outlines indicate changing singleton-target and distractor elements, respectively. Note that in the actual experimental sequence, these outlines were not present. In the corresponding high-contrast and low-contrast "static singleton" conditions, no placeholder arrays were presented

of the singleton that underwent change also contributed. If, as some recent accounts have suggested, it is the magnitude and suddenness of the change that is important in attentional capture, it should not matter whether, at the end of the trials, the singletons are higher or lower contrast, relative to other search elements (Franconeri et al., 2005; von Muhlenen, Rempel, & Enns, 2005). Some advantage of high-saliency singletons can be expected on the base of findings with static luminance differences (Lu & Han, 2009; Proulx & Egeth, 2006, 2008; Todd & Kramer, 1994; Yantis & Egeth, 1999). These studies indicated that attentional capture by an irrelevant luminance singleton was dependent on these specific luminance relationships: The singleton of unique luminance captured attention when it was bright among dim items, but not if it was dim among bright items.

In order to differentiate whether irrelevant luminance singletons capture attention simply because of their uniqueness and regardless of attentional priority attained by luminance transients, for every dynamic luminance change condition, we included a comparable static luminance difference condition. The latter conditions contained the same combinations of stimuli as the dynamic change conditions (illustrated in Figs. 2, 3) but did not include a placeholder array. In such static conditions, a fixation cross display was directly followed by a search array with a unique singleton. If dynamic luminance transients uniquely contribute to attentional capture, the degree of attentional capture should be more pronounced with the dynamic luminance transients, as compared with the static luminance differences of the same absolute magnitude.

We also included a polarity reversal condition in which dynamic luminance change and static luminance difference corresponded to a change/difference in contrast polarity, without variations in the absolute contrast magnitude. For example, in this condition, a low contrast increment relative to the background became a low contrast decrement. The luminance change associated with such reversals in contrast polarity was equal in its absolute magnitude to luminance changes in other experimental conditions. Enns et al. (2001) found no attentional capture by this type of dynamic singleton, but as with other types of dynamic changes they studied, this might have been compromised by the heterogeneity of the search displays they used.

In our study, dynamic luminance changes and static luminance differences were embedded in spatially homogeneous placeholder and search arrays to ascertain the extent to which

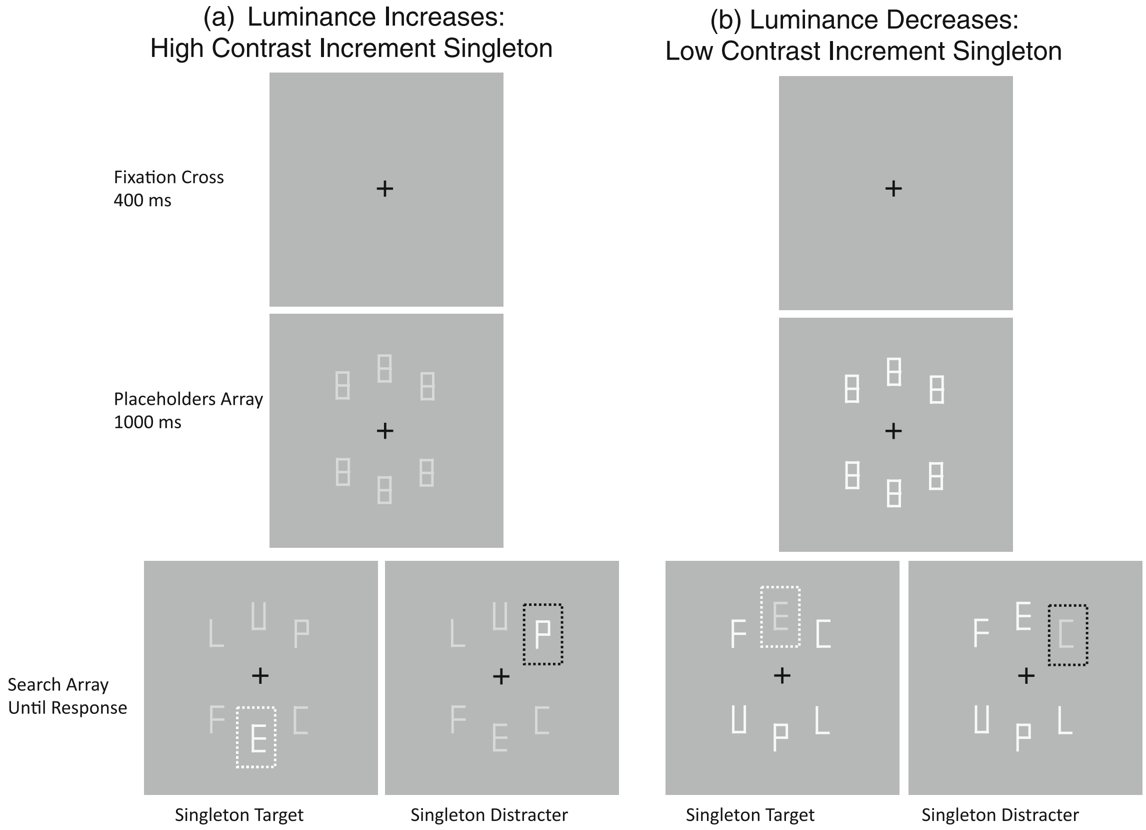

**Fig. 3** Experimental sequence for the luminance change singletons in increment arrays: **a** Singleton increases in luminance to become a high-contrast increment; **b** singleton decreases in luminance to become a low-contrast increment. White and dark gray dashed schematic outlines indicate changing singleton-target and distractor elements, respectively. Note that in the actual experimental sequence, these outlines were not present. In the corresponding high-contrast and low-contrast "static singleton" conditions, no placeholder arrays were presented

the uniqueness and saliency of the irrelevant brightness singleton would contribute to attentional capture. It should be noted that although homogeneous, our displays did not contain a single, uniquely localized and isolated luminance change. We used standard displays in which all of the items underwent a small luminance change caused by line segment deletions at the point of transition between the placeholder and search displays.

We used an irrelevant singleton paradigm in which participants searched for a specified target letter among other nontarget letters in displays with one singleton letter differing from others in luminance (Jonides & Yantis, 1988). The spatial position of the singleton was random and provided no clue to the spatial position of the target letter. However, in addition to the singleton-target and singleton-distractor trials, we also employed no-singleton trials; they involved search for the same prespecified target but did not contain singletons of any kind. Although the irrelevant singleton paradigm does not typically involve the use of no-singleton trials, these trials are useful for disambiguating the overall differences in response times between the singleton-target and singleton-distractor trials. In particular, these differences might be indicative of either a real processing advantage for an irrelevant singleton (whereby its spatial location in a search array is attended and processed first) or spatially nonspecific filtering costs due to an increased display heterogeneity (Becker, 2007; Kahneman, Treisman, & Burkell, 1983; Owens & Spehar, 2008).

