Title

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Authors

Alonso-Díaz, Santiago
Cantlon, Jessica F.

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Santiago Alonso-Díaz[a], **Jessica F. Cantlon**[b]
[a]Department of Economics, Universidad Javeriana, COL, 110231 alonsosantiago@javeriana.edu.co
[b]Department of Psychology, Carnegie Mellon, US, 15213, jcantlon@andrew.cmu.edu

Abstract

Numerosity is informative for living organisms. It can transmit, among many things, amount of food available, heading direction of the troop, which group could win a territorial dispute, the decision of were to build a beehive. Given its ecological importance, we test the hypothesis that numerosity captures visual selection. In five experiments we confirmed that an irrelevant visual stimulus that was numerically large slowed down participants in detecting a task-relevant visual target (Exp. 1 and 2). This capture was not driven by sensory variables that could correlate with numerosity: cumulative area (Exp. 3) and element size (Exp. 4). We also confirmed that the underlying numerosity representations were analogue, not set-based (Exp. 5). In a crowded visual scene numerosity is a relevant cue for visual selection, but represented only in approximate/coarse fashion.

Keywords: Attention; Attention capture; Numerosity

Introduction

Numbers can guide visual selection (Hamilton, Mirkin, & Polk, 2006; Reijnen, Wolfe, & Krummenacher, 2013; Sobel, Puri, & Faulkenberry, 2016; Utochkin, 2013). Imagine going to a crowded town fair for the first time, with different novel attractions. Your decision on where to look will be affected by the number of people around each attraction. Number is a natural and intuitive cue for behavior in uncertain contexts (Arganda, Pérez-Escudero, & de Polavieja, 2012).

A recent review proposed a list of features that could guide attention in visual search and placed them in a scale with five levels of certainty (Wolfe & Horowitz, 2017). The "undoubted guiding attributes" were color, motion, orientation, and size. On the lower side of the scale, the "probably not guiding attributes" were, among others, material type, blur, optic flow, and 3D objects. Importantly, our feature of interest, namely numerosity, was on the third level of certainty: "Possible guiding attributes". This means that even though there are some indications in the literature that it is a guiding feature, more research is required.

A classic task to study attention capture is the additional singleton search task (Theeuwes, 1992). This is a visual search task in which participants have to locate a distinct shape, say a diamond, among many other homogenous shapes present in the visual field, say circles. All the shapes have a line segment inside and subjects must report the orientation of the line in the distinct shape. The main experimental manipulation is that in a set of trials one of the homogenous shapes is turned into a distractor, usually by coloring it differently (e.g. all the shapes are green, including the target, but one is red, the distractor). The notable result is that response times are slower when there is a distractor, suggesting interference in the visual selection of the target. Moreover, the singleton search task is a compound task: participants perceive shape but report line orientation thus the effect is due to perceptual interference not response difficulty.

In a series of experiments we modified the singleton search task and created a distractor by placing more lines inside one of the non-target circles (Fig. 1; Exp. 1) or making the target more numerous while displaying a shape distractor (Exp. 2). A slower response time in the former and no distraction in the latter would indicate spontaneous capture of attention by numerosity.

We further explored whether equating total whiteness inside each of the shapes (Exp 3) (lines were white against a black background) or reducing element size/width could modify the effect (Exp. 4). The overall results indicate that the presence of number capture is robust to those perceptual features and they are consistent with the idea that number is a perceptual dimension guiding visual selection on its own terms (Anobile, Cicchini, & Burr, 2016).

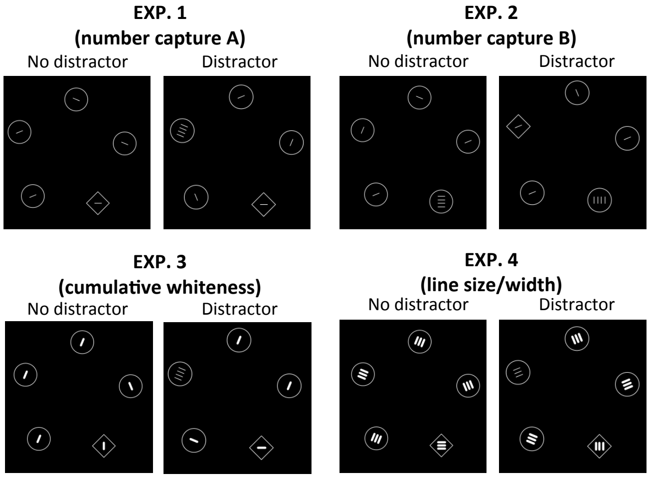

Figure 1: Tasks. In experiments 1,3, and 4 participants had to report the orientation of the line(s) inside the diamond shape (vertical or horizontal). In experiment 2 they reported the orientation of the more numerous one i.e. shape is the distractor. In half of the trials there was a distractor (counterbalanced blocked design). There were 3 different set sizes: 3, 5 (presented here), and 7.

