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Biased competition and visual search: the role of luminance and size contrast

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Abstract The biased-competition theory of attention proposes that objects compete for cortical representation in a mutually inhibitory network; competition is biased in favor of the attended item. Here we test two predictions derived from the biased-competition theory. First we assessed whether increasing an object's relative brightness (luminance contrast) biased competition in favor of (i.e., prioritized) the brighter object. Second we assessed whether increasing an object's size biased competition in favor of the larger object. In fulfillment of these aims we used an attentional capture paradigm to test whether a featural singleton (an item unique with respect to a feature such as size or brightness) can impact attentional priority even when those features are irrelevant to finding the target. The results support the prediction that a singleton with respect to luminance contrast receives attentional prioritization and extend the biased-competition account to include size contrast, because a large singleton also receives attentional prioritization.

Introduction

The biased-competition theory of attention proposes that objects compete for cortical representation in a mutually inhibitory network; attention prioritizes objects for further processing by biasing the competition in favor of the attended item (Desimone & Duncan 1995). Maunsell and McAdams (2000) noted that the neuronal effects of attention in visual cortex resemble that of manipulating stimulus properties such as increasing contrast (see also Chun & Marois 2002). For instance, orientation-selective cells respond more strongly if a stimulus at the preferred orientation is made brighter; this functions as a bottom-up mechanism to bias competition in favor of the brighter stimulus. Likewise, the same cells will also respond more strongly if a stimulus is attended; this functions as a top-down mechanism to bias competition in favor of the attended stimulus (Moran & Desimone 1985; Reynolds, Pasternak, & Desimone 2000). Top-down attentional allocation and bottom-up stimulus enhancement therefore might trigger a similar cellular response (see Reynolds & Desimone 2003, for evidence that suggests this). These two forms of "bias" might be ultimately distinguishable, but they may both evoke attentional prioritization in a similar manner at the cellular level (for a thorough review, see Reynolds & Chelazzi 2004).

Psychophysical and neurophysiological evidence supports the idea that objects with greater luminance contrast are processed more quickly and accurately than lower contrast items (e.g., Bundesen 1990; Maunsell & McAdams 2000; Pashler & Badgio 1985; Reynolds & Desimone 2003). Note that there is an asymmetry, such that a bright singleton is processed more quickly and accurately than other relatively dimmer objects, but a dim singleton is not processed preferentially over relatively brighter objects (cf. Braun 1994). In this paper we consider just bright singletons, not dim ones.

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The feature of being brighter is related to the conspicuity of the object. Thus, a brighter object is enhanced both physiologically and psychologically. Psychologically, an object that is seen more easily leads to a clearer representation of the object; thus, one can more easily make discriminations about the object as well (see Bundesen 1990; Pashler & Badgio 1985; note that this would likely be true from a signal-detection theory perspective as well, see Verghese 2001). From a physiological perspective, a population of neurons selective for orientation will respond more to a bright bar than a dim one (see Maunsell & McAdams 2000; Reynolds & Desimone 2003). The biased-competition account (Desimone & Duncan 1995) readily applies to how the competition might be biased in favor of a stimulus of enhanced contrast such as a singleton. This is because a manipulation like increasing luminance contrast can enhance an orientation-selective cell's response to an oriented bar (e.g., Rossi, Rittenhouse, & Paradiso 1996) much as top-down attentional selection would (Reynolds & Desimone 2003). Note that the effects of contrast on cellular response might apply to other types of feature contrast as well (e.g., motion and orientation; Kastner, Nothdurft, & Pigarev 1997).

