Does apparent size capture attention in visual search? Evidence from the Müller–Lyer illusion

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Is perceived size a crucial factor for the bottom-up guidance of attention? Here, a visual search experiment was used to examine whether an irrelevantly longer object can capture attention when participants were to detect a vertical target item. The longer object was created by an apparent size manipulation, the Müller–Lyer illusion; however, all objects contained the same number of pixels. The vertical target was detected more efficiently when it was also perceived as the longer item that was defined by apparent size. Further analysis revealed that the longer Müller–Lyer object received a greater degree of attentional priority than published results for other features such as retinal size, luminance contrast, and the abrupt onset of a new object. The present experiment has demonstrated for the first time that apparent size can capture attention and, thus, provide bottom-up guidance on the basis of perceived salience.

Keywords: attention, apparent size, Müller–Lyer, visual search

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Introduction

Attention is a fundamental mechanism used to prioritize the processing of relevant or salient information at the expense of momentarily irrelevant information. Visually perceived objects compete for cortical representation in a mutually inhibitory network and top-down attention can bias this competition in favor of the attended item for further processing (Desimone & Duncan, 1995; Reynolds & Heeger, 2009). Bottom-up manipulations of attention, such as increasing the contrast of an object, can also bias the competition in favor of the higher contrast objects (Reynolds & Desimone, 2003).

Top-down and bottom-up manipulations of attention have significant effects on behavior. Response times decrease and accuracy increases as a function of both top-down, sustained attention and bottom-up, transient attention (Müller & Rabbitt, 1989a, 1989b; Nakayama & Mackeben, 1989). Increased luminance contrast can also capture attention in a bottom-up manner, independent of top-down task goals (Proulx & Egeth, 2008). Recent studies have demonstrated that size contrast can capture attention in a bottom-up manner (Proulx, 2010), even in effortful, conjunction search (Proulx, 2007). This complements findings that object size is a top-down, guiding attribute of attention in visual search tasks (Treisman & Gormican, 1988; Wolfe & Horowitz, 2004), by demonstrating that size can also operate in a bottom-up manner and capture attention.

Is perceived size crucial for the guidance attention in visual search? In the studies described so far, there has been no conflict between the retinal and apparent size of the objects. That is, the number of pixels (and thus the relative size of the objects on the retina) that makes up each object in the visual search tasks correlates with the perception of apparent size for the participants. However, it has been established that the perception of luminance, rather than the simple sensation of it, drives neuronal responses in V1 (Ress & Heeger, 2003; Rossi, Rittenhouse, & Paradiso, 1996). Might the perception of apparent size also be a crucial determinant of how size guides attention?

In the previous studies that have demonstrated that length can capture attention (Proulx, 2010; Proulx & Egeth, 2008), the feature of increased length enhanced the detection of stimulus orientation. That is, it is easier to detect the orientation of a stimulus when it is longer or when it is brighter (Proulx & Egeth, 2008). One way to avoid that problem is to increase the apparent size of an object without increasing its overall size in terms of the number of pixels. Another solution is to increase the apparent length of an object without lengthening the segment that is crucial for the task. The present study used a manipulation of apparent length, the Müller–Lyer illusion, to overcome the potential problem with examining size in prior work because each object in this study contained the same number of pixels as every other object and the overall increase in size of the object would not necessarily enhance the detection of the orientation of the central segment. Indeed, as can be seen in Figure 1, the additional line segments present in the display added to the orientation contrast and task-relevant load with which the participants had to contend. Furthermore, the orientation

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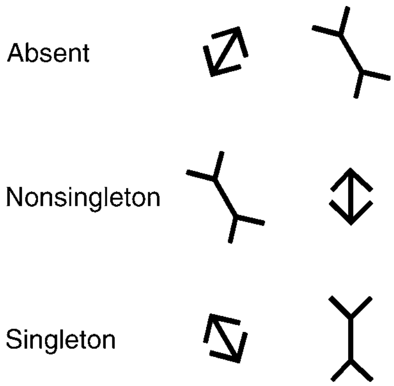

Figure 1. Example of the stimuli by trial type: target absent; target present but a non-singleton; or target present and the size singleton, made larger by the Müller–Lyer illusion. The target, when present, was the vertical, central bar regardless of whether the arrow wings at either end faced inward or outward. Note that each object contained the same number of pixels. The visual search displays were presented as in Proulx (2010) with a set size of 3, 5, or 9 items.

of the vertical line segment was the simplest target template one could depend on given that the target would appear with inward-facing wings on the vast majority of the target-present trials and outward-facing wings on the remainder of the trials.