Experiments 1-4: Numerosity Guides Visual Selection

Methods

All experimental procedures adhered to university standards, as approved by the Research Subjects Review Board. For each experiment we aimed to recruit 10 subjects, based on sample sizes of similar attention capture studies (Theeuwes, 2010).

Participants. 42 university students participated in four experiments (26 females, mean age: 21.21 years, s.d.: 3.43. We assigned 10 to each experiment; 2 were dropped due to lack of task enhancement (sleepiness and high error rate). They received $10 as compensation. The task took approximately 60 minutes, including instructions.

Stimuli. Display elements were equally spaced around a fixation point of an imaginary circle (3.4° in radius). Each display element was either a circle (1.4° in diameter) or a diamond (1.4° on each side). Inside each shape there was one or four line segments (0.42° in length) randomly oriented. The orientation inside the target was not random; it could be either vertical or horizontal. Shapes and lines were white on a black background. Participants saw three different set sizes: 3, 5, or 7 shapes equally distributed across trials (Fig. 1 has examples of set size 5).

Procedure. Subjects sat 50 cm from screen and placed their head on a chin rest. Each trial began with a fixation cross and eyes were monitored with an EyeLink 1000 desktop mount system. Images only appeared if fixation was confirmed. After a random fixation time (700 ms – 1700 ms), the fixation-cross disappeared and the shapes became visible. Set size changed randomly on each trial, as well as the position of the target and distractor. The task was to report the orientation of the lines in the target using ’z’ and ’/’ in a qwerty keyboard to indicate vertical or horizontal, respectively. In experiment 1,3, and 4 the target was the diamond shape, and in experiment 2 the shape with more lines inside. Distractors were number (Exp. 1 and 3), a diamond shape (Exp. 2), or line width (Exp 4) (Fig. 1). Instructions emphasized a quick but accurate response. If a response was not detected after 1200 ms., the display images disappeared, the trial aborted, and a reminder text indicated that the response was too slow.

There were 240 training trials and 300 test trials with four resting breaks. Training and test trials were identical but we only analyzed test trials. The objective of training was to make subjects as fast as possible. Trials were blocked. One half had no distractor and the other did. Half of the subjects started with no distractor. Before starting, participants received an explanation of the blocked design and saw example images of each block with the main elements (target and distractor) pointed out. When a new block started, an on-screen instruction reminded participants whether there was going to be a distractor or not.

Data analysis. We analyzed each experiment individually using repeated measures ANOVAs on response times. To statistically compare effect sizes across experiments, we bootstrapped the distribution of effect size differences and compute a 95% confidence interval (samples = 1000) (Kirby & Gerlanc, 2013). For effect size we used the generalized Eta squared of the ANOVAs, suited for repeated measures analysis (Bakeman, 2005). No response time outlier detection was implemented as all trials were forced to last less than 1200 ms (see Procedures above). We report correct trials in the main text (error rates were low). All analysis were done in R.

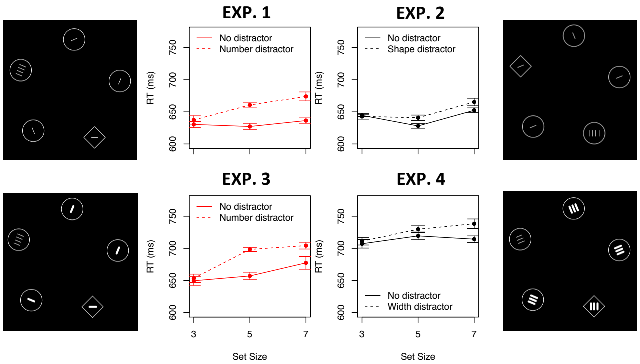

Figure 2: Experiment results. Alongside each plot there is an example image of the corresponding distracting condition (set size 5). Plots are colored red for significant distractor effects ($p < 0.05$). Bars are within subject standard errors (Cousineau et al., 2005).