The biased-competition account of attention makes some clear behavioral predictions. Objects with high luminance-contrast should receive attentional prioritization over lower contrast objects. A recent study by Pashler, Dobkins, and Huang (2004) sought to contrast this prediction with the hypothesis that contrast is a feature just like color, and the visual system can either select it or not, just as one can voluntarily attend to either red items or green items (e.g., Green & Anderson 1956). Pashler et al. found some evidence that luminance contrast is like any other feature in that participants could selectively attend to either low or high contrast, suggesting that high contrast objects do not necessarily receive attentional prioritization through biased competition. However, in a later experiment Pashler et al. reported that when participants searched for a target based on location (rather than low or high contrast), the presence of high contrast distractors was more disruptive than the presence of low contrast distractors. This suggested that the high contrast objects might receive enhanced processing as predicted by biased competition.

In addition to challenging the idea that contrast acts as just a standard feature in visual search (which was one of the possibilities considered by Pashler et al. 2004), the idea that a singleton influences attentional prioritization would not be predicted by the contingent capture hypothesis (Folk, Remington, & Johnston 1992). A strong version of the contingent capture hypothesis would hold that irrelevant singletons do not capture attention because attentional control is solely guided by top-down processes. Thus, if the feature singletons used in the current study influence attentional prioritization, then this version of contingent capture might require modification.

Note that it is already established that irrelevant singletons can capture attention in efficient search tasks for a singleton target (e.g., Bacon & Egeth 1994; Theeuwes 1991, 1992). The present experiments focus instead on a task that is inefficient, such that the response times on target-present trials increase as a function of the number of elements in the display. The ability of a singleton to influence attentional control in an inefficient search task is still uncertain (see, e.g., Folk & Annett 1994; Jonides & Yantis 1988; Todd & Kramer 1994; Turatto & Galfano 2000; Yantis & Egeth 1999). Models of visual search, such as Guided Search (Wolfe 1994), account for performance in inefficient search tasks by assuming that attention is guided on the basis of top-down information rather than bottom-up information. This is contrasted with a highly efficient task, where attention can be guided solely on the basis of bottom-up information, either intentionally (cf. singleton detection mode; Bacon & Egeth 1994) or automatically (Theeuwes 1991). There is substantial evidence that a singleton defined by the abrupt onset of an object can capture attention in many visual search tasks (e.g., Yantis & Jonides 1984), however, the evidence for attentional capture by other feature singletons, such as bright ones, is mixed.

Present research

We aimed to test two predictions derived from the biased-competition theory. First, the present study was conducted to provide a further behavioral test of the biased-competition theory of attention (Desimone & Duncan 1995) and to test the suggestion by Pashler et al. (2004) that the visual system may select high contrast items by default when luminance contrast is not a part of the attentional set or definition of the target. Note that Pashler and colleagues did not test their suggestion with an irrelevant feature singleton as we do here. In their study, they presented multiple items of high contrast, such that there was never a singleton present. Furthermore, in two of the experiments the subjects were either explicitly told to attend to contrast to find the target or given the implicit ability to do so by having the target always appear at high or low contrast in separate blocks, such that contrast was not necessarily irrelevant. In addition to bright singletons, other singletons with related properties that increase the conspicuity of an object, such as size, might also evoke attentional prioritization. The second prediction, then, is that feature contrast created by increasing the size of an object would have the same effect as increasing an object's brightness. To fulfill these aims we used an attentional capture paradigm to test whether a singleton that is unique due to the feature contrast of size or luminance can impact attentional priority even when those features are irrelevant for finding the target. Because of well-known asymmetries in visual search, only a large singleton or a bright singleton was used (Braun 1994; Treisman & Gormican 1988).

We employed the irrelevant feature search task (e.g., Yantis & Jonides 1984). Participants searched for a target vertical bar among distractor bars randomly tilted 30° clockwise or counterclockwise, which we expected to be an inefficient search task, where response times would increase as a function of the number of elements in the display (Wolfe, Friedman-Hill, Stewart, & O'Connell 1992; for evidence that a luminance-contrast singleton can capture attention in an efficient search task for a color singleton, see Theeuwes 1991). One of the bars on each trial was either a large or bright singleton; the target and the singleton only coincided on $1/d$ proportion of the trials (where d is the number of elements in the display). Each observer saw each singleton type on randomly mixed trials.