One study found that the apparent size of objects can be used as a top-down attentional setting in visual search by using the Müller–Lyer illusion (Busch & Müller, 2004). For the first time, the present study investigated whether apparent size guides attention in a bottom-up manner in visual search. It is hypothesized that apparent size will capture attention in visual search given that the grouping of line segments in the Müller–Lyer illusion has been found to occur in the absence of attention (Moore & Egeth, 1997; Rensink & Enns, 1995) and can arise in a remarkably rapid fashion (Schulz, 1991). In fact, Rensink and Enns also reported that search for Müller–Lyer objects could occur very efficiently (less than 5 ms/item), which is likely before much attentional processing can occur.

Rensink and Enns (1995) concluded that the overall length of the object formed by grouping the elements of the Müller–Lyer illusion was the key factor for preemption effects in visual search rather than apparent length. Certainly, overall length may account for the prior findings of attentional capture by size (Proulx, 2010; Proulx & Egeth, 2008; Yantis & Egeth, 1999). Note that Rensink and Enns could not discount the role of configural differences because participants could strategically search with an angle-defined target template rather than a size-defined target template. In contrast, this strategy was not available in the experiments by Busch and Müller (2004) because the target was not adjoined by a unique type of arrow wings. It is important to keep in mind that these two studies focused on the top-down search for items created by the Müller–Lyer illusion. The present experiment instead had apparent length as a bottom-up factor because the task required detection based on orientation independent of size or arrow context. Indeed, the target in the present experiment could be a vertical line with either inward- or outward-directed wings, thus making both configuration and size uninformative, indeed irrelevant, features. This manipulation of apparent length as a bottom-up factor, rather than a top-down factor in prior studies, provides the main motivation to consider perceived salience due to apparent size giving rise to attentional capture rather than the retinal size of the task-relevant object.

Methods

Participants

The participants were 15 students (6 males) from Queen Mary University of London who received £5 for participation. One participant was excluded from analysis for failing to follow instructions.

Design and procedure

The apparatus and procedure were modified from previous reports to incorporate the Müller–Lyer illusion (Proulx, 2007, 2010). The objects were dispersed randomly in the cells of an invisible grid with 7×7, 8×8, and 9×9 grid sizes, respectively, for a corresponding set size of 3, 5, or 9 items. This manipulation kept object density relatively constant even as set size increased. The objects were dispersed randomly and were 2° apart, center to center. All of the stimuli were identical, save one unique singleton with a longer apparent length manipulated using the Müller–Lyer illusion (see Figure 1). The central bar segment subtended 1.1° in length and 0.15° in width, and the wing segments on either end subtended 0.6° in length and were separated by a 90° angle. Crucially, the same number of pixels was present in all objects. As noted in the Introduction section, and as seen in Figure 1, only the central line segment was the task-relevant object part as the task was to detect the presence or absence of a central vertical line segment that could appear anywhere in the display and with either inward- or outward-facing wing segments. The target line (vertical, or 0°) was presented among non-target line segments that were rotated 30° to the left or right of vertical.

There was only one large object on each trial, as defined by apparent size (Figure 1). The apparently large item (with outward-facing wings) coincided with the vertical target (“singleton”) with chance probability, that is, on $1/d$ of the trials, where d is the set size for a given trial (3, 5, or 9 objects). The size singleton coincided equally often with each distractor type on the remainder of the trials, where either the vertical target was present but not the apparent size singleton (“non-singleton”) or the target was “absent.”

Participants were instructed to detect the presence of a central, vertical bar and were informed of the chance, $1/d$

relationship between the apparent size of the objects and the target. Errors were signaled with auditory feedback. Each trial began after a 1500-ms intertrial interval. Each subject participated in 2 blocks of 270 trials per block. Each block included an equal number of target-absent and target-present trials and an equal number of trials for each set size. Order of trial types was randomized. Feedback was displayed at the end of each block, including response time and accuracy for each block. Participants began with a practice block of 20 trials and each block began with three warm-up trials. Data from the practice and incorrect trials were not included in the statistical analyses.