Results

The presence of a number distractor increased response times in participants of Exp. 1 (Fig. 2). A repeated measures ANOVA on response times found main effects of distractor ($F(1, 9) = 41.138$, $p < 0.001$, $\eta_g^2 = 0.099$), set size ($F(2, 18) = 4.166$, $p = 0.032$, $\eta_g^2 = 0.046$), and their interaction ($F(2, 18) = 4.998$, $p = 0.018$, $\eta_g^2 = 0.029$). The slope of response time in no distractor trials is indistinguishable from zero (1.73 ms per shape; Table 1) and when there is a distractor it increases (9.31 ms/shape) causing the interaction effect. These slopes are really shallow suggesting that the diamond shape can be located in parallel when there is no distractor and even when there is a distractor the detection is much faster than a traditional serial process (Bacon & Egeth, 1994).

In the next experiment we aimed to check if capture occurred due to the generic presence of structured, but irrelevant, information in the visual field. With the same stimulus a different set of participants did the mirror task of Experiment 1: report the line orientations of the circle with more lines and be distracted by the diamond shape (Fig. 1). This time there was no significant attention capture (Fig. 2; distractor: $F(1, 9) = 0.651$, $p =$

0.440, η_g^2 = 0.002, set size: F(2, 18) = 18.914, p > 0.001, η_g^2 = 0.017, interaction: F(2, 18) = 1.038, p = 0.374, η_g^2 = 0.002). Even though not significant, there was still a minimal distraction in Exp. 2 in the same direction as Exp. 1 (Fig. 2) In such cases is important to statistically compare effect sizes (Nieuwenhuis, Forstmann, & Wagenmakers, 2011). We bootstrapped the difference of the effect sizes (η_g^2) of the distractor in both experiments (Exp. 1 minus Exp. 2). The obtained 95% confidence interval is positive [0.037, 0.142], meaning that the effect of distractor is highly unlikely to be larger in Exp. 2., confirming that subjects were at most weakly distracted by shape.

This is not saying that number is uniquely special. In a supplemental experiment we found that a square shape can also capture attention and previous work has established that forms are attractive (Theeuwes, 1992). The unique finding of Exp. 1 and 2 is that sensory stimulation was identical but when human observers are asked to find shape they are distracted by number but not vice versa. This asymmetry is not self-evident as in both versions number and shape are irrelevant for orientation detection.

An alternative explanation for the asymmetry is that in Exp. 2 the distractor was a shape which has nothing to do with the target (lines) and so is less distracting. In Exp. 1, on the other hand, the distractor were lines and the task was to detect orientation of lines, and so is more distracting. However, we selected the Theeuwes task precisely to avoid such confounds. Participants need to detect the relevant feature, shape or number, and then report the orientation. The alternative strategy of trying to directly detect line orientations in this type of task has been shown to be too inefficient (Theeuwes, 2010). That being said, if the alternative explanation holds, our result would implicate that numerosity breaks the strategy of detecting the feature and reporting the orientation; an interesting finding on its own terms that does not invalidate Exp. 1 findings.

In our stimulus capture seems to be driven by a parser that detects more lines. During training and between blocks participants were reminded that the distractor had more segments. And, prefacing the next set of experiments, attention capture was not detectable when numerosity was equal (Exp. 4). It only appeared when there was an increase in the number of lines (Exp. 3).

The next pair of experiments probe with more detail the sensory aspects of the more numerous lines that could have mobilized attention. In Exp. 3 we equated total amount of whiteness in all shapes by making single segments four times thicker (Fig. 1). If the observed number capture in Exp. 1 is due to an overall integration of whiteness (cumulative area/brightness) then distraction should disappear. This was not observed. There were detectable interferences of the irrelevant more numerous location (Fig. 2; distractor: F(1, 9) = 4.137, p = 0.072, η_g^2 = 0.040, set size: F(2, 18) = 8.702, p = 0.002, η_g^2 = 0.071, interaction: F(2, 18) = 4.618, p = 0.024, η_g^2 = 0.016). A direct comparison of effect sizes in Exp. 1 and Exp. 3 actually includes the possibility that the distractor effect is larger when cumulative area is controlled for (95% CI of Exp. 1 minus Exp. 3: [-0.006, 0.116]). The slopes relating set size and RT were again really low (Table 1), lower than a steorotypical serial search (Bacon & Egeth, 1994; Treisman & Gelade, 1980), indicating that the task was done in partially parallel fashion. Number capture is not related in a simple manner to an attraction to overall whiteness.