The first experiment we performed was a control task, in which there were no irrelevant feature singletons; this served as a potential neutral, baseline comparison. In the second experiment, we presented large or relatively bright singletons in randomly mixed trials. In the third experiment, we examined the ceiling efficiency at which the feature singletons used in the experiments could be detected, by making the singleton 100% predictive of the target location.

General method

Participants

Johns Hopkins University undergraduate and graduate students and a postdoctoral researcher all reporting normal or corrected-to-normal vision participated either in partial fulfillment of a course requirement or for payment. Naive observers were recruited for every experiment reported herein. A total of 41 observers participated in the study.

Apparatus and stimuli

The apparatus, stimuli, and procedure largely replicated that of Yantis and Egeth (1999). Participants were 55 cm from the screen and a chin rest was used to stabilize their head location. An Artist Graphics TI34020-based graphics accelerator board (TIGA) displayed the stimuli on a 21-in. Taxan color monitor in a dimly lit room.

Each stimulus display had a black background with a luminance of 0.1 cd/m^2. Three, six, or nine oriented bars appeared for each trial. The nonsingleton bar size subtended 0.6° of visual angle in length and 0.15° in width. In the condition with the large singleton in Experiment 2, the larger singleton bar subtended 0.9° in length and 0.15° in width. Table 1 contains all of the luminance values and the red, green, blue (RGB) parameters for the stimuli in each experiment. All luminance recordings were taken using a Lite Mate III Model 504 with Spot Mate Model 502 System 500 (Photo Research Division of Kollmorgen Corporation; by comparison, RGB parameters of 255, 255, 255 had a luminance of 73.4 cd/m^2).

To control display density, the bars were dispersed in the cells of an invisible grid subtending 6°, 7°, or 8° of visual angle (with 7 × 7, 8 × 8, and 9 × 9 grid sizes, respectively) for a corresponding display numerosity (three, six, or nine bars, respectively). If the area of the display had remained constant, then the density of the bars would have increased as a function of the display numerosity. The bars were arranged within a subset of the cells of the grid, which were 1° apart, center-to-center; and the bar positions were each displaced by a random vertical and horizontal factor of ±0.2° to reduce rectilinear configuration effects (e.g., collinearity). The bar positions were selected randomly. The target bar was vertical (and appeared on half of the trials) and nontarget bars were randomly tilted either −30° or +30°, with approximately half at each orientation. There was no fixation point for any of the trials. Any deviations from this description or the following procedure are noted in the introductions to the individual experiments below.

Procedure

A display of bars appeared on each trial and the observer pressed the right button on a custom response box if the vertical target bar was present, and the left button if it was absent. As noted previously, the target was present on half of the trials.

Table 1 Luminance values (and RGB parameters) by stimulus type and experiment

	Nonsingleton	Singleton
Experiment 1	9.2 cd/m^2 (0, 0, 240)	None
Experiment 2	2.0 cd/m^2 (0, 0, 144)	9.2 cd/m^2 (0, 0, 240)
Experiment 3	2.0 cd/m^2 (0, 0, 144)	9.2 cd/m^2 (0, 0, 240)

Observers were instructed to respond as rapidly as possible while making fewer than 5% errors. They were informed of the probabilistic relationship between the singleton and the target. In particular, all observers in Experiment 2 were told that the singleton was *not* predictive of the target and would only coincide with the target on 1/*d* of the trials, where *d* is the number of elements in the display. The singleton was either large or bright, and each observer saw each singleton type on randomly mixed trials. Incorrect responses were followed by a 1 kHz feedback tone for 100 ms and a recovery trial. Each trial began after a 2-s inter-trial interval after each response was made. At the end of each block, the participants received visual feedback including their reaction time and accuracy for that block. If their error rate exceeded 5%, the screen displayed the message: "Your error rate is too high! Please slow down a little and try to be more careful." Otherwise, the screen displayed: "Your error rate is terrific! Keep up the good work!" Participants began with a practice block of 20 trials and each block began with three warm-up trials. Data from the practice, warm-up, incorrect, and recovery trials were not included in the RT analyses.

