ARTICLE IN PRESS

Cognition xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Brief article

Out of control: Attentional selection for orientation is thwarted by properties of the underlying neural mechanisms

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ARTICLE INFO

Article history:
Received 27 August 2011
Revised 17 February 2012
Accepted 9 May 2012
Available online xxxx

Keywords:
Attention
Contingent capture
Top-down control
Orientation-based selection

ABSTRACT

To avoid sensory overload, people are able to selectively attend to a particular color or direction of motion while ignoring irrelevant stimuli that differ from the desired one. We show here for the first time that it is also possible to selectively attend to a specific line orientation—but with an important caveat: orientations that are perpendicular to the target orientation cannot be suppressed. This effect reflects properties of the neural mechanisms selective for orientation and reveals the extent to which contingent capture is constrained not only by one's top-down goals but also by feature preferences of visual neurons.

1. Introduction

In order to avoid sensory overload people must process only a subset of a scene at any one time. Indeed, mechanisms exist that allow us to selectively process stimuli based on features that match our current goal, such as orientation (Haenny, Maunsell, & Schiller, 1988; Haenny & Schiller, 1988; Maunsell, Sclar, Nealey, & DePriest, 1991), color and luminance (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Motter, 1994a, 1994b), or motion direction (Treue & Martinez-Trujillo, 1999; Treue & Maunsell, 1996). It is also possible to restrict attention to a limited area of the visual field (Eriksen & St. James, 1986; Mangun, 1995; McAdams & Maunsell, 1999; Posner, 1980), but the spatial selection is not perfect: Salient stimuli (Christ & Abrams, 2006; Yantis, 1993) or stimuli that match the target color (Du & Abrams, 2008, 2010; Folk, Leber, & Egeth, 2002; Serences et al., 2005) can capture our attention even when they appear outside of the area of interest.

Attentional selection for features such as color and motion has been extensively studied (Bichot, Rossi, & Desimone, 2005; Martinez-Trujillo & Treue, 2004; Motter, 1994a, 1994b; Serences & Boynton, 2007; Treue & Maunsell, 1996), but relatively little is known about the behavioral impact of selection for orientation. Since the analysis of orientation is critical not only for representing contours and textures but also for segregating figures from the background, in the present experiments we explore for the first time the extent to which attention is captured by a sought-for orientation. To anticipate the results, we found that distractors matching a sought-for orientation did indeed capture attention involuntarily even if they appeared in a location known to be irrelevant to the task. In that sense selection for orientation is similar to that for color or motion. More importantly, we also found that orientations perpendicular to the target also captured attention. This is the first result showing that contingent capture of attention is not completely under top-down control. Although unexpected, the result is consistent with known features of the neural mechanisms that are selective with respect to orientation (Anzai, Peng, & Van Essen, 2007; Haenny et al., 1988), and reveals an important constraint of those mechanisms on attentional selection: In

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http://dx.doi.org/10.1016/j.cognition.2012.05.013

particular, they undermine a person's ability to establish complete top-down control of selective attention.

1.1. Overview of experiments

To determine whether attention can be captured by an irrelevant distractor with a target orientation we developed a variation of Folk et al's (2002) spatial blink paradigm. The general procedure is shown in Fig. 1. Subjects looked for a target letter defined by a specific orientation in a rapid stream of mixed-orientation letters presented at fixation while ignoring peripheral distractors that sometimes contained a unique orientation singleton. In different conditions, we varied the relation between the orientation singleton and the target orientation. To assess capture we measured the extent to which a particular distractor impaired the subjects' ability to identify the target letter.

2. Experiments 1A, 1B and 1C

2.1. Apparatus and procedure

Stimuli were presented on a 19-in. CRT with a 100 Hz refresh rate in a dimly lit room at a viewing distance of 56 cm. Each trial began with a 500 ms presentation of a gray fixation cross in the center of the screen, followed by the sequential presentation of 20 uppercase black letters at the center of the display for 50 ms each, followed by a 50 ms blank interval. The letters were selected randomly without replacement from the English alphabet, excluding the letter "I". Every letter (1.0° wide, 1.3° high) was presented in a gray bar (1.3° wide, 4.5° high) which was in the same orientation as the letter. Orientations were vertical, horizontal, 45° clockwise, or 45° counterclockwise from vertical. The target letter, which was defined by a specific orientation and differed across experiments, appeared in the 10th through 14th frame of the letter sequence. Participants reported target identity by keyboard after each trial.