## Method

*Subjects* Subjects were 54 undergraduate University of New South Wales students who participated to receive course credit. They were naïve as to the purpose of the study. All had normal or corrected-to-normal visual acuity.

*Apparatus and stimuli* Stimuli were presented on a 19-in. Gateway VX900 monitor at a resolution of 800 × 600 with a refresh rate of 144 Hz. Individual search elements were 1.5 cm high and 0.9 cm wide on a screen approximately 65 cm away from the subjects' eyes. Each individual search element thus subtended a visual angle of 1.32° × 0.79°. The search display as a whole was 6 cm high and 5.2 cm wide, resulting in a visual angle of 5.29° × 4.58°.

Six search elements were presented on a gray background with a mean luminance of 40 cd/m$^2$. Depending on the condition, the placeholders and search elements were one of four luminance levels: 70 cd/m$^2$, 50 cd/m$^2$, 30 cd/m$^2$, or 10 cd/m$^2$. In baseline conditions, all the search elements were the same luminance level. With dynamic luminance change singletons and static luminance difference singletons, one of the search elements (the singleton) was a different luminance level, with the remaining five elements the same luminance level. Across various conditions, the luminance contrast of the search elements, expressed as Weber contrasts ($L_{\text{letter}} - L_{\text{background}}/L_{\text{background}}$), was either 0.25 or 0.75.

The placeholder arrays were used with the dynamic luminance change singletons. The luminance and the contrast of the "figure 8" placeholders matched those of the nonsingleton search elements (as indicated in Figs. 2, 3). The details of luminance combinations across different conditions are provided in Table 2.

*Design* The dynamic luminance change and static luminance difference singleton trials were identical in all respects except for the use of placeholders. The dynamic luminance change singletons were created by changing the luminance of one of the elements of the placeholder array into a brighter or darker element of a search array. With the static luminance difference singletons, the placeholders were not used, and the singleton was defined only by its static unique luminance difference, relative to the other display elements.

There were five different experimental conditions.

1. *High saliency decrement singleton.* In this condition, all search elements were darker than the mid-gray background, and the singleton had the lowest luminance in the search array and the highest contrast with the background. The dynamic singletons were created by suddenly decreasing the luminance of one of the placeholder elements at the point of transition into the search array (Fig. 2a).
2. *Low saliency decrement singleton*. In this condition, all the elements were darker than the background, but the singleton had the highest luminance and lowest contrast with the background, as compared with the other search elements. The dynamic luminance change singletons were created by suddenly increasing the luminance of one of the placeholder elements at the point of transition into the search array (Fig. 2b).
3. *High saliency increment singleton.* In this condition, all the elements were brighter than the background, and the singleton had the highest luminance and the highest contrast with the background. The dynamic luminance change singletons were created by suddenly increasing the luminance of one of the placeholder elements at the point of transition into the search array (Fig. 3a).
4. *Low saliency increment singleton.* In this condition, all the elements were brighter than the background, but the singleton had the lowest luminance and the lowest contrast with the background. The dynamic luminance change singletons were created by suddenly decreasing the luminance of one of the placeholder elements at the point of transition into the search array (Fig. 3b).
5. *Contrast polarity change singleton.* We also used a luminance change condition that was associated with a reversal in a singleton's contrast polarity, without a change in a singleton's contrast magnitude. The contrast polarity reversal singletons were created by luminance decreases to one of the placeholder elements in an increment search array. However, both kinds of stimuli were of equally low contrast with the background and corresponded to low contrast increment and low contrast decrement elements, respectively (Fig. 4).

In each condition, the singletons were equally associated with all the search elements, resulting in 1/6 proportion of singleton-target trials and 5/6 proportion of singleton-distractor trials. The baseline trials involved the same sequence of frames relevant to the condition, with equivalent luminance for the placeholders and search items, the only difference being that, in the final search array, no singleton was present. The baseline and singleton trials were intermixed within respective blocks. Each of the experimental conditions was presented in a separate block consisting of 70 trials, and all blocks were presented in a random order.

*Procedure* Subjects searched for one of two target letters (E or H) in a display containing several other distractor letters (A, C, U, F, L, P, S). One of the target letters was always

**Table 2** Luminance values corresponding to the singleton and nonsingleton display elements in different experimental conditions in Experiment 1

| | | Luminance (cd/m$^2$) | | Weber Contrast ($\Delta L/L$) | |
|---|---|---|---|---|---|
| Display | Change type | Singleton | Nonsingleton | Singleton | Nonsingleton |
| Increments | Increase | 70 | 50 | 0.75 | 0.25 |
| Increments | Decrease | 50 | 70 | 0.25 | 0.75 |
| Decrements | Increase | 10 | 30 | 0.75 | 0.25 |
| Decrements | Decrease | 30 | 10 | 0.25 | 0.75 |

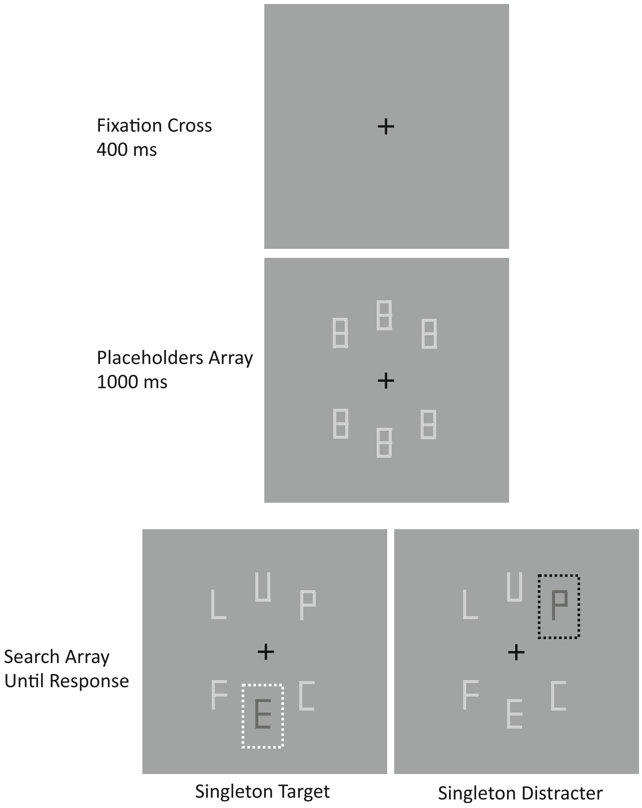

**Fig. 4** Experimental sequence for the contrast polarity reversal singletons: Singleton decreases in luminance to become an opposite contrast polarity singleton. White and dark gray dashed schematic outlines indicate changing singleton-target and distractor elements, respectively. Note that in the actual experimental sequence, these outlines were not present. In the corresponding high-contrast and low-contrast "static singleton" conditions, no placeholder arrays were presented

present, and the subject had to respond with a preselected keypress indicating which one was present. Subjects were told that there would sometimes be a uniquely bright or dark stimulus located in the target array but that this was unrelated to the location of the target stimulus. Trials generally consisted of a fixation cross for 400 ms, followed in *change* conditions by a placeholder array for 1,000 ms and then followed by the search array, which was present until subjects responded. Feedback was given on each trial in the form of a "beep" if the subject responded correctly and a "buzz" if they did not.

