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Limited featured-based attention to multiple features

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ABSTRACT

Attending to a feature (e.g., color or motion direction) can enhance the early visual processing of that feature. However, it is not known whether one can simultaneously enhance multiple features. We examined people's ability to attend to multiple features in a feature cueing paradigm. Each trial contained two intervals consisting of a random dot motion stimulus. One interval (noise) had 0% coherence (no net motion), while the other interval (signal) moved in a particular direction with varying levels of coherence. Participants reported which interval contained the signal in one of three cueing conditions. In the one-cue condition, a line segment preceded the stimuli indicating the direction of the signal with 100% validity. In the two-cue condition, two lines preceded the stimuli, indicating the signal would move in one of the two cued directions. In the no-cue condition, no line segment appeared before the dot stimuli. In several experiments, we consistently observed a lower detection threshold in the one-cue condition than the no-cue condition, showing that participants can enhance processing of a single feature. However, detection threshold was consistently higher for the two-cue than one-cue condition, indicating that participants could not simultaneously enhance two motion directions as effectively as one direction. This finding revealed a severe capacity limit in our ability to enhance early visual processing for multiple features.

1. Introduction

Attention is thought to be an adaptive mechanism that has evolved to cope with a capacity limit in information processing (Anderson, van Essen, & Olshausen, 2005; Carrasco, 2011). It allows us to selectively process a small set of information from the vast amount of sensory input. Importantly, attention can be allocated voluntarily according to goal-relevant features, as in the example of searching for a particular colored fruit in the jungle. This type of attention is commonly referred to as feature-based attention.

A basic finding in the literature is that feature-based attention can modulate early sensory representations (Maunsell & Treue, 2006). For instance, a single-unit recording study has demonstrated direction-specific attentional modulation of neuronal activity in monkey middle temporal (MT) area during a motion perception task (Treue & Martinez-Trujillo, 1999). Psychophysical tasks in humans further support these findings. For example, attending to a direction in a compound motion stimulus modulates motion aftereffects (Lankheet & Verstraten, 1995), suggesting that attention can bias activity in low-level direction-selective mechanisms. These early observations were further corroborated by later studies utilizing psychophysical (Arman, Ciaramitaro, & Boynton, 2006; Liu & Hou, 2011; Liu & Mance, 2011; Saenz, Buracas, & Boynton, 2003; White & Carrasco, 2011), brain imaging (Liu, Larsson, & Carrasco, 2007; Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007), and neurophysiological (Cohen & Maunsell, 2011; Martinez-Trujillo & Treue, 2004) measures. Furthermore, these attention-modulated sensory responses could be the mechanism underlying target selection during visual search. Indeed, such a conjecture is supported by the finding of enhanced neuronal response in V4 during visual search when the stimulus within a neuron's receptive field matched the target feature (Bichot, Rossi, & Desimone, 2005).

Although these studies of feature-based attention have shown that participants can selectively modulate representations of a single feature, it is not known how many features one can simultaneously modulate. This question pertains to the capacity limit of attentional modulation, and its answer will provide useful constraints on models of attention. In the domain of spatial attention, similar questions have been investigated by systematically varying the size of attended region and demonstrating a decrease in processing power and resolution with larger attended areas—a phenomenon likened to a "zoom lens" (Castiello & Umilta, 1990; Eriksen & St James, 1986). However, analogous questions for visual features have not been addressed. In the current study, we investigated how efficiently one can attend to multiple features.

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A related question has been addressed in a number of recent studies using visual search. In those studies, it was found that participants can use two different features to guide search (Adamo et al., 2008; Beck, Hollingworth, & Luck, 2012; Irons, Folk, & Remington, 2012; Moore & Weissman, 2010). In some cases, participants were just as efficient in constraining search based on one vs. two features (Beck, Hollingworth, & Luck, 2012; Becker, Alzahabi, & Jelinek, 2011; Moore & Weissman, 2010). To the extent that visual search involves the enhancement of feature-specific sensory responses (Bichot, Rossi, & Desimone, 2005), these studies could imply that early sensory responses can be modulated for two features efficiently. However, this is not a foregone conclusion, as attentional selection might also be implemented by later, post-perceptual processes such as selective pooling of information in a post-perceptual decisional stage (Eckstein, 2011). In addition, visual search is a complex task that involves both spatial and feature selection and the typical performance measure of reaction time is difficult to relate to the state of early sensory representations. These considerations prompted us to use a threshold psychophysical task to examine how well attention can simultaneously modulate early sensory representations for multiple features.

We chose to test direction of motion as it offers a continuous scale for ease of manipulating feature similarity, and it is also the most widely used in studies of feature-based attentional modulation of early sensory responses. We tested participants' ability to detect global motion signals using the classic random dot motion stimulus (Newsome & Pare, 1988). Performance on this task has been shown to be causally linked to MT neuronal activity (Parker & Newsome, 1998), thus offering a proxy for testing attentional effects on neural activity in early visual processing.