2.2. Distractor conditions

For trials containing peripheral distracting bars, two sets of three white bars flanked the central letter stream either two frames before (distractor–target lag of +2) or after (lag of −2) that containing the target letter. Different conditions in the experiments were created by differences

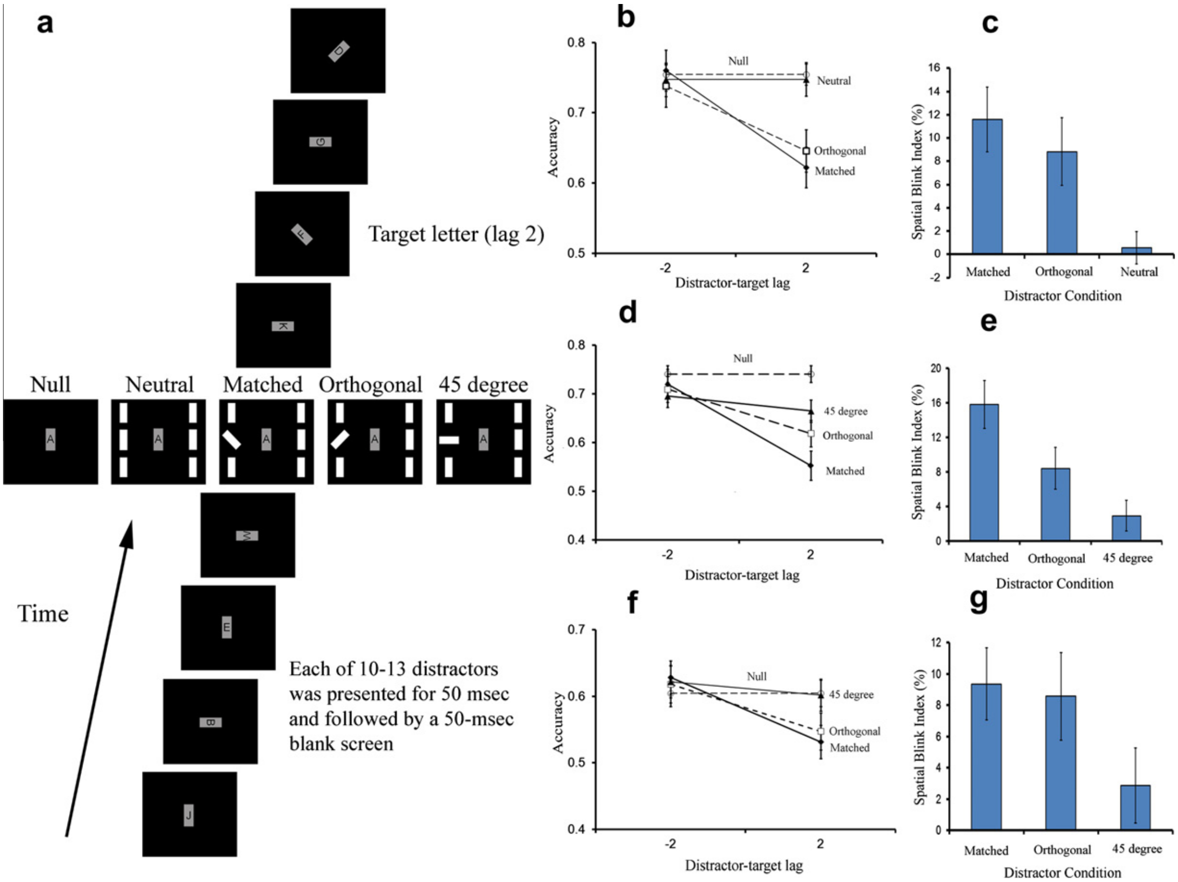

Fig. 1. Procedure and results from Experiments 1a–1c. (a) Sequence of events on trials in Experiments 1a and 1b. See text for additional explanation. (b) Accuracy of target identification in Experiment 1a. (c) Spatial blink index (SBI) based on the results from Experiment 1a. The SBI quantifies the magnitude of the impairment caused by each type of distractor. See text for details. (d) Accuracy of target identification in Experiment 1b. (e) Spatial blink index based on the results from Experiment 1b. (f) Accuracy of target identification in Experiment 1c. (g) Spatial blink index based on the results from Experiment 1c. Error bars show one standard error.