## Results

Error trials, which made up fewer then 1% of all trials, were excluded from the analysis and were analyzed only to check for speed–accuracy trade-offs. The mean response times in the dynamic luminance change and static luminance difference conditions are graphed in Figs. 5a and 5b, respectively. The column triplets represent the mean response times in the five experimental conditions for the singleton-target (white columns), no-singleton (gray columns), and singleton-distractor (black columns) trials, respectively. The two experimental conditions with the singleton of high saliency are represented on the left (high saliency decrement and high saliency increment, respectively), followed by the two experimental conditions with the singleton of low saliency (low saliency decrement and low saliency increment, respectively). The rightmost experimental condition is where the singleton was of different contrast polarity.

The analyses, detailed below, reveal several main features of our results. In all experimental conditions, the differences in response times between the singleton-target, no-singleton, and singleton-distractor trials were much more pronounced with the dynamic luminance change (Fig. 5, top panel), as compared with static singletons (Fig. 5, bottom panel). Also, the direction of observed response time differences between the singleton-target, singleton-distractor, and no-singleton trials was different for the singletons of high and low saliency. With the singletons of high saliency, the response times were shorter for the singleton-target trials, as compared with the singleton-distractor and no-singleton trials. In contrast, with the singletons of low saliency, the response times were longer for the singleton-target trials, as compared with the singleton-distractor and no-singleton trials. When the singleton was of different contrast polarity, the response times on the singleton-target trials were shorter, as compared with the singleton-distractor trials, but were not different from the response times on the no-singleton trials.

We first performed an overall repeated measures ANOVA with singleton type (static, dynamic), experimental condition (high saliency increment, high saliency decrement, low saliency increment, low saliency decrement, polarity change), and trial type (singleton target, singleton distractor, and no singleton) as factors. There was a significant main effect of singleton type, $F(1, 53) = 159.214$, $p < .000$, with longer response times associated with the dynamic than with the static singletons. The main effects of condition and trial type were also significant, $F(1, 53) = 3.759$, $p < .009$, and $F(1, 53) = 19.461$, $p < .000$, respectively. Most important, the three-way interaction between these factors was also significant, $F(1, 53) = 6.898$, $p < .000$.

In order to further explore the observed interaction, we performed separate repeated measures ANOVA for each experimental condition, with singleton type (static, dynamic) and trial type (singleton target, singleton distractor, and no singleton) as factors. The outputs of these analyses are summarized in Table 3. In all conditions, there was a significant main effect of singleton type, such that response times were, overall, longer with the dynamic singletons. While there was a significant main effect of trial type in all experimental conditions, the direction of this effect was different in conditions with the singletons of high and low

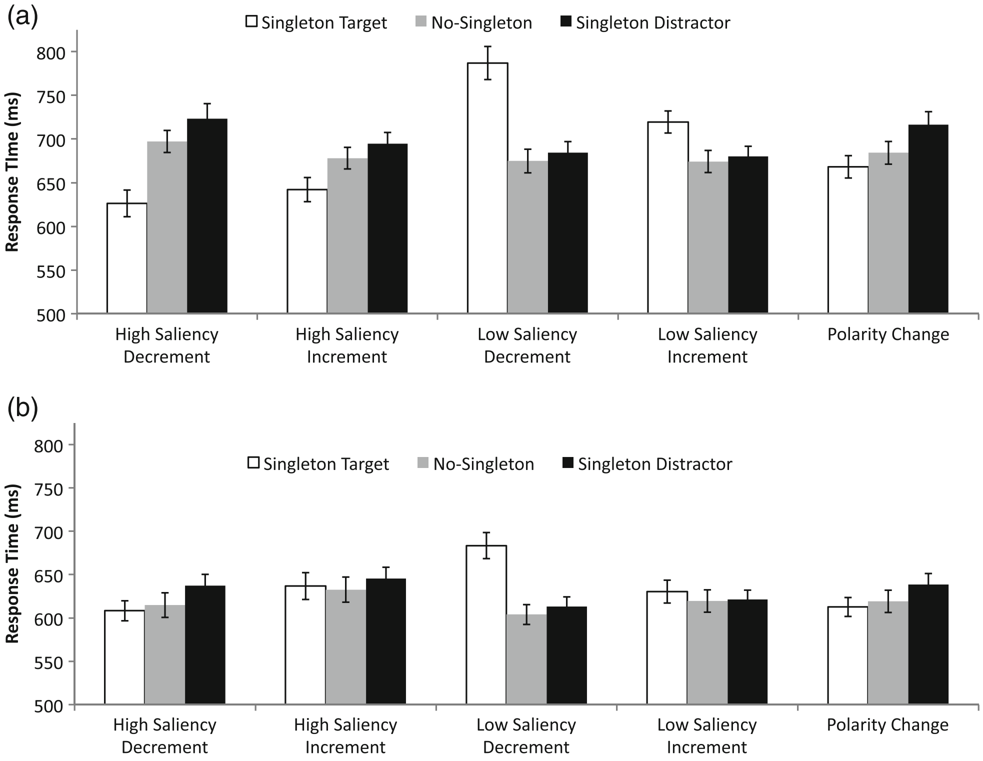

**Fig. 5** Mean response times in **a** luminance change and **b** static conditions. Columns represent the singleton-target (white columns), no-singleton (gray columns), and singleton-distractor (black columns) trials. Error bars represent ±1 standard error of the mean

saliency. In addition, in four conditions where luminance changes resulted in changes of singleton contrast, there was a significant interaction between singleton and trial types, showing that the differences between different trial types were more pronounced with dynamic singletons. There was no significant interaction between singleton type and trial type in conditions where luminance changes resulted in a change of a singleton's contrast polarity.

**Table 3** Summary ANOVA outputs in different experimental conditions in Experiment 1

| Condition | Effects | *F* | *p* |
|---|---|---|---|
| High saliency increment | Singleton type | 11.650 | .001 |
| | Trial type | 10.277 | .002 |
| | Interaction | 9.149 | .001 |
| High saliency decrement | Singleton type | 37.179 | .000 |
| | Trial type | 45.476 | .000 |
| | Interaction | 17.763 | .000 |
| Low saliency increment | Singleton type | 69.410 | .000 |
| | Trial type | 9.420 | .000 |
| | Interaction | 5.688 | .005 |
| Low saliency decrement | Singleton type | 79.923 | .000 |
| | Trial type | 136.222 | .000 |
| | Interaction | 4.790 | .010 |
| Polarity reversal | Singleton type | 49.993 | .000 |
| | Trial type | 22.842 | .000 |
| | Interaction | 1.656 | .196 |

*Planed contrast analysis* The effects of trial type and the observed interaction effects were further explored by a planned contrast analysis of differences in response times between singleton-target, singleton-distractor, and no-singleton trials for static and dynamic singletons. The differences in mean response times between different trial types in different experimental conditions and their statistical significance (adjusted for Bonferroni multiple comparisons) are shown in Table 4, with the lightly shaded cells indicating response time differences that were statistically significant at $p < .05$.