Results

Table 1 presents the mean response time (RT) and percentage correct for each trial type by set size. The RT data, shown in Figure 2, demonstrate that the variation in apparent size and set size both impacted the efficiency of detecting the target bar. A repeated-measures ANOVA of the RT data revealed significant main effects of trial type, $F(2, 20) = 66.9$, $p < 0.001$, $\eta_p^2 = 0.87$, set size, $F(2, 20) = 138.2$, $p < 0.001$, $\eta_p^2 = 0.93$, and an interaction between these two factors, $F(4, 40) = 48.2$, $p < 0.001$, $\eta_p^2 = 0.83$. The rate of processing, as determined by the slopes of the trial type functions in Figure 2, reveals that apparent size captured attention. Participants were more efficient at detecting the target when it was the larger object due to apparent size (17 ms/item) than when a distractor was the larger item (96 ms/item). This finding was supported by a separate ANOVA for just the target-present trials that also found a significant interaction between trial type and set size, $F(2, 20) = 17.3$, $p < 0.001$, $\eta_p^2 = 0.63$.

Previous work has reported data that could serve as a baseline comparison of processing efficiency to the results reported here. For example, a prior study presented a similar task (vertical target detection among non-targets rotated 30° to each side) in the absence of any singleton manipulation. Proulx and Egeth (2008) reported a target-present search slope of 37 ms/item. Although comparisons

Set size	Target-present type: Singleton	Non-singleton	Target-absent type
	Mean correct RT		
3	997	960	1195
5	1145	1209	1655
9	1123	1549	2495
	Mean percentage correct		
3	92	94	99
5	89	95	100
9	86	88	99

Table 1. Response times and percentage correct by trial type and set size.

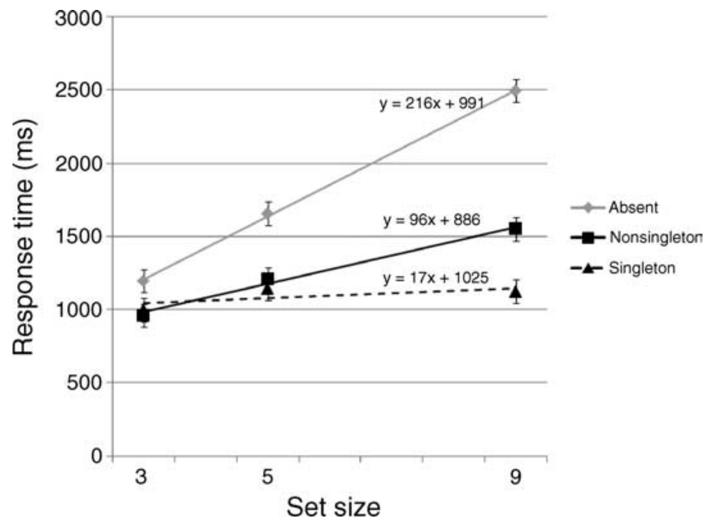

Figure 2. Plot of response times for each trial type as a function of set size. Error bars are 95% confidence intervals, calculated according to Loftus and Masson (1994). The linear slope and intercept for each trial type function is provided directly above the corresponding data.

with such a baseline to assess costs and benefits should be made with care, this implies that the manipulation of apparent size in the present study speeded response times when the target was apparently longer and slowed response times when a non-target was apparently longer.

Besides capturing attention, the addition of the wing segments might have impacted discrimination of the target more in one condition than the other. This alternative can be addressed by examining RT for target detection in the smallest set size (3) as a means of assessing target detection in a relatively low perceptual load situation. The vertical target bar was detected faster on trials when it was apparently shorter (inward-facing wing segments; 960 ms) than when it was the apparently longer item (outward-facing wing segments; 997 ms). This suggests that although the apparently longer object captured attention, it did not confer additional benefits for target discrimination because it took longer to determine the orientation of the apparently longer bar.

In addition, note that the RT data revealed that creating size variation with the Müller–Lyer illusion made the target detection task more difficult overall than with a retinal size manipulation. Here, the target non-singleton slope and the target-absent slopes were 96 ms/item and 216 ms/item, respectively. In a previous study that increased the length of the bars with additional pixels, the respective slopes were 54 ms/item and 134 ms/item; however, the target singleton slope was also 17 ms/item in the prior study (Proulx, 2010). Importantly, this suggests that the task-irrelevant wings increase the task difficulty due to the need for the subject to disregard the wings to successfully detect the presence of the task-relevant vertical bar.

