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Feature-based attention elicited by precueing in an orientation discrimination task

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ABSTRACT

Specific visual features can be attended to and processed with a higher priority by our brain, termed feature-based attention (FBA). Two potential mechanisms for FBA have been suggested: goal-driven attentional mediating and stimulus-driven feature priming. Some researchers argued that several reported top-down FBA effects might also involve the influence of feature priming. To clarify this confusion, we used an orientation discrimination task in which the target was tilted randomly from the horizontal or vertical axis and presented at one of four iso-eccentric positions. The target's orientation was precued from trial to trial by an oriented line (Experiment 1) or by a symbolic arrow presented peripherally (Experiment 2) or centrally (Experiments 3/4). The cue could be either valid or invalid according to the congruency of its indicating orientation with the target's nearest cardinal axis. Our results demonstrate that the discrimination speed was significantly faster following a valid than an invalid cue (validity effect) in the session with 80% cue validity when both response accuracy and speed were emphasized. Moreover, this validity effect could also be observed in the session with 50% cue validity using the line cue (Experiment 1), even though its magnitude was significantly reduced, which illustrates the impact of feature priming. However, we did not find the validity effect in the session with 50% cue validity using the symbolic cue (Experiments 2/3). These modulations on the magnitude of the validity effect should be ascribed to top-down attentional mediating that is independent of spatial attention (illustrated by Experiment 3). Importantly, when response accuracy was stressed over speed in Experiment 4, the accuracy was significantly higher following a valid than an invalid cue in the session with 80% cue validity but not in the session with 50% cue validity. Our findings indicate that both top-down attentional mediating and feature priming are important mechanisms for FBA.

1. Introduction

Due to the brain's limited processing capacities, behaviorally relevant visual information receives prioritized processing in the brain, while the rest is ignored. The visual attributes processed in priority can be certain particular features, such as color, orientation, and direction of motion. This feature-based attention (FBA) plays an important role in our daily lives since it is indispensable for common visual searches. Previous psychophysical, electrophysiological and neuroimaging studies investigating the mechanism of FBA showed various effects (Carrasco, 2011). Directing attention to a feature was reported to improve the detection accuracy of the stimuli with the same feature (Rossi & Paradiso, 1995) and enhance the firing rates of neurons that were tuned to the attended feature in monkey visual cortices (Martinez-Trujillo & Treue, 2004; Maunsell & Treue, 2006; Treue & Martinez-Trujillo, 1999). Functional magnetic resonance imaging (fMRI) results also revealed that attending to a feature can not only enhance the responses of cortical visual areas that are selective to that feature but also suppress the sensory signals of similar, but not identical, features globally across the visual field (Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007; Störmer & Alvarez, 2014).

For these reported FBA effects, the authors more or less implied that these effects result from a top-down attentional mechanism, which means it is goal-driven, and the stimulus feature does not play a key role. Zhang and Luck (2009) even explicitly indicated that their results which showed a competition between the attended and unattended colors provided a clear evidence for top-down FBA leading to enhanced feed-forward information processing. In some reviews, it has been suggested that the neurobiological mechanisms underlying FBA and top-down spatial attention (SA) may possibly be the same (Maunsell,

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2015; Maunsell & Treue, 2006). A recent study recorded neuron activities in the ventral prearcuate region of the prefrontal cortex while monkeys performed a visual search task and found that this region exhibited feature-based attentional modulation with a time course early enough to be a major source of top-down FBA (Bichot, Heard, DeGennaro, & Desimone, 2015).

However, the bias in processing specific features can also be explained by a stimulus-driven mechanism called feature priming. The feature of an encountered item influences a person's ability to detect subsequent stimulus with the same or related features (Kristjánsson, 2006). It has even been proposed that these priming effects are not overcome by knowledge, expectancy, or intention (Nakayama, Maljkovic, & Kristjánsson, 2004). The effects of feature priming are commonly observed in visual searches and might work by cueing with a similar feature or through intertrial priming (Theeuwes, 2013). In a visual search task, subjects were asked to detect a singleton target (unique in color or shape), which was precued by the shape or color singleton presented at the fixation point, from nine stimuli equally distributed in the peripheral visual field (Theeuwes, Reimann, & Mortier, 2006). Their results showed that the detection speed was faster in the trials with a valid cue (the cued singleton matched with the target singleton), whether in counterinformative sessions (17% trials with valid cues) or highly informative sessions (80% cue validity). They proposed that this RT benefit was owing to feature priming because of the cue presence, and top-down FBA is not effective in guiding visual search. Intertrial priming is another way of generating the effect of feature priming, characterized by an improvement of behavioral performance with the repetition of target and/or distractor features over consecutive trials (Maljkovic & Nakayama, 1994). A recent study reported that the search speed was faster when the target feature remained constant across trials than when it switched from trial to trial (Yashar, Makovski, & Lamy, 2013). The effect of intertrial priming depends on the sequence of the trials and is not driven by goal.