In conditions with high-saliency dynamic singletons, the singleton-target trials were significantly faster, as compared with the singleton-distractor trials (a difference of 57.72 ms with increments and 98.86 ms with decrements). The opposite pattern was observed in conditions with low-saliency dynamic singletons, where the singleton-target trials were significantly slower, as compared with singleton-distractor trials (a difference of 39.58 ms with increments and 102.8 ms with decrements). In addition, as compared with no-singleton trials, the dynamic luminance changes leading to an increased singleton's saliency also resulted in significantly shorter response times on the singleton-target trials, indicating significant processing benefits (a difference of 36.01 and 70.90 ms with increments and decrements, respectively). On the other hand, and consistent with significant processing costs, dynamic luminance changes leading to a reduced contrast singleton resulted in significantly longer response times on the singleton-target trials, as compared with the no-singleton trials (a difference of 45.21 and 112.23 ms for increments and

**Table 4** Mean response time differences between the singleton-target, singleton-distractor, and no-singleton trials in the experimental conditions in Experiment 1

| | | Response Time Difference | | |
|---|---|---|---|---|
| | | Singleton-Target - Singleton-Distractor | Singleton-Target - No-Singleton | Singleton-Distractor - No-Singleton |
| Dynamic Luminance Change Conditions | High saliency increment | −57.72** | −36.01** | 16.17 |
| | High saliency decrement | −96.86** | −70.90** | 29.96 |
| | Low saliency increment | 39.58** | 45.21** | 5.64 |
| | Low saliency decrement | 102.80** | 112.23** | 9.43 |
| | Contrast polarity | −48.09** | −16.04 | 32.04** |
| Static Luminance Differences Conditions | High saliency increment | −8.69 | 4.10 | 12.79 |
| | High saliency decrement | −29.23 | −6.56 | 22.67 |
| | Low saliency increment | 9.15 | 10.87 | 1.72 |
| | Low saliency decrement | 70.12** | 79.56** | 9.44 |
| | Polarity reversal | −25.78 | −6.46 | 15.29 |

decrements, respectively). When singletons were static luminance differences, the response times did not statistically differ between different trial types. The only exception was with the low-saliency decrement singleton, which exhibited the same pattern as the dynamic low-contrast decrements, although of a somewhat lower magnitude.

When the target was associated with a dynamic reversal in the singleton's contrast polarity, the response times were shorter, as compared with the singleton-distractor trials. As compared with the no-singleton trials, the response times were significantly longer on the singleton-distractor trials. No differences reached statistical significance when contrast polarity differences were of a static nature.

## Discussion

Our results suggest that dynamic luminance changes are considerably more effective in affecting attentional allocation than is a static luminance difference of the same absolute magnitude. In all experimental conditions, the response time differences between the singleton-target and singleton-distractor trials were more pronounced with dynamic luminance changes, as compared with static luminance differences. Importantly, the differences in a singleton's end point saliency affected the direction of observed response time differences between singleton-target, singleton-distractor, and no-singleton trials.

When the dynamic changes resulted in an increase in a singleton's luminance contrast with the background (or increased saliency), the response times on the singleton-target trials were significantly shorter than those on the singleton-distractor trials. On the other hand, dynamic luminance changes that reduced a singleton's luminance contrast with the background resulted in longer response times on the singleton-target, as compared with the singleton-distractor, trials. The results in Experiment 1 also showed that when dynamic luminance changes increased the singleton's saliency, the response times on the singleton-target trials were significantly shorter, as compared with the no-singleton trials, indicating that in these conditions, the irrelevant singleton afforded significant processing benefits. This pattern of results is consistent with claims that if a singleton is truly capturing attention, it should lead to shorter response times when associated with a target, as compared with no-singleton baseline trials (Becker, 2007; Owens & Spehar, 2008). On the other hand, the dynamic luminance changes that decreased the singleton's saliency resulted in significantly longer response times on the singleton-target trials, as compared with the singleton-distractor and no-singleton trials, indicating no attentional prioritization for these singletons.

The dynamic luminance changes associated with a change in the singleton's contrast polarity without changes in contrast magnitude yielded somewhat different results. Although the response times on the singleton-target trials were shorter, as compared with response times on the singleton-distractor trials, they did not differ from those on the no-singleton trials. This meant that the response times on the singleton-distractor trials were significantly longer, as compared with the no-singleton trials. Together, these results seem to indicate that with the polarity change singletons, there was no processing advantage on the singleton-target trials. At most, this effect of polarity changes is suggestive of filtering costs due to an increased display heterogeneity.

Our results demonstrate the critical importance of the specific nature of the luminance change in attentional capture. When items *become* higher in contrast (either positive or negative) with their respective background and, thus, more salient, they capture attention, causing a large and reliable processing advantage. However, luminance changes that result in reduced contrast levels between the singleton and the background (or reduced saliency) do not capture attention. We believe that the observed "high-contrast–low-contrast" asymmetry with luminance transients is not simply “perceptual” in origin, with low-contrast targets producing longer reaction times because they are difficult to see and high-contrast targets resulting in shorter reaction times because they are easier to see. As is evident in baseline conditions where all items are either uniformly high contrast or uniformly low contrast, there was no difference in response times between low and high contrast increments or decrements (see Figs. 5a, b).

We can be reasonably assured that any effects we obtain from the change conditions cannot be attributed solely to the prolonged availability of the singleton during the search processes. The control conditions with singletons defined by static luminance differences revealed a pattern of results very different from that observed with the dynamic luminance change singletons. With the high-saliency static luminance singletons, there were no statistically significant processing advantages when they were associated with the target in either increment or decrement displays. The low-saliency static singletons resulted in significantly longer response times on the singleton-target, as compared with singleton-distractor, trials for decrement displays, but not for increment displays. In summary, static singletons slowed performance when they were less salient but never caused reliable processing advantages when they were of higher saliency. That the effect was somewhat more pronounced with luminance decrements than with luminance increments might be due to the visual system’s overall greater sensitivity at lower luminance levels (Kelly, 1977).