Experiment 1: baseline performance with no singleton

Experiment 1 served as a control task, in which there were no feature singletons. All bars had a length of 0.6° and a brightness of 9.2 cd/m^2. Nine participants were instructed to search for the vertical target on each trial, and no singleton appeared in any display.

The results from Experiment 1 are shown in Fig. 1. Response times increased as a linear function of the number of items in the display. Responses were quicker on target-present trials than on target-absent trials, and with fewer items in the display than with many. A repeated-measures analysis of variance (ANOVA) supported these conclusions with significant main effects of display numerosity, $F(2,16) = 37.4$, $P < 0.001$, and target presence, $F(1,8) = 22.3$, $P < 0.001$. The interaction of display numerosity and target presence was significant as well, $F(2,16) = 28.8$, $P < 0.001$. The error rates are shown in Table 2. Participants were more likely to make errors in target-present trials than target-absent trials. This suggests that participants had a tendency to guess "absent" after some period of time had elapsed as a "deadline" strategy. Chun and Wolfe (1996) presented a model of this strategy as a combination of an activation threshold and a timing mechanism, consistent with Guided Search 2.0 (Wolfe 1994).

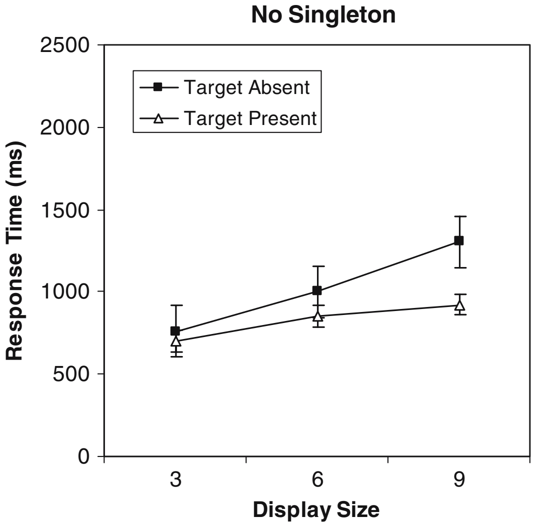

Fig. 1 Results from Experiment 1. Response time is shown as a function of display numerosity for target-present and target-absent conditions. No singletons were presented in any trial. *Vertical lines* depict standard errors of the mean in this and all figures

Table 2 Error rates for each condition in Experiment 1

Condition	Display size		
	3	6	9
No singleton			
Target present	3.7	6.3	9.4
Target absent	1.0	1.2	0.7

The analysis of these data demonstrated that this task was an inefficient search and therefore appropriate for using the irrelevant feature search task's method of varying display numerosity (cf. Yantis & Egeth 1999). The slope for the target-absent function was 90 ms per item, over twice that for the target-present function, which was 37 ms per item.

Experiment 2: size or luminance-contrast singletons

This experiment tested whether size or luminance singletons could affect attentional prioritization with two types of singletons appearing in mixed trials. All bars were blue; on the large singleton condition trials, one bar was longer than the others. On the bright singleton condition trials, one bar was brighter than the others. Sixteen participants contributed to Experiment 2. Each observer participated in three blocks of 216 trials apiece. Participants were informed about the existence of the two singleton types and about the 1/*d* relation between the target and the singleton.

The results from Experiment 2 are shown in Fig. 2. The search functions are plotted by target type: target-absent, and two target-present types (target nonsingleton or target singleton). There was a singleton present on every trial. The target-absent trials contained a distractor that was a singleton. The target nonsingleton trials contained a target that was not the irrelevant feature singleton but also contained a distractor that was a singleton. The target singleton trials contained the target, which was also the irrelevant feature singleton. As previously noted, the display numerosity could be three, six, or nine bars.