2. Experiment 1a: cueing one or two directions with fixed directions

In this experiment, we compared whether participants can attend to two directions as well as to one direction. Importantly, we tested participants' ability to attend to two *distinct* directions, as when two directions are very similar, they become essentially one direction (De Bruyn & Orban, 1988). For this purpose, we tested two maximally dissimilar configurations: orthogonal directions and opposite directions. We used a cueing paradigm to manipulate feature-based attention to motion.

To quantify performance, we measured coherence threshold to detect a weak motion signal in a two interval forced choice (2-IFC) procedure. Two random dot moving patterns were shown on each trial, one in each interval. One pattern moved in one of four possible directions at varying level of coherence (*signal*), whereas the other pattern had zero coherence (no net motion). Participants reported the interval that contained the motion signal. For the baseline condition, no prior information about the signal direction was provided; for the one-cue condition, a single cue informed participants about the signal direction; for the two-cue condition, two cues (either orthogonal or opposite) indicated the possible directions of the signal (Fig. 1). Cues were always valid, thus prompting participants to attend to the cued direction(s).

2.1. Methods

2.1.1. Participants

A total of eleven observers participated in this experiment. Two participants were authors (T.L. and M.J.), while the remaining nine participants were graduate and undergraduate students at Michigan State University and were naïve as to the purpose of the experiment. All participants had normal or corrected-to-normal vision. Participants gave informed consent and all (except the authors) were compensated at the rate of $10/h. All experimental protocols were approved by the Institutional Review Board at Michigan State University.

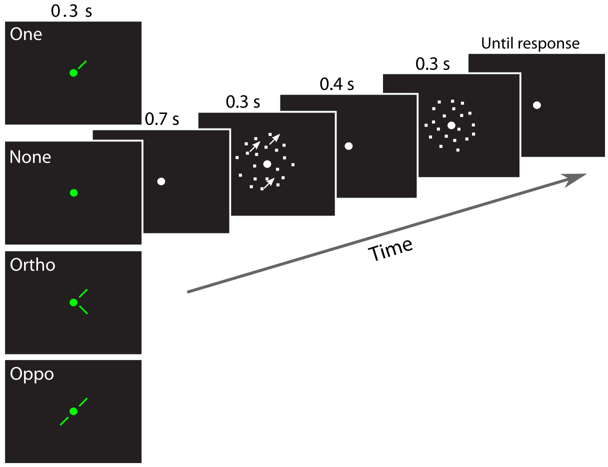

Fig. 1. Schematic of a trial in Experiment 1a. At the beginning of the trial, one of the four possible cue types was presented.

2.1.2. Visual stimuli

Visual stimuli were generated using MGL (http://gru.brain.riken.jp/doku.php?id=mgl:overview), a set of OpenGL libraries running in Matlab (Mathworks, Natick, MA). The random dot motion stimulus was based on classic studies in neurophysiology (Newsome & Pare, 1988). The motion stimulus consisted of white moving dots (size: 0.05°) in a circular aperture (6°), presented on a dark background. The circular aperture was centered on the fixation point (white, size: 0.3°), which was surrounded by a small occluding region (0.7°) of the background luminance such that no dots would appear too close to the fixation point. The dots were plotted in three interleaved sets of equal number, with an effective density of 16.8 dots/deg^2/s and a speed of 4 deg/s. Each single dot was presented on the screen for one video frame (16.7 ms). Importantly, only a portion of dots moved in a particular direction between frames, while the rest of the dots were re-drawn in random locations. The proportion of coherently moving dots (motion coherence) is the key stimulus parameter that we manipulated to measure performance. The stimuli were presented on a 19″ CRT monitor refreshed at 60 Hz and set at a resolution of 1024 × 768. Observers were stabilized with a chinrest and viewed the display from a distance of 114 cm in a dark room.

2.1.3. Task and procedure

Observers detected the presence of coherent motion in a 2-IFC task. Each trial started with a cue display for 0.3 s, followed by a 0.7 s fixation interval, after which two intervals of random dot motion stimuli were shown, each for 0.3 s, and separated by 0.4 s (Fig. 1). One interval always contained 0% coherent motion (noise) while the other interval contained a motion stimulus at one of six coherence levels: 2%, 4%, 8, 16%, 28%, and 49% (signal). The presentation order of the signal and noise intervals was randomized. Observers were instructed to report which interval contained the coherent motion signal by pressing the "1" or "2" key on the numeric keypad of a standard computer keyboard. Observers were instructed to respond as accurately as possible. A sound was played as feedback on incorrect trials. An inter-trial interval of 1.2 s followed their key press response.

The motion signal moved in one of four directions on any given trial: 45°, 135°, 225°, and 315° (i.e., the four inter-cardinal directions). To manipulate feature-based attention, we presented one