The somewhat surprising finding of overall shorter response times on the static, as compared with the dynamic, singleton trials is consistent with Gibson (1996), who found that in a visual search task, all display elements not preceded by placeholders are responded to more quickly. Gibson argued that these differences are attributable to the degree of forward masking produced by the placeholders, which is obviously absent when the search display is not preceded by them.[2] According to the masking account, the patterns of results typically taken to indicate stimulus-driven attentional capture by an irrelevant singleton, “tend to occur only in certain experimental contexts that artificially increase the ease with which such singletons are perceived” (Gibson, 1996). While the masking hypothesis represents a plausible account of the overall difference in response times on trials with dynamic and static singletons, we believe that several features of our data are inconsistent with the simple masking account. In particular, we do not believe that the advantage of high-saliency dynamic changes over their low-saliency counterparts can be attributed solely to the differential levels of forward masking produced by their respective placeholders (see Figs. 2, 3). The overall degree of forward masking by the placeholders in our high-saliency and low-saliency target arrays can be estimated by comparing the response times on no-singleton trials in these experimental conditions. The isolated and spatially unpredictable changes associated with an irrelevant singleton had to be detected against this background, and as is evident in Fig. 5, the differences in response times in the no-singleton trials across conditions of high and low saliency are small and not significant.

## Experiment 2

While Experiment 1 utilized cost–benefit analysis to infer attentional capture by irrelevant dynamic and static luminance singletons, the most conventional and unambiguous method for inferring attentional capture is through set size manipulations and the associated search slopes as indices of search efficiency. If a salient irrelevant singleton captures attention and is attended first, response times to find a singleton target should be unaffected, or at least less affected, by variations in the number of search elements. Although we are confident that the results observed in Experiment 1 are indicative of attentional capture by the dynamic luminance changes that increase singleton saliency, in Experiment 2, our aim was to provide converging and unambiguous evidence for this effect by using set size manipulations with the irrelevant singleton paradigm.

Previous investigations of attentional capture by irrelevant luminance singletons, mostly focusing on static luminance singletons, have yielded somewhat mixed results. For example, Jonides and Yantis (1988) and Folk and Annett (1994) investigated the influence of irrelevant bright singleton among dimmer elements and reported no evidence of attentional capture. Both target singleton and target nonsingleton trials yielded rather steep and nearly identical search slopes, ranging from 20 ms/item to nearly 50 ms/item for both target singleton and target nonsingleton trials across different studies and experiments.

However, Todd and Kramer (1994) found a flatter search slope for uniquely bright singleton targets among dimmer elements (17 ms/item), as compared with a relatively less efficient search efficiency for bright but nonunique targets (24.8 ms/item). They found no such advantage for uniquely dim singletons among brighter elements (with search slopes of 24.1 ms/item and 23.7 for dim unique and dim nonunique

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[2] In fact, Gibson (1996) proposed that the advantage of the sudden-onset elements in capturing attention can be attributed to the reduced forward masking at the spatial location at which they appear (as compared with the locations of old objects in the display). However, Yantis and Jonides (1996) dismissed this account by arguing that forward masking by a temporally leading stimulus is minimal for long forward mask durations, as is the case in the irrelevant singleton paradigm where the placeholders are presented for 1,000 ms prior to the appearance of the search array. It was shown by DiLollo (1980) that the interference by the temporally preceding mask is highest at very short mask durations (20 or 40 ms), after which it decays rapidly and is virtually nonexistent for mask durations of 320 ms and above.

targets, respectively). Because their obtained search slope for singleton targets was nonzero, Todd and Kramer referred to this phenomenon as "attentional misguidance," to differentiate it from stronger forms of attentional capture (e.g., those created by sudden onsets, which can yield flat search slopes). The same pattern of a more efficient visual search with bright singleton targets, as compared with non-singleton targets, has been observed in a number of subsequent studies (Lu & Han, 2009; Proulx & Egeth, 2006, 2008; Yantis & Egeth, 1999).

Proulx and Egeth (2006) suggested that attentional capture by irrelevant singletons is affected by the degree of similarity between target and nontarget elements in a search display: As target–nontarget element similarity is increased, the prioritization of the salient irrelevant singleton is reduced. They used a visual search for a vertical target among obliquely oriented nontarget elements in conditions of low, medium, and high target–nontarget similarity in orientation. When the target was very different in orientation from the nontarget elements, the search slope for a bright singleton target was shallower than that for a nonsingleton target (22 and 36 ms/item, respectively). This difference, while still significant in the medium similarity condition (35 and 55 ms/item for the singleton-target and nonsingleton-target trials, respectively), was eliminated in the condition of high target–nontarget similarity (84 and 114 ms/item for the singleton-target and nonsingleton-target trials, respectively). Proulx and Egeth (2006, 2008) have also argued that varying degrees of target–nontarget similarity across different studies in this area could have potentially contributed to the conflicting evidence regarding attentional capture by the irrelevant luminance singletons.

The few studies that have investigated the ability of dynamic luminance changes to capture attention have reported search slopes of similar efficiency to those observed for static luminance singletons. For example, Yantis and Hillstrom (1994) found that singleton-target trials on which the target was briefly brightened yielded flatter search slopes, as compared with target trials without such transient changes (search slopes of 19 and 26 ms/item, respectively). In the Enns et al. (2001) study, search slopes for the luminance change singleton trials ranged from 20 ms/item for luminance changes of higher contrast magnitude to 50 ms/item for luminance changes of lower contrast magnitude. However, in both of these studies, the luminance changes were very short-lived and did not lead to very salient modifications in the appearance of the item with which they were associated. For example, in Yantis and Hillstrom, the singleton was brightened for only 50 ms before retuning to its original luminance, which was the same as that of the other search elements. As was argued previously, in Enns et al., the large luminance changes were obscured by the heterogeneity in luminance and the contrast polarity of search elements.

Here, we investigated how luminance changes that lead to a permanent change in the singleton's luminance and contrast (at least for the duration of search display) affect search efficiency. As in Experiment 1, the dynamic luminance changes were equivalent in magnitude and differed only in the luminance and contrast of search elements. On the basis of the pattern of data observed in Experiment 1, we expected dynamic luminance changes that led to an increased contrast and a higher saliency of the irrelevant singleton to yield shallower search slopes, as compared with luminance changes that led to a reduction in contrast and lower saliency. In addition, dynamic luminance changes that increased the saliency of the irrelevant singleton were expected to lead to a more efficient search than the static luminance differences of equal magnitude. For the sake of brevity, these predictions were tested only with the two luminance decrement conditions from Experiment 1 (conditions 3 and 4): luminance decreases that lead to an increased singleton saliency and luminance increases that lead to a decreased singleton saliency, respectively.

## Method

*Subjects* Thirty-three undergraduate University of New South Wales students participated to receive course credit. They were naïve as to the purpose of the study. All had normal or corrected-to-normal visual acuity.

*Design* Separate groups of participants were used for dynamic luminance change singleton ($n = 16$) and static luminance difference singleton ($n = 17$). For each singleton type, within-subjects factors were 2 (singleton's saliency: high and low) × 2 (trial type: singleton-target vs. nonsingleton target) × 2 (set size: 4 and 8). With a set size of 4, the singleton was associated with the target on 25% of the trials, and with a set size of 8, the singleton was associated with the target on 12% of the trials. There were a total of 384 trials, 192 for each set size. On half of the trials, the singleton was associated with a decrease in luminance, which led to an increase in the singleton's contrast or saliency, and on half of the trials, the singleton was associated with an increase in luminance, which led to a decrease in the singleton's contrast or saliency. The trials with high and low saliency changes (differences) were run as four separate blocks of each type in a randomized order.