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in the peripheral distracting bars. On one-fourth of the trials in each experiment, there were no distracting bars in the periphery. This was the *null* condition, which served as a baseline. On the remaining trials, one randomly chosen letter in the 8th through 16th frame was flanked by two sets of white bars (each 0.7° wide, 2.5° high) whose inner edges appeared 6° away from the display center. In the *neutral* condition all of the distractors were vertical. In the *matched*, *orthogonal* and 45° conditions five of the bars were vertical and one bar either to the left or right of center was oriented at either a 45° angle from vertical, or was horizontal. In the *matched* condition, the orientation singleton in the distractors matched the participant's assigned target orientation; in the *orthogonal* condition the orientation singleton was perpendicular to the target orientation; in the 45° condition, the orientation singleton was horizontal and hence was 45° from the target orientation.

2.3. Design

One half of the participants in each experiment were required to identify an oblique letter tilted 45° clockwise from vertical; the others searched for a 45° counterclockwise letter. Each experiment included four different distractor conditions (including the *null* condition). Trials in the various distractor conditions were mixed and presented to each subject in a random order. Each experiment contained 24 replications of each combination of four distractor-conditions and two distractor–target lags, for a total of 192 trials. Participants first served in one block of 16 trials for practice. After every 64 trials, they received a brief break.

2.4. Experiment 1a results

Forty-four undergraduates participated in this experiment which included the *null*, *neutral*, *matched* and *orthogonal* conditions. The accuracy of target identification is plotted in Fig. 1b. There were three main findings. First, we found a main effect of distractor–target lag, with lower accuracy as lag increased, $F(1,43) = 14.049$, $p = 0.001$, $\eta_p^2 = 0.246$. Next, there was a main effect of distractor condition, with lower accuracy in the *matched* and *orthogonal* conditions, $F(3,129) = 10.213$, $p < 0.001$, $\eta_p^2 = 0.192$. Most importantly, consistent with previous studies on selection for color (e.g., Du & Abrams, 2008, 2010; Folk et al., 2002), there was a significant interaction between distractor–target lag and distractor condition ($F(3,129) = 11.803$, $p < 0.001$, $\eta_p^2 = 0.215$), confirming that impaired target identification (a *spatial blink*) for the *matched* and *orthogonal* conditions occurred only at lag 2 (i.e., when the distractor appeared before the target but not when distractor appeared after the target). We calculated a *spatial blink index* (SBI) to estimate the magnitude of attentional capture in each condition as the accuracy difference between the two lags for each condition divided by the sum of the accuracies at the two lags. The magnitude of the spatial blink in the null condition was zero in all experiments (as would be predicted since there were no distractors there). The SBIs for the other three conditions are plotted in Fig. 1c. A comparison of the SBIs to zero confirmed the presence of a large spatial blink in the matched and orthogonal conditions but not the neutral condition, $t(43) = 4.072$, $p < 0.001$; $t(43) = 3.043$, $p = 0.004$; $t(43) = 0.421$, $p = 0.676$, respectively. In addition, SBIs in the matched and orthogonal conditions were larger than that in the neutral condition, $t(43) = 3.82$, $p < 0.001$; $t(43) = 3.106$, $p = 0.003$, respectively. But SBIs of matched and orthogonal conditions were not different, $t(43) = 1.27$, $p = 0.211$. Thus, while searching for a particular orientation, subjects were distracted by stimuli of the same orientation but not by an array of elements that differed from the target orientation by 45°, revealing top-down selection of orientation. But most surprisingly, they were also distracted by stimuli that differed from the target by 90°, which cannot be accommodated by contingent capture theory.

