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Perception of ensemble statistics requires attention

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ABSTRACT

To overcome inherent limitations in perceptual bandwidth, many aspects of the visual world are represented as summary statistics (e.g., average size, orientation, or density of objects). Here, we investigated the relationship between summary (ensemble) statistics and visual attention. Recently, it was claimed that one ensemble statistic in particular, color diversity, can be perceived without focal attention. However, a broader debate exists over the attentional requirements of conscious perception, and it is possible that some form of attention is necessary for ensemble perception. To test this idea, we employed a modified inattentional blindness paradigm and found that multiple types of summary statistics (color and size) often go unnoticed without attention. In addition, we found attentional costs in dual-task situations, further implicating a role for attention in statistical perception. Overall, we conclude that while visual ensembles may be processed efficiently, some amount of attention is necessary for conscious perception of ensemble statistics.

1. Introduction

What is the relationship between attention and consciousness? Is our moment-to-moment awareness limited to the few things we can attend to, or are certain aspects of the world experienced outside of attention? These questions are central to a broader debate about whether visual perception is relatively "rich" or "sparse" (Block, 2011; Cohen & Dennett, 2011; Dehaene, 2014; Gross & Flombaum, in press; Lamme, 2010; Phillips, 2016; Ward, Bear, & Scholl, 2016).

Recently, a potential solution to this debate was proposed that attempts to reconcile our subjective impressions of a rich phenomenal world with empirical observations that suggest a severely limited perceptual bandwidth (Cohen, Dennett, & Kanwisher, 2016). According to this proposal, our perception is neither as rich as is intuitively believed, nor as sparse as dominant models of visual attention and working memory suggest. The key insight is that in addition to the few items that can be focally attended, the visual system represents large swaths of the visual world as "ensemble representations". These ensembles, or "summary statistics", can be represented across a wide range of visual dimensions including average orientation, motion direction, speed, size, position, density, facial expression, etc. (Whitney, Haberman, & Sweeny, 2014). Ensembles are encoded efficiently (Alvarez & Oliva, 2009), unconsciously (Moore & Egeth, 1997), and are likely processed by dedicated neural mechanisms in parallel to the detailed processing of individual items (Cant & Xu, 2012).

What remains unclear, however, is whether our *conscious experience* of visual ensembles requires attention. In a recent study, Bronfman, Brezis, Jacobson and Usher (2014) asked if one particular summary statistic — color diversity — could

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be perceived without focal attention. Using a variation of the Sperling paradigm (Sperling, 1960) in which the letters either had low color diversity (i.e., sampled from few adjacent regions on the color wheel) or high color diversity (i.e., sampled from the entire color wheel), they pre-cued one row of letters and measured how many letters could be reported during a single task (report letters only) versus a dual task (report letters and color diversity). Surprisingly, they found that there was no decrease in performance on the letter task when participants had to also report the color diversity of the non-cued letters, and that color diversity judgments for the non-cued letters were significantly above chance. These results have been interpreted as evidence for "cost free" awareness of ensemble statistics that does not rely on cognitive functions such as attention and working memory (Block, 2014).

Recently, Ward et al. (2016) replicated Bronfman et al.'s (2014) main results but challenged some of their interpretations. In a series of experiments, Ward et al. (2016) tested whether awareness of color diversity was possible despite a lack of awareness of the individual (differentiated) colors. Bronfman et al. posited that color diversity statistics could not be perceived without a "differentiated representation" of the individual colored elements. They further argued that this differentiated representation must have been briefly experienced. Ward et al.'s (2016) results, however, demonstrated that accurate color diversity judgments can persist even when participants fail to notice that the color of every single element changed halfway through the trial. By swapping the colors of individual letters while holding the color diversity statistic constant, Ward et al. (2016) found that performance on the statistical judgments was above chance despite robust change blindness for the individual colors. These results suggest that we can consciously perceive summary statistics that are derived from unconscious differentiated representations.

While Ward et al.'s (2016) study challenged some of the interpretations of Bronfman et al.'s (2014) results, participants in both studies were always partially attending to the colors in the non-cued rows because color diversity judgments were part of the task and were required on every trial. Thus, even though focal attention was allocated to the cued row of letters, it is likely that attention was divided, or perhaps that non-focal, diffuse attention was allocated to the stimuli in the non-cued rows, in order to carry-out the secondary color diversity judgment task. Therefore, the question of whether color diversity statistics, or any summary statistics, can be consciously perceived without (any type of) attention remains open. While it is obviously difficult to create a situation in which zero attention is allocated to a stimulus, one of the best methods to approximate such a situation is with inattentional blindness (Mack, 2003; Mack & Rock, 1998).

The current study asked if ensemble perception is possible without attention by modifying the Bronfman et al. task into an inattentional blindness paradigm. We hypothesized that Bronfman et al.'s and Ward et al.'s findings of above chance color diversity judgments may be explained by participants distributing their attention across the two tasks. With inattentional blindness paradigms, unlike well-practiced dual-tasks, participants do not have the motivation or opportunity to distribute their attention across tasks.

In a series of four experiments, we tested whether participants spontaneously experience ensemble statistics (color diversity, as well as size diversity and mean size) despite having no reason to attend to these ensembles. In essence, this set-up approximates many everyday situations in which we feel like we experience a rich phenomenal world without having a specific task or reason to attend to all aspects of the visual scene. If some form of attention is necessary for awareness of ensemble statistics, we should find robust inattentional blindness rates for color diversity and other summary statistics. Alternatively, if task-irrelevant ensemble statistics are consciously perceived "for free" (without attention), we should observe above-chance noticing rates for these statistics.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Participants were 50 Reed College students, all over the age of 18 with normal or corrected-to-normal vision. All were recruited volunteers and gave informed consent prior to beginning the experiment. Experimental procedures were approved by the Reed Institutional Review Board. Sample size was selected based on previous inattentional blindness experiments with similar designs (Cohen, Alvarez, & Nakayama, 2011; Mack & Clarke, 2012).

2.1.2. Apparatus and stimuli

Stimuli were created in Presentation 17.0 (Neurobehavioral Systems, Berkeley, CA) and presented on a Dell 24″ LCD monitor with a resolution of 1920 $\times$ 1200 pixels and a screen refresh rate of 60 Hz. Screen viewing distance was approximately 41 cm. All stimuli were presented on a black background. All trials included a 6 $\times$ 4 array of capital letters, in Courier New Bold font, which were sampled randomly from the nine letters R, T, F, N, B, P, L, M, and K. Arrays were approximately 9 cm wide and 6 cm tall. In every trial, letters in one of the four rows were white with font size 50 pt. Colors and sizes of letters in the other three rows varied throughout the experiment (see procedure below). In "high color diversity" trials (i.e., high color variance), the colors of non-cued-row letters were sampled randomly from 19 colors selected from around the color wheel (see Bronfman et al., 2014, for RGB values). In "low color diversity" trials (i.e., low color variance), colors were sampled from a randomly selected set of six adjacent colors. In "high size diversity" trials, non-cued-row letter sizes were sampled randomly from font sizes 40–60 pt. In "low size diversity" trials, all letters were font size 50 pt (i.e., zero size variance). Example