After carefully reviewing the experimental designs in the previous studies, Theeuwes (2013) argued that those reported top-down FBA effects resulted from feature priming instead of top-down attentional mediating. In the aforementioned work by Zhang and Luck, the attended feature was not changed within a block. This blocked design, also used in other studies on FBA (Chawla, Rees, & Friston, 1999; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990), could not exclude the interference of intertrial priming, which complicates the interpretation of their results (Theeuwes, 2013). A recent work investigating FBA adopted a Posner-like paradigm, in which the attended feature (color, in their case) was precued and varied from trial to trial (Störmer & Alvarez, 2014). However, since the cue they used had a similar color to the target, the effect of feature priming still cannot be ruled out, according to Theeuwes' arguments (Theeuwes, 2013).

To clarify this confusion, it is necessary to investigate FBA with a paradigm that is capable of distinguishing the effects of attentional mediating and feature priming. In the present study, we used a Posner-like two-alternative forced-choice (2AFC) orientation discrimination task to investigate FBA. The target orientation was precued by a peripheral line or a central/peripheral symbolic arrow on a trial-by-trial basis. The line cue had a task-relevant orientation, while the symbolic arrow cue consisted of lines with task-irrelevant orientations. We proposed that the effect of feature priming would be elicited by the line cue but not the symbolic arrow cue. The usage of different types of cues and cue informativeness can help us investigate the effects of top-down attentional mediating and feature priming, and obtain a more comprehensive understanding of the underlying mechanisms of FBA.

2. Experiment 1

2.1. Subjects

Nine subjects (age 19–34 years, 4 male, 5 female) were recruited in the experiment. All subjects except one author were naïve to the purpose of the experiment. They had normal or corrected-to-normal vision and provided informed consent. The sample sizes in our experiments were comparable to those in previous psychophysical studies on FBA (Theeuwes & Burger, 1998; Tsal & Lamy, 2000; White, Rolfs, & Carrasco, 2015) and were able to guarantee that statistically significant effects with $p < 0.05$ could be generalized to the majority of the population, according to a previous study on statistics in psychophysics (Anderson & Vingrys, 2001). All experimental procedures conformed to the ethical standards of the Ethical Committee of Shanghai Jiao Tong University and the guidelines of the Declaration of Helsinki.

2.2. Apparatus

A 24-inch liquid crystal display (LCD) monitor (BenQ xl2411t, Taipei, Taiwan, 1920 × 1080 pixels, 100 Hz refresh rate) positioned 57 cm in front of the subject was used to display the visual stimuli. The screen had a mean luminance of 15.5 cd/m^2. The subject's head was restrained in a chin rest. An infrared imaging-based eye tracker (Tobii X60; Tobii Technology AB, Stockholm, Sweden) was adopted to monitor the eye movement. Stimulus presentation and data collection were achieved using MATLAB (MathWorks) with the Psychtoolbox extension (Brainard, 1997; Pelli, 1997). Data analyses were conducted with the Statistical Package for Social Sciences (SPSS, Inc.) and OriginPro software (OriginLab Corporation).

2.3. Stimuli and procedure

Subjects were instructed to fixate on a black cross (0.4° × 0.4°; Fig. 1), which was presented throughout the whole experiment at the center of the screen with a distance of 57 cm. Then, a line cue was presented for 250 ms at one of four iso-eccentric locations at 5.5° eccentricity. After an interval of 500 ms, a Gabor was presented for 50 ms between the cue position and the fixation cross at 4° eccentricity. The Gabor patch (σ = 0.2°, 4 cycles/deg., 50% contrast) was tilted slightly away from either horizontal or vertical (randomized on each trial). Observers were instructed to press key '6' if the target was tilted clockwise (CW) from its cardinal axis (i.e., horizontal or vertical), or press key '4' if the tilt was counterclockwise (CCW). Speed and accuracy were equally emphasized. The next trial began after an intertrial interval (ITI) of 1950 ms. Those trials that had fixation breaks (the fixation went outside a 2° window) or reaction times (time interval between the target onset and the response) longer than 2 s or shorter than 150 ms were considered as incorrect and were repeated at the end of the current block of trials.

The cue was a horizontal or vertical line with length of 0.4°, which was used to introduce a feature attentional bias to vertical or horizontal orientation when subjects were performing the orientation discrimination task. The cue could be either valid or invalid based on whether its indicating orientation was congruent or incongruent with the orientation of the target's nearest cardinal axis.

Each subject completed two experimental sessions, including eight blocks in which the proportion of trials with valid cues was 80% and eight blocks in which the proportion of valid and invalid trials was equal, respectively. The order of the two sessions was randomly determined for each subject. Before the beginning of the session with 80% or 50% cue validity, observers were explicitly told that the cues were informative regarding the target orientation and there was a benefit in using the cues to perform the task, or that the orientations indicated by the cues were randomized and uninformative about the target orientation. Then, the observer's orientation discrimination thresholds for the target's tilt from horizontal and vertical were measured using the double three-down one-up staircase procedure. The two threshold values of each subject were used as the tilted angles of Gabor in the following formal experiments. Within each session, the tilted angles of Gabor were adjusted according to the response accuracy in the previous