2.5. Experiment 1b results

In Experiment 1a, the distractors in the matched and orthogonal conditions contained orientation singletons, so it is possible that they captured attention merely due to their saliency—and not due to the relation between their orientation and the target orientation. To rule-out this possibility, here we replaced the *neutral* condition with the 45° condition (see Fig. 1) that contained a horizontal orientation singleton (45° away from the target orientation). If attentional capture in Experiment 1a was due to the perceptual salience of the orientation singletons in the matched and orthogonal conditions, then the horizontal singleton here should capture attention and impair target identification in the 45° condition. Forty-four undergraduates participated.

Results are shown in Fig. 1d and e. There was a main effect of lag, $F(1,43) = 25.035$, $p < 0.001$, $\eta_p^2 = 0.368$, Next, there was a main effect of distractor condition, with accuracy lowest in the *Matched* and *Orthogonal* conditions, $F(3,129) = 18.070$, $p < 0.001$, $\eta_p^2 = 0.296$, and the important interaction between distractor–target lag and distractor condition ($F(3,129) = 15.881$, $p < 0.001$, $\eta_p^2 = 0.270$) showing that a spatial blink occurred in the matched and orthogonal conditions, as in Experiment 1a. Analysis of the SBI confirms the presence of a spatial blink in the matched and orthogonal conditions but not the 45° condition ($t(43) = 5.722$, $p < 0.001$; $t(43) = 3.579$, $p = 0.001$, *and* $t(43) = 1.662$, $p = 0.104$, respectively). Again SBIs in *matched* and *orthogonal* conditions were larger than that in the 45° condition, $t(43) = 4.85$, $p < 0.001$; $t(43) = 2.265$, $p = 0.029$, respectively. Unlike in Experiment 1a, the SBI was larger in the matched condition than the orthogonal condition, $t(43) = 3.493$, $p = 0.001$.

2.6. Experiment 1c results

Experiments 1a and 1b included only one orthogonal letter that was perpendicular to the target letter in the central stream. This sole occurrence of an orthogonal letter might make it as special as the target letter. To make the orthogonal letter less special and force participants to narrow their top-down control setting to a specific

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orientation, Experiment 1c presented two orthogonal letters in each trial (one before the target, and one after the target) while keeping everything else the same as Experiment 1b. If the spatial blink in the orthogonal condition was due to a single occurrence of an orthogonal letter in the central steam, it should be eliminated in Experiment 1c. Forty-eight undergraduates participated.

Results are shown in Fig. 1f and g. There was a main effect of lag, $F(1,47) = 18.443$, $p < 0.001$, $\eta_p^2 = 0.282$, but no main effect of distractor condition, $F(3,141) = 1.977$, $p = 0.120$, $\eta_p^2 = 0.040$. Importantly, distractor–target lag and distractor condition interacted, $F(3,141) = 6.424$, $p < 0.001$, $\eta_p^2 = 0.120$, indicating that a spatial blink occurred in the matched and orthogonal conditions. Consistent with Experiments 1a and 1b, a spatial blink occured in the matched and orthogonal conditions but not the 45° condition ($t(47) = 4.116$, $p < 0.001$, $t(47) = 3.066$, $p = 0.004$, and $t(47) = 1.177$, $p = 0.245$, respectively). And SBIs in the *matched* and *orthogonal* conditions were larger than that in the 45° condition, $t(47) = 2.107$, $p = 0.040$; $t(47) = 2.59$, $p = 0.013$, respectively. But the SBI in the matched condition was not different from that in the orthogonal condition, $t(47) = 0.246$, $p = 0.807$.

3. Experiment 2

In Experiments 1a–1c attention was captured by an orientation singleton that had the same orientation as the target (an oblique line), and by a singleton that was perpendicular to the target orientation (also an oblique line), but not by a horizontal singleton that differed from the target orientation by 45°. It is possible that those results are due to the fact that oblique orientations might be processed differently from horizontal and vertical orientations (Appelle, 1972; Wolfe, Freidman-Hill, Stewart, & O'Connell, 1992). To rule out that possibility we had subjects here search for horizontal or vertical targets.