Although an increase in difficulty brought about by increased perceptual load (such as decreased target–distractor similarity) normally results in reduced attentional capture (Proulx & Egeth, 2006), here it was found that the attentional capturing ability of a larger object due to apparent size is resistant to the impact of increasing perceptual load that arises from the additional orientation heterogeneity (Lavie & Tsal, 1994), consistent with other work that challenges load theory (Cosman & Vecera, 2010). This is particularly acute when the slope ratios are considered for the present study versus the previous one. The slope ratio is computed as the difference in the target-present slopes, divided by the non-singleton slope. The slope ratio for apparent size was 0.82, compared to the slope ratio of 0.69 for actual size (Proulx, 2010). These ratios are much greater for size than for a previous study that examined the impact of task difficulty on luminance contrast, where the highest ratio reported was 0.39 (Proulx & Egeth, 2006). Note that this slope ratio was also higher than that reported for attentional capture by the abrupt onset of an object, for example, at 0.68 (Yantis & Jonides, 1984).

The accuracy data were also subjected to a repeated-measures ANOVA, which resulted in a significant main effect of trial type, $F(2, 20) = 10.0$, $p < 0.01$, $\eta_p^2 = 0.50$, but no effect of either set size, $F(2, 20) = 5.9$, $p = 0.05$, $\eta_p^2 = 0.37$, or the interaction between these two factors, $F(4, 40) = 2.0$, $p > 0.10$, $\eta_p^2 = 0.17$.

Discussion

This study examined whether the bottom-up guidance of attention by size was affected by the perceived size of the object. Here, it was found that larger objects, as determined by the Müller–Lyer illusion, captured attention even though all of the objects had the same number of pixels. Participants detected the presence of a vertical target made longer by apparent size more efficiently than when a distractor was made longer by apparent size. The task was made more difficult by the complex configuration of each item with the additional task-irrelevant oriented bars (Proulx & Egeth, 2006); this aspect was controlled for by calculating the slope ratio to account for task difficulty brought about by target–distractor discriminability to allow comparison with other features in the attention capture literature. Despite this increase in task difficulty, the guidance of attention by apparent size was stronger than that of actual size in a previous study (Proulx, 2010) and that reported for luminance contrast (Proulx & Egeth, 2006), and even greater than that reported for the abrupt onset of a new object (Yantis & Jonides, 1984). Of course, these comparisons are taken across studies in the literature with other experimental differences, and future work making direct comparisons of the attention capturing ability of these visual features would be of great interest.

In the present study, a number of manipulations were important to attribute the results to apparent rather than retinal size. For example, the number of pixels was kept constant among all items and it allowed an increase in the apparent length of an object without lengthening the central segment that was crucial for the task. This is because the overall length of the configuration was increased by the addition of the inward-facing or outward-facing wings to the central line segments that were displayed at either vertical or 30° from vertical. Thus, the increase in the size of the configuration would not enhance the detection of a vertical central segment. Although a saliency analysis of actual increased length would result in higher contrast at the location of the longer item, the additional orientation contrast created by the Müller–Lyer wings would eliminate any such boost in low-level salience (Harel, Koch, & Perona, 2006). In fact, the addition of the other segments makes the primary task more difficult in two additional ways: first, the orientation of the central segment is harder to detect with additional orientation heterogeneity added to the display as demonstrated by the elevated absent and non-singleton search slopes compared to other studies of attentional capture (Proulx, 2010); second, the target template must either remain just the central, vertical segment or instead comprise of two distinct configurations featuring a vertical segment and wings that face inward in one case and outward for the other. Given that the configuration that had the most efficient search slope was also the least often to appear, we suggest that apparent length, rather than overall configuration length, gave rise to attentional capture. In addition, even though the primary task was made more difficult by the addition of the wings, it is surprising to see that this manipulation resulted in some of the strongest attentional capture results ever reported in terms of slope ratio, which even accounts for task difficulty. In some ways, this parallels the arguments of Müller and Busch (2006) who noted that the distracting contextual information in their study made the primary task more difficult; however, this was overcome by the strength of the size illusion (p. 697). It is important to note, however, that overall length could still be a primary factor even though this includes distracting information. This makes the greater magnitude of the attentional capture effect compared to retinal length surprising, however, and suggests that the manipulation of apparent size confers additional benefits for attracting attentional priority. Further addressing these alternatives would be an important avenue for future research on this important topic.