On dynamic luminance change trials, placeholders preceded the search array, resulting in one of the elements suddenly becoming brighter or darker than other, unchanged search elements (nonsingletons). On static luminance singleton trials, search arrays were presented without placeholders, so the singleton was defined only by its static unique luminance difference relative to the other display elements (singleton brighter or darker than other, nonsingleton search elements). Figure 6 shows examples of placeholder (top panel), singleton-target (middle panel), and singleton-distractor (bottom panel) displays for dynamic luminance changes at the two set sizes. In all these

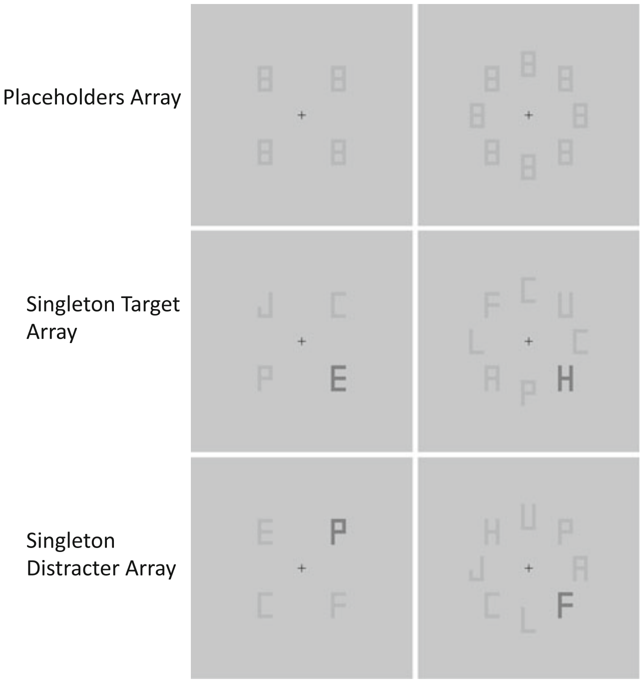

**Fig. 6** Examples of set size variations in search displays used in Experiment 2. The top panel shows placeholder arrays with four and eight elements used in conditions where luminance changes led to increased singleton contrast and saliency. The middle and bottom panels show the corresponding search arrays with target singleton and distractor singleton, respectively

examples, luminance changes associated with singletons led to an increased contrast or saliency. Static luminance difference displays were identical, except that they were not preceded by the placeholder array.

*Apparatus, stimuli, and procedure* Details of the apparatus, stimuli, and experimental procedure were the same as in Experiment 1.

## Results

The mean response times for singleton-target and singleton-distractor trials in four experimental conditions are graphed in Fig. 7. Errors trials were excluded from the analysis and were analyzed only to check for speed–accuracy trade-offs. In addition to error trials, which made up fewer than 2.1% of all trials in all conditions, correct response times greater than 3 standard deviations above the individual observer's mean were also excluded. Together, approximately 3.5% of all trials were removed from the analysis.

The four graphs in Fig. 7 represent response times for the singleton target (solid lines) and singleton distractor (dashed lines) when the irrelevant singleton was a dynamic luminance change that resulted in the singleton's increased saliency (panel a), the most salient static item in the display (panel b), a dynamic change that resulted in the singleton's reduced saliency (panel c), and the least salient static item in the display (panel d).

The comparison of search slopes for the four experimental conditions depicted in Fig. 7 reveals a large difference in the search efficiency between the singleton-target and singleton-distractor search slopes only when the singleton was a dynamic luminance change of high saliency (panel a). With the static luminance singleton of high saliency, the search slope on the singleton-target trials is more efficient than in the singleton-distractor trials, but the difference is not as pronounced as with the dynamic luminance change singletons (Fig. 7b). With the singletons of low saliency, regardless of whether they are dynamic or static, search efficiency on the singleton-target trials is not very efficient and is no different from that observed on the singleton-distractor trials (Fig. 7c, d).

An overall ANOVA with a between-subjects factor of singleton type (static, dynamic) and within-subjects factors of singleton saliency (low saliency, high saliency), trial type (singleton target, singleton distractor), and display size (four, eight) was performed first. It revealed main effects of singleton saliency, $F(1, 31) = 17.290$, $p < .000$, trial type, $F(1, 31) = 29.80$, $p < .000$, and display size, $F(1, 31) = 232.739$, $p < .000$. Significant two-way interactions were observed between singleton type and singleton saliency, $F(1, 31) = 10.549$, $p < .003$, saliency and trial type, $F(1, 31) = 78.585$, $p < .000$, and trial type and display size, $F(1, 31) = 26.431$, $p < .000$. Significant three-way interactions were observed between singleton type, singleton saliency, and trial type, $F(1, 31) = 10.424$, $p < .003$, and between singleton type, trial type, and display size, $F(1, 31) = 4.021$, $p < .039$. The four-way interaction between singleton type, singleton saliency, trial type, and display size was also significant, $F(1, 31) = 5.070$, $p < .032$.

In order to further explore these interactions, we performed separate ANOVAs for each singleton saliency condition, with a between-subjects factor of singleton type and within-subjects factors of trial type and display size. On the basis of the findings from Experiment 1, we were primarily interested in significant interaction effects with singleton type as a factor.

In the low-saliency condition, there were only significant main effects of trial type, $F(1, 31) = 10.781$, $p < .03$, and display size, $F(1, 31) = 217.980$, $p < .000$, and no significant interaction effects. However, in the high-saliency condition, in addition to the significant main effects of trial type and display size, $F(1, 31) = 144.657$, $p < .000$, and $F(1, 31) = 156{,}177$, $p < .000$, respectively, there were significant two-way interactions between trial type and display size, $F(1, 31) = 64.576$, $p < .000$, as well as between singleton type and trial type, $F(1, 31) = 15.824$, $p < .000$. Most important, there was also a significant three -way interaction between singleton type, trial type, and display size, $F(1, 31) = 4.930$, $p < .034$. This significant three-way interaction suggests that the difference