3.1. Participants and procedure

Sixty-two undergraduates participated. Twenty participants were required to report the sole vertical letter in the stream. The critical events on such trials are shown in Fig. 2a. There were multiple tilted letters (45° from vertical) and two horizontal letters in the central stream to serve as masks for the target. One horizontal letter was presented before the target; the other after the target. The other 42 participants were required to report the sole horizontal letter. Half of them looked for a horizontal letter facing left, the others searched for a horizontal letter facing right. The central stream contained multiple tilted letters (45° from vertical) and two vertical letters. One vertical letter was before the target; the other after the target. Other parameters are the same as those in Experiment 1.

3.2. Distractor conditions

On one-fourth of the trials, there were no distracting bars in the periphery (*null*). The other trials contained peripheral distractors, and were evenly distributed among three conditions (*neutral*, *matched*, and *orthogonal*). The neutral condition presented six homogeneously tilted bars so that the neutral condition had neither an orientation singleton nor a bar that matched the target orientation. In the matched condition, however, one bar either to the left or right of center was either a vertical or a horizontal bar that matched the target orientation. The other five peripheral bars were homogeneously tilted (45° from vertical). The orthogonal condition had either a horizontal bar or a vertical bar that was orthogonal to the target, with the remaining five bars tilted in the same direction (45° from vertical). The frame containing the peripheral distracting bars was equally likely to appear either two frames before the target (distractor–target lag of +2) or two frames after the target (lag of −2). If the mechanism selective for orientation in the earlier experiments is in operation here, the singletons in both the matched and orthogonal conditions should capture attention.

4. Results

Fig. 2b shows the target identification accuracy. Again there was a main effect of lag, $F(1,61) = 4.11$, $p = 0.047$, $\eta_p^2 = 0.063$, a main effect of distractor condition, $F(3,183) = 3.053$, $p = 0.03$, $\eta_p^2 = 0.048$, and an interaction between distractor–target lag and distractor condition revealing a spatial blink in both the matched and the orthogonal conditions ($F(3,183) = 4.723$, $p = 0.003$, $\eta_p^2 = 0.072$). The SBIs for the three conditions are plotted in Fig. 2c. There was a significant spatial blink in both the matched and orthogonal conditions ($t(61) = 2.475$, $p = 0.016$; $t(61) = 2.794$, $p = 0.007$, respectively), but not in the neutral condition, $t(61) = 0.074$, $p = 0.941$. And SBIs in the *matched* and *orthogonal* conditions were larger than that in the *neutral* condition, $t(61) = 2.782$, $p = 0.007$; $t(61) = 3.483$, $p = 0.001$, respectively. In addition, the SBI in the matched condition was not different from that in the orthogonal condition, $t(61) = 0.145$, $p = 0.885$.

In conclusion, attention was captured by distractors that matched the target orientation and also ones that were perpendicular to it even when participants were searching for either vertical or horizontal targets.

5. General discussion

All four experiments showed that peripheral distractors in a sought-for orientation can involuntarily capture attention even when searching for a single target orientation at fixation. But distractors tilted 45° from the target orientation did not capture attention. With those findings, the present study is the first to show that involuntary capture of attention is contingent upon a sought-for orientation and furthermore that orientation-specific capture overrides the focus of spatial attention. In that sense selection for orientation is similar to that for attributes such as color and motion (Du & Abrams, 2008, 2010; Folk et al., 1994, 2002), and it likely plays a role in our ability to make sense out of a visually-complex world.