Target-present type interacted with display numerosity, suggesting that the feature singletons commanded attentional priority in this experiment. This is shown by the results of two separate repeated-measures ANOVAs that analyzed the target-present data for each singleton condition. For the bright singleton condition, there were main effects of both display numerosity and target type (singleton versus nonsingleton), $F(2,30) = 30.4$, $F(1,15) = 20.3$, $P < 0.001$, respectively. Likewise for the large singleton condition, effects of display numerosity and target type were also significant, $F(2,30) = 73.0$, $F(1,15) = 100.3$, $P < 0.001$. More importantly, there was a significant interaction between display numerosity and target type: $F(2,30)=7.9$, $P < 0.005$ for bright singletons; $F(2,30) = 8.0$, $P < 0.005$ for large singletons.

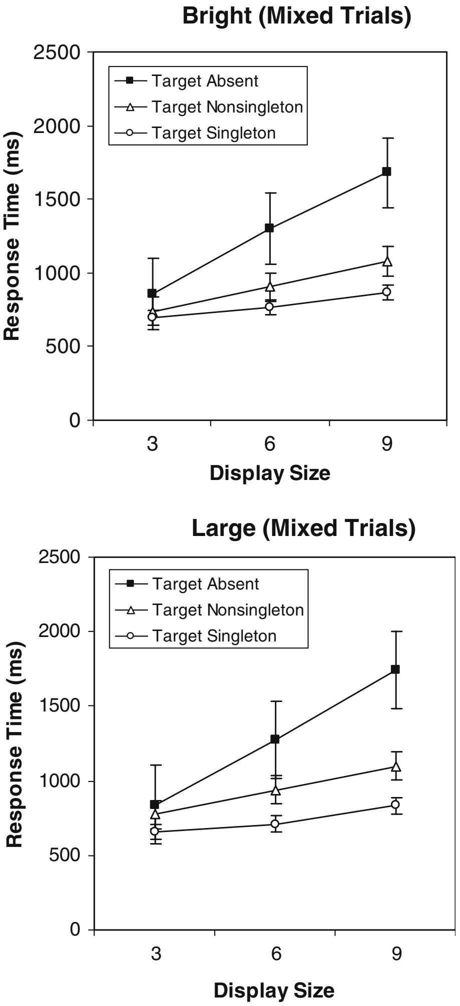

Fig. 2 Results from Experiment 2, in which the singleton type (luminance or size) was randomized across mixed trials. Response time is displayed as a function of display numerosity for the target-absent, target-present nonsingleton, and target-present singleton conditions. The *Bright* graph displays the data for the trials that featured a bright singleton. The *Large* graph shows the data for the trials that featured a size singleton

The error rates are displayed in Table 3. The error rates generally increased with display numerosity. The error rates for target-present trials were larger than target-absent trials, again suggesting the possible adoption of a deadline strategy by participants. The error rates were lowest for the target-absent trials.

Of particular interest in this experiment were the differences between target types as seen in the significant interactions of target-present type and display numerosity. The singleton element commanded greater prioritization than nonsingleton elements in the search display. The search slopes when the target was present and it was a singleton were 29 ms per item for the bright singletons and 30 ms per item for the large singletons. By comparison, the slopes for the target nonsingleton conditions were 57 and 55 ms per item for the brightness and size conditions, respectively. The slopes for the target-absent conditions were 137 and 150 ms per item for the brightness and size conditions, respectively. In general, although the search slopes for the target singleton conditions are indicative of an inefficient search, they are significantly shallower than the target nonsingleton conditions, demonstrating an impact of size and luminance contrast on attentional priority.