The present experiment has demonstrated for the first time that apparent size can also capture attention and, thus, guide attention on the basis of bottom-up salience independent of the top-down task set of the observer, thus fulfilling the necessary criteria for the capture of attention (Burnham, 2007). Further analysis revealed that the longer Müller–Lyer object received a greater degree of attentional priority than published results for other features such as retinal size, luminance contrast, and the abrupt onset of a new object. Although it might be surprising that greater length as created by the Müller–Lyer illusion captures attention to a greater degree than retinal size, this finding might be predicted when natural image statistics are considered. Howe and Purves (2005) discovered that the Müller–Lyer manipulation of adding wings to a line segment might not be an illusion at all but instead provide a better representation of how size is computed normally. They found that the perception of size by the Müller–Lyer effect arises from a probabilistic process relating the likeliest real-world source for the retinal image that is produced; in this sense, the Müller–Lyer effect is not an illusion at all but a highly probable and accurate perception based on the forms of contextual information that are used normally to perceive size. The study of why size and apparent size matters in vision will benefit from further work that addresses how contextual information influences the apparent size of an object, from primary visual cortex to association areas that are the neural basis of attentional priority.

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References

Burnham, B. R. (2007). Displaywide visual features associated with a search display's appearance can mediate attentional capture. *Psychonomic Bulletin & Review, 14,* 392–422.

Busch, A., & Müller, H. J. (2004). Visual search for apparent-length targets is modulated by the Muller–Lyer illusion. *Spatial Vision, 17,* 417–441.

Cosman, J. D., & Vecera, S. P. (2010). Attentional capture under high perceptual load. *Psychonomic Bulletin & Review, 17,* 983–986.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193–222.

Harel, J., Koch, C., & Perona, P. (2006). Graph-based visual saliency. *Proceedings of Neural Information Processing Systems (NIPS), 19.*

Howe, C. Q., & Purves, D. (2005). The Müller–Lyer illusion explained by the statistics of image-source relationships. *Proceedings of the National Academy of Sciences of the United States of America, 102,* 1234–1239.

Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics, 56,* 183–197.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review, 1,* 476–490.

Moore, C. M., & Egeth, H. (1997). Perception without attention: Evidence of grouping under conditions of inattention. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 339–352.

Müller, H. J., & Busch, A. (2006). Visual search for size-defined target objects is modulated by the Ebbinghaus apparent-size illusion: Facilitatory and inhibitory effects of the context objects. *Perception, 35,* 671–700.

Müller, H. J., & Rabbitt, P. M. A. (1989a). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 315–330.

Müller, H. J., & Rabbitt, P. M. A. (1989b). Spatial cueing and the relation between the accuracy of "where" and "what" decisions in visual search. *Quarterly Journal of Experimental Psychology, 41A,* 747–773.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29,* 1631–1647.

Proulx, M. J. (2007). Bottom-up guidance in visual search for conjunctions. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 48–56.

Proulx, M. J. (2010). Size matters: Large objects capture attention in visual search. *PLoS One, 5,* e15293.

Proulx, M. J., & Egeth, H. E. (2006). Target–nontarget similarity modulates stimulus-driven control in visual search. *Psychonomic Bulletin & Review, 13,* 524–529.

Proulx, M. J., & Egeth, H. E. (2008). Biased competition and visual search: The role of luminance and size contrast. *Psychological Research/Psychologische Forschung, 72,* 106–113.

Rensink, R. A., & Enns, J. T. (1995). Preemption effects in visual search: Evidence for low-level grouping. *Psychological Review, 102,* 101–130.

Ress, D., & Heeger, D. J. (2003). Neuronal correlates of perception in early visual cortex. *Nature Neuroscience, 6,* 414–420.

Reynolds, J. H., & Desimone, R. (2003). Interacting roles of attention and visual salience in V4. *Neuron, 37,* 853–863.

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron, 61,* 168–185.

Rossi, A. F., Rittenhouse, C. D., & Paradiso, M. A. (1996). The representation of brightness in primary visual cortex. *Science, 273,* 1104–1107.

Schulz, T. (1991). A microgenetic study of the Muller–Lyer illusion. *Perception, 20,* 501–512.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review, 95,* 15–48.

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience, 5,* 495–501.

Yantis, S., & Egeth, H. E. (1999). On the distinction between visual salience and stimulus-driven attentional capture. *Journal Experimental Psychology: Human Perception and Performance, 25,* 661–676.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 601–621.