Selection for orientation, however, is more complicated than those results suggest: Attention was also captured by distractors that were perpendicular to the target

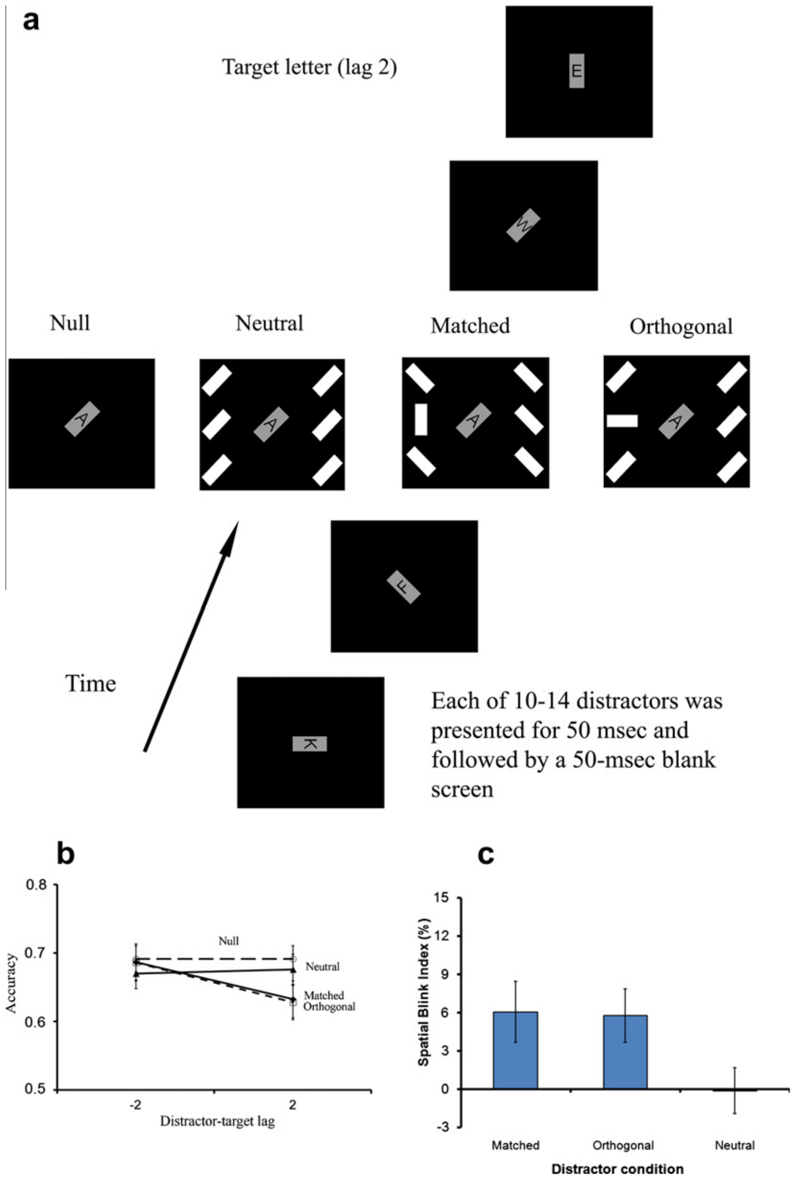

Fig. 2. Procedure and results of Experiment 2. (a) Sequence of events in the vertical target condition. See text for additional explanation. (b) Accuracy of target identification. (c) Spatial blink index based on the accuracy results of Experiment 2.

orientation. This occurred despite the fact that distractors only 45° away from the target orientation did not capture attention.

The unexpected attentional capture by perpendicular distractors appears to reflect properties of orientation-selective neural mechanisms. In particular, single cell recording studies have shown that many visually sensitive neurons respond best to multiple orientations, most commonly with the two most preferred orientations about 90° apart (Anzai et al., 2007; Felleman & Van Essen, 1987). These neurons are believed to play an important role in contour perception and object recognition. Importantly, as the present results have shown, they may also undermine one's ability to selectively attend to a specific orientation. In particular, a person searching for a specific orientation as in the present study might selectively activate visual neurons that prefer the sought-for orientation, but many such neurons might have bimodal orientation tuning curves with two peaks 90° apart. As a result, attention could be involuntarily captured by two orientations that were perpendicular to each other. Interestingly, the neurons with bimodal tuning curves make up only about 30% of those that were studied—the remaining ones have unimodal tuning curves (Anzai et al., 2007). Thus, the spatial blink caused by matched distractors would be expected to be larger than that for orthogonal distractors. Nevertheless, only in Experiment 1b was the spatial blink induced by matched distractors

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larger