Experiment 3: informative size or luminance-contrast singletons

We conducted this experiment to find the ceiling efficiency with which a size or luminance-contrast

Table 3 Error rates for each condition in Experiment 2

Condition	Display size		
	3	6	9
Bright			
Target present: singleton	0.3	0.0	0.0
Target present: nonsingleton	3.8	8.6	8.2
Target absent	0.7	0.3	1.5
Large			
Target present: singleton	1.4	1.4	1.0
Target present: nonsingleton	4.0	6.8	8.6
Target absent	0.5	0.5	0.3

singleton can be detected. It is possible that informative feature singletons have a baseline set size effect greater than zero ms per item, and that the slopes we have already presented are not likely to get any closer to zero than this baseline (cf. Yantis & Egeth 1999). The search rates for informative singletons can be construed as the ceiling efficiency at which observers can use the large or bright singleton salience to respond to the vertical target when directing their attention to the singleton on every trial.

Each observer saw only one singleton type or the other for the duration of the experiment. The singleton was always the target bar on target-present trials. Thus the participant could approach the task by orienting to the singleton and determining whether or not it was vertical, because if the vertical bar was present, it was always the feature singleton as well. On target-absent trials, the singleton was simply one of the nontargets. This experiment had two conditions: (a) bright singleton (parameters the same as Experiment 2), (b) large singleton (parameters the same as Experiment 2). Each condition had eight observers and each participant served in only one condition. Each observer participated in five blocks of 108 trials per block.

The results are given in Table 4. The slopes are all relatively shallow, suggesting that the singletons could be found efficiently in all conditions. The target-present slope for the luminance condition was 9 ms per item, and for the size condition was 11 ms per item. Separate repeated-measures ANOVAs for the target-present conditions of each singleton type reveal main effects of display numerosity for the luminance and size conditions, $F(2,14) = 79.2$ and $F(2,14) = 20.9$, $P < 0.001$, respectively. This suggests that these slopes were significantly different from zero. A 0 ms per item slope (as has been reported for abrupt onsets, though see Franconeri & Simons 2003, for a critical examination of that evidence) might be out of reach for these conditions. If the target singleton slope in Experiment 2 (on average 30 ms/item) were closer to 10 ms per item, then perhaps we could have interpreted it as indicative of a robust capture of attention. In any case, these results support the conclusion that attentional prioritization by large or bright singletons took place in these experiments.

Summary of results

Table 4 contains the slope and intercept data from Experiments 1 through 3. This display allows an easy comparison of the performance in the different conditions of the different experiments. One striking feature of these slopes is that both the target singleton slopes and the target nonsingleton slopes differ from the target-present slope for the control Experiment 1, with shallower target singleton slopes and steeper target nonsingleton slopes, relative to the target-present slope. The target-absent slopes are steeper than the corresponding control slope as well. These comparisons lead to the conclusion that the bright or large singletons conferred both a benefit, when the target was a singleton, and a cost, when the target was either a nonsingleton or absent. Obviously one must be careful when making comparisons to such a baseline, as other baselines could possibly be constructed for comparison (Jonides & Mack 1984). However, these differences are consistent and compelling.

Table 4 Search slopes, in ms per item, and intercepts in ms (in italics) by target type and experiment

	Target status		
	Present		Absent
Experiment 1			
No singleton	37 (*604*)		90 (*481*)
Experiment 2	Singleton	Nonsingleton	
Bright	29 (*606*)	57 (*569*)	137 (*457*)
Large	30 (*557*)	55 (*610*)	150 (*384*)
Experiment 3			
Bright	9 (*506*)		8 (*527*)
Large	11 (*502*)		16 (*525*)

General discussion

The results of these experiments demonstrate that the irrelevant stimulus properties of brightness and size attracted attentional prioritization in a stimulus-driven manner. We provided here a clear case where a bright singleton influenced visual search performance, and the implications of this finding for the attentional capture literature are discussed below. We also presented the more novel finding that a large singleton can also influence visual performance, even when this size contrast is irrelevant for the task.