Table 1. RT slopes

	Exp. 1	Exp. 2	Exp. 3	Exp. 4
No distractor	1.73	1.31	6.79*	1.21
Distractor	9.31*	5.58*	11.56*	6.98*

* p<0.05

It is possible that what drove number capture in Exp. 3 was the width of the lines (Fig. 1). In Exp. 4 we fixed the number of lines inside each of the shapes and made their line width three times bigger than the one in the distractor. If line width is the critical distracting aspect in Exp. 3, then Exp. 4 should reveal attention capture. This was not observed (Fig. 2; distractor: F(1, 9) = 1.332, p = 0.278, η_g^2 = 0.007, set size: F(2, 18) = 2.767, p = 0.089, η_g^2 = 0.011, interaction: F(2, 18) = 1.079, p = 0.360, η_g^2 = 0.003). A comparison of the effect sizes of Exp. 3 and 4 indicates that distraction was more notable in the latter (95% CI of Exp. 3 minus Exp. 4: [0.004, 0.066]). Again, the slopes were really shallow suggesting an efficient search process, close to parallel (Table 1). Line width draws little attention in our visual stimulus.

Discussion

Attention is captured by numerosity, beyond basic perceptual features that could correlate with number: cumulative area/whiteness and element size/width. This was obtained with a compound visual search task that differentiates perception from response difficulty. This is important because distractor effects can be traced back to perceptual interference and not to response interference (Theeuwes, 2010). The overall results are consistent with the idea that numerosity is a basic perceptual feature that guides attention (Anobile et al., 2016; Wolfe & Horowitz, 2017).

Previous reports have demonstrated the importance of number for attentional process. Reijnen et al., 2013 used a task where the target and distractors were numerical. However they used large numerosities and the task of participants actually required numerical estimation. Here we confirmed attentional effects with a much simpler compound visual task with small numerosities.

Utochkin, 2013 found that numerosity guides attention as an aide to find perceptual features, in their case color. Thus, numerosity was actually useful in their task. Our Exp. 1 - 4, numerosity was irrelevant and as such is closer to the notion of attention capture.

Attention capture is usually framed around the conceptual dichotomy of bottom-up or top down sources of the observed distraction (Theeuwes, 2010). However, the notion of priority maps, a working space that integrates current goals, selection history, physical salience, is perhaps more relevant (Awh, Belopolsky, & Theeuwes, 2012). For our purposes, number must induce a priority signal and be a relevant source of information for the nervous system to be able to capture attention. Visual selection would emulate other decision contexts in which numerosity is routinely used, mostly as an heuristic to solve complex uncertain choices (Gigerenzer & Brighton, 2009; Reyna & Brainerd, 2008).

There is great deal of debate on the abstract or sensory nature of number (Anobile et al., 2016; Gebuis, Kadosh, & Gevers, 2016; Leibovich, Katzin, Harel, & Henik, 2017) . We argue that the number capture observed here is consistent with the proposal that number is abstract and a basic perceptual feature. First, the sensory aspects evaluated (cumulative whiteness and element size/width) failed to capture attention. Second, the shallow slopes relating set sizes and response times were not so different from previous attention capture studies using other basic perceptual stimulation (e.g. color) ((Bacon & Egeth, 1994; Theeuwes, 1992). They were not necessarily different from zero to claim any preattentive mechanism, but they are certainly really close to those previous works that demonstrated attention capture from basic features.

There are at least three limitations of our study. First, we did not control for line separation, which may be a feature driving attention in our task. If line separation means frequency then we are not sure how to distinguish frequency from number as they would correlate perfectly. Also, even though we cannot rule out that possibility, a recent review on features that have been found to guide attention did not report line separation (Wolfe & Horowitz, 2017).

The second limitation is that we did not control for overall contrast. We manipulated line width to control for cumulative area effects (Exp. 3 and 4) and the number distractor ended up looking more dim (Fig. 1). We would argue that this actually made our results more robust because it is not about higher contrast. Still, it would have been interesting to determine how much of the effect changes with different contrast levels.

The third and final limitation is that attention may have been driven by the presence of a texture formed by the patch with more lines. However, we would argue that texture is a vague term and we narrowed down on an aspect, namely numerosity. Also, texture is obtained preattentively (Julesz, 1981) and search slopes in Exp. 1-4 were different from zero.

In general, as with most studies of numerosity, it is almost impossible to discard 100% that our results are not influenced by a preattentive sensory features. They may indeed have a role in the underlying effect but we think that there is sufficient evidence in the literature to believe that number is a basic sensory aspect (Anobile et al., 2016); and we think our results add to that line of research.

In many behavioral contexts numerosity is a basic heuristic that hinders or facilitates learning and decision-making (Gigerenzer & Brighton, 2009; Reyna & Brainerd, 2008). Also, the approximate number system seems to influence higher order behavior such as risk attitudes and math scores (Halberda, Mazzocco, & Feigenson, 2008; Schley & Peters, 2014). Our study furthers the link between numerosity and attention which may provide clues on why raw numerosity is such a strong driver of learning and behavior.

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