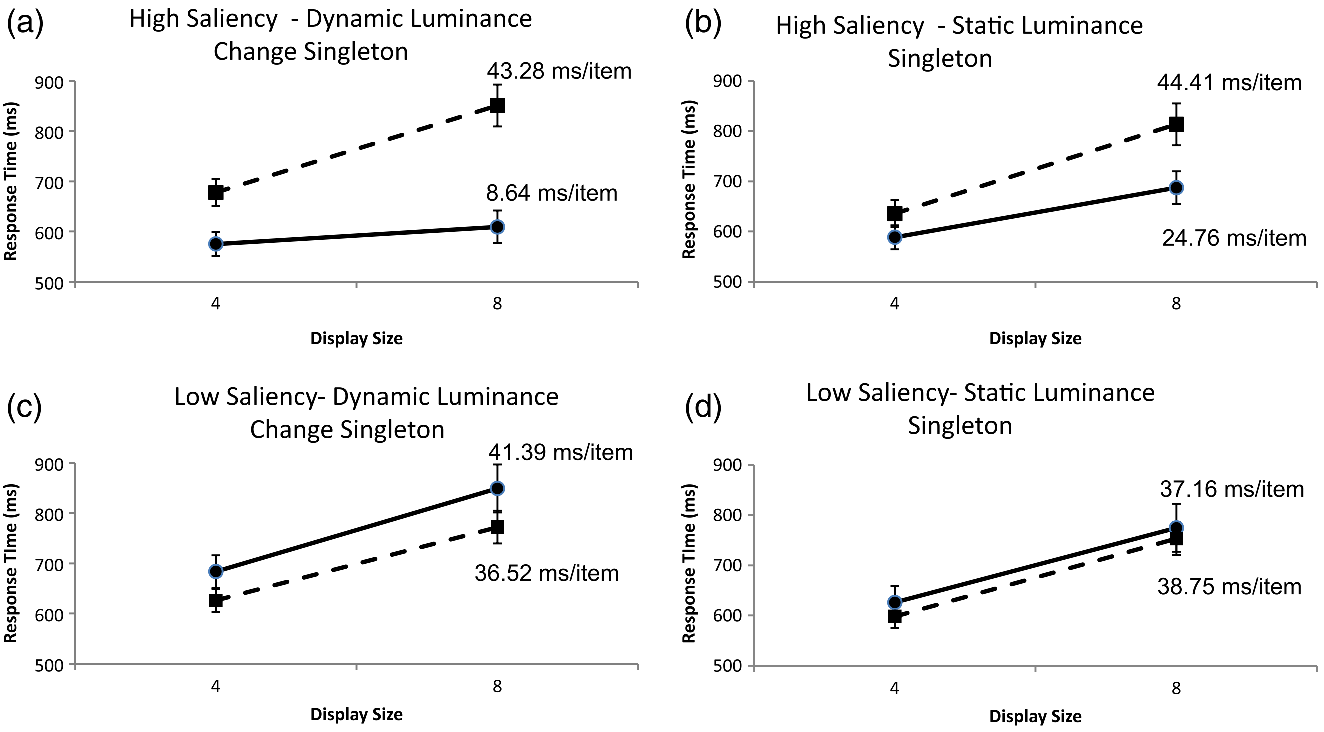

**Fig. 7** Mean response times in target singleton and distractor singleton trials with manipulations of set size. Solid lines represent trials where luminance changes resulted in increased singleton contrast or saliency. Dashed lines represent trials where luminance changes resulted in decreased singleton contrast or saliency. Error bars represent ±1 standard error of the mean. **a** Dynamic luminance change singleton of high saliency. **b** Static luminance difference singleton of high saliency **c** Dynamic luminance change singleton of low saliency. **d** Static luminance difference singleton of low saliency

between singleton-target and singleton-distractor search slopes was greater in conditions in which the singleton was a dynamic luminance change, as compared with static luminance differences.

These significant interactions are reflected in differences between search slopes on the singleton-target and singleton-distractor trials in different conditions of singleton type and saliency. The search slopes on the singleton-target trials in both dynamic and static luminance singletons of high saliency were shallower than the search slopes on the singleton-distractor trials in those conditions ($p < .000$ and .0004, respectively). The mean search efficiency on the singleton-target trials was higher with the dynamic luminance singleton of high saliency, as compared with the static luminance singleton of high saliency (8.64 and 24.76 ms/item, respectively). This difference in mean search slopes between dynamic and static luminance singletons of high saliency was significant ($p < .000$). The mean search slopes on the singleton-target and the singleton-distractor trials did not differ in conditions of dynamic and static luminance singletons of low saliency.

## Discussion

The purpose of this experiment concerned the nature and the locus of the differences in search efficiency for the different types of luminance changes and differences found in Experiment 1. In particular, set size manipulations allow one to disambiguate whether the advantage in search efficiency found for luminance changes resulting in an increased singleton saliency occurs prior to the operation of visual selective attention or whether it reflects more efficient allocation of attention to this type of luminance change. If the locus of processing advantage associated with luminance changes that increase or decrease singleton saliency is prior to the operation of visual selective attention in visual search tasks, there should be no difference in the observed search slopes between conditions leading to increases and decreases of a singleton's saliency. Instead, in such a case, one might observe overall shorter reaction times for luminance changes that increase singleton saliency, as compared with those that decrease it.

The results obtained in this experiment clearly do not follow this pattern and show pronounced differences in search efficiency, and the associated search slopes, between the experimental conditions leading to increases and decreases in the saliency of the irrelevant singleton. We found that the mean search slopes for the dynamic singleton-target trials of high saliency were nearly flat (8.64 ms/item), while the mean search slope for the singleton-target trials with static luminance singletons of high saliency was relatively less efficient (24.76 ms/item). However, both of these search slopes were more efficient, as compared with search slopes for the corresponding singleton-distractor trials (43.28 and 44.41 ms/item, respectively). For the singleton-target and the singleton-distractor trials of low saliency, regardless of whether they were dynamic luminance changes or static luminance differences, the search slopes were inefficient, ranging from 36.52 to 41.39 ms/item.

The relative advantage in processing efficiency with static luminance singletons of high saliency is a pattern observed in several previous studies investigating the ability of static luminance singletons to capture attention (Lu & Han, 2009; Proulx & Egeth, 2006, 2008; Todd & Kramer, 1994; Yantis & Egeth, 1999). While most of the studies reported somewhat shallower search slopes for singleton trials of high saliency, these were associated with the higher magnitude of the singletons' contrast with the background.[3] However, regardless of the differences in the absolute and relative luminance of the irrelevant singleton, the advantage of our approach is a direct comparison between dynamic changes and static luminance differences of equal magnitude.

Similar to what was observed in Experiment 1, the response times were generally shorter with the static luminance singletons, as compared with the dynamic luminance singletons. Previously, we have attributed this pattern of results to the forward masking created by placeholders in dynamic luminance change conditions. However, given that the presence of placeholders characterized the difference between the dynamic and static conditions in this experiment as well, it is possible that this could somehow influence the observed differences in search efficiency between these conditions. In order to rule out this possibility, we ran an additional control condition where we compared the search efficiency for detecting a target in dynamic (placeholders) and static (no placeholders) conditions, but this time without any singletons. These conditions were essentially a set size manipulation of the two baseline conditions (no-singleton conditions) from Experiment 1. If there is a masking-related contribution to the differences observed in search efficiency with the placeholder and no-paceholder displays, the search slopes in these two conditions should differ. However, the search efficiency in these two conditions was very similar, with search slopes of 40 and 35 ms/item for the dynamic (placeholders) and static (no placeholders) conditions, respectively. We conclude that the differences in search efficiency with the dynamic and static luminance singletons are attributable to the attentional prioritization of luminance transients.

## General discussion

Our results strongly suggest that it is the nature of luminance change more than its absolute magnitude that needs to be taken into account when evaluating processing efficiency in relatively uniform displays. While both increases and decreases in luminance seem to have captured attention when they resulted in an item's having higher contrast, relative to the other elements in the display, the reverse was not the case. The changes in contrast polarity where luminance changes did not lead to increases or decreases in a singleton's contrast with the background were also effective in modulating attentional allocation. However, while the dynamic luminance changes that increased a singleton's contrast magnitude led to a significant decrease in response times, relative to no-singleton trials, the dynamic changes leading solely to contrast polarity reversals resulted mostly in a substantial increase in response times on the singleton-distractor trials. We believe that these differences, relative to no-singleton trials, are indicative of different patterns of processing benefits and filtering costs afforded by dynamic luminance changes of different types. Whether the observed costs, in the absence of processing benefits, reflect genuine attentional capture is debatable, since the mere need to filter out irrelevant stimuli could easily account for these findings (Becker, 2007).

The observed "high-contrast–low-contrast" asymmetry with luminance transients is consistent with the well-documented phenomena of search asymmetry with purely static search displays, where targets that possess greater values on some quantitative dimensions among distractors of lesser value are found more easily than in the opposite case (Treisman & Gormican, 1988). The asymmetry is also consistent with search models that assume that an object's salience is determined not solely by its uniqueness in comparison with other items in search displays, but on the level of the relative activity generated by that object (Cave & Wolfe, 1990; Koch & Ullman, 1985).

That this high-contrast–low-contrast asymmetry was more pronounced for decrements than for increments is also consistent with the role of relative sensory-level activity generated by the elements in a search display. Although incremental and decremental singleton and nonsingleton search elements were equated in terms of Weber contrasts ($\Delta L/L$), they were not equated in terms of the other common definition of contrast of luminance differences, the Michelson contrast: $(L_{\mathrm{maximum}} - L_{\mathrm{minimum}})/\ (L_{\mathrm{maximum}} + L_{\mathrm{minimum}})$. The Michelson contrast values for decremental singleton and nonsingleton search elements were either 0.60 or 0.14, differing approximately by a factor of 4.2, causing a considerable difference in saliency between singleton and nonsingleton search elements. In contrast, the Michelson contrast values for incremental singleton and nonsingleton search elements were either 0.27 or 0.11, differing approximately by a factor of

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[3] Nearly all of the studies presented their search elements as luminance increments against a black background, which has contributed to much higher levels of singleton contrasts, as compared with our study, which used a mid-gray background with a much higher luminance level.

2.4 and resulting in a smaller difference in saliency between singleton and nonsingleton search elements.

In Experiment 2, we manipulated display size to obtain more widely used indices of attentional prioritization by static and dynamic luminance singletons. The findings for static luminance singletons of high saliency replicated the previously reported advantage of bright static luminance singletons in prioritizing attentional allocation (Lu & Han, 2009; Proulx & Egeth, 2006, 2008; Todd & Kramer, 1994). However, the search efficiency observed with dynamic luminance singletons of high saliency was significantly higher and in the range of efficient visual search slopes (8.86 ms/item). The obtained search slope with dynamic luminance singletons of high saliency was considerably shallower than the ones reported by Yantis and Hillstrom (1994) and Enns et al. (2001). While all the studies used similar search elements (eight-digit placeholders and subsequently transformed target and distractor letters), the duration of dynamic luminance change singletons and their conspicuity in the search display were different between the studies. In Yantis and Hillstrom, the singleton was only temporarily brightened (for 50 ms) before returning to the original luminance and was otherwise indistinguishable from other search displays. Similarly, in Enns et al., the high heterogeneity of search display elements made the luminance change less noticeable. Our results suggest that luminance changes need to be associated with a relatively permanent increase in a singleton's saliency in order to be able to effectively prioritize attentional allocation. Although requiring a "permanent" change in a singleton's appearance, the dynamic luminance changes were more effective in attentional prioritization than were otherwise equal static luminance differences.

In no sense could our results reflect contingent involuntary orienting (after Folk, Remington, & Johnston, 1992), because neither the static nor the dynamic singletons shared any relationship with either the location or the nature of our targets. However, it is possible that our subjects were set to attend to the display-wide "feature" of a unique luminance[4] (Burnham, 2007; Gibson & Kelsey, 1998). This form of top-down influence in atentional allocation prioritizes certain features because of their temporal association with the appearance of the search array. Certainly, in our paradigm, when the luminance singletons appeared, they were uniquely associated with the appearance of search arrays in the context of individual blocks; however, the inclusion of no-singleton trials throughout would have greatly diluted or delayed the formation of a task set for singletons. Nevertheless, the display-wide set for unique luminance could potentially account for the differences between dynamic and static singletons, since dynamic luminance change certainly represents a stronger display-wide signal about the appearance of the search array.

However, it is not clear how the inclusion of a display-wide set for an uninformative luminance singleton would predict the observed differences between conditions with the irrelevant singletons of high and low saliency. Both types of dynamic luminance changes/differences were equally informative of the appearance of the search array and should thus have led to similar patterns of attentional capture.

Together, these results are consistent with findings indicating the importance of luminance (or sensory) change in attentional prioritization, and our findings suggest important boundary conditions for the circumstances in which dynamic cues might be effective in guiding attention. In particular, only changes that result in increased singleton saliency seem to be capable of producing substantial processing costs and benefits.

Our final note is that the observed pattern of costs and benefits and search slopes associated with luminance changes that increase a singleton's contrast is similar to that previously observed for sudden onsets (Owens & Spehar, 2008). Although we are aware that similar patterns of results do not necessarily indicate similar underlying mechanisms, especially in the absence of a direct comparison, we believe that our findings have implications for the contrasting views emphasizing either the role of sensory change or new-object-based considerations in attentional capture by dynamic visual cues. Namely, it has been proposed that in addition to sudden onsets, other dynamic visual cues might be able to capture attention via mechanisms involved in maintaining the spatiotemporal continuity of established object files. According to this view, sufficiently large featural changes to an existing object can lead to the disruption of object continuity and might be treated by the visual system as an instantiation of a new object (Rauscheberger, 2003; Yantis & Jonides, 1996). Our results clearly indicate that only changes that result in increased singleton saliency were effective in capturing attention. It is not obvious how either the spatiotemporal object continuity or the simple sensory change hypothesis can accommodate the asymmetry between luminance changes that were equal in magnitude but different in end point saliency, observed in our study.

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[4] We thank M. Proulx for this suggestion.

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