The prioritization of the large or bright singleton suggests that the visual system selects high contrast items by default, as predicted by the biased-competition theory. Table 4 provides a summary of the experimental conditions and findings that will aid the following discussion. Experiment 1 confirmed that the task used was an inefficient search task in the absence of any singletons. Experiment 2 demonstrated that bright singletons and large singletons could receive priority even though the singleton features were irrelevant for finding the target. This supports the assertion by Pashler et al. (2004) that the visual system might select items of high contrast by default even when luminance contrast is not a part of the attentional set or definition of the target. By extension, this also supports the biased-competition account of attentional prioritization, in that items of high luminance-contrast bias competition in their favor (Reynolds & Desimone 2003), and extends the biased-competition account to items of high size contrast. These results are also consistent with models of attentional allocation that emphasize the role of bottom-up feature contrast (e.g., Itti & Koch 2000; Parkhurst, Law, & Niebur 2002). Size has previously been ignored in most studies of attentional capture (for an exception, see Yantis & Egeth 1999), and the present results suggest that an increased focus on this feature is warranted.

As noted in Sect. "Introduction," a strong version of the contingent capture hypothesis would not predict that the irrelevant singletons in Experiment 2 would have influenced attentional prioritization (cf. Folk et al. 1992). However, if a modified version of contingent capture is assumed, where increased brightness or increased size are a part of a "default" attentional set of the observers, then this perspective can still hold (cf. Folk, Remington, & Johtnston 1993; see also Yantis 1993). Whether this default setting is due to an explicit top-down attentional set held by the observers or due to an implicit set that arises from the nature of biased-competition processes in the brain is an important question for future research.

One might question why we found support for the biased-competition account via evidence of attentional prioritization by bright singletons (as did Yantis & Egeth 1999; Todd & Kramer 1994), while some researchers (e.g., Folk & Annett 1994; Jonides & Yantis 1988) have not. Obviously there are many differences among the tasks used in the present research (and by Yantis and Egeth 1999), and in those studies using a search for a letter (Folk & Annett 1994; Jonides & Yantis 1988; Todd & Kramer 1994). One aspect of visual search tasks that might explain these different findings is target-nontarget similarity (cf. Duncan & Humphreys 1989). Perhaps the orientation target we used and the custom sans serif font letter targets used by Todd and Kramer produced a more salient target than the figure 8-style letters used by Jonides and Yantis, and Folk and Annett. This variability in the stimuli might be responsible for the different results that were reported. The role of target–nontarget similarity and other variables that differentiate the methodologies used will have to be addressed by future research; we have begun addressing these variables, and target–nontarget similarity does appear to impact attentional priority in an inefficient search task (Proulx & Egeth in press; see also van Zoest & Donk 2004; for evidence in an efficient singleton-search task, see Theeuwes 1992). A recent behavioral study by Mounts and Tomaselli (2005) supports the idea that items rendered salient by either being an abrupt onset or being near an onset received attentional priority, as would be predicted by the biased-competition account of attention.

The results as a whole support and extend some aspects of the biased-competition account of attention. In Experiment 2 we found significant attentional prioritization for high luminance-contrast and high size-contrast items, supporting and extending the predictions derived from the biased-competition account (Desimone & Duncan 1995). The novel finding that increasing the size of an item also biases the competition in favor of larger items, just as increasing the brightness does, provides an interesting avenue for future single-unit recording studies of the effects of biased competition in visual cortex.

It is important to note that the precise mechanisms that prioritize size might differ from those that prioritize brightness. Increased brightness serves to segregate an object (or even a single pixel of it) from the background. A bright singleton thus has increased contrast with respect to the background and with respect to the other objects in the display. Increased size does not have increased contrast with respect to the background in the same localized manner (e.g., with respect to a single pixel), and thus primarily has increased contrast only with respect to the other objects in the display. However, even with possibly different mechanisms, both size and brightness contribute to an object's conspicuity. Determining precisely how a size singleton captures attention will be an important goal of continuing research on attentional prioritization via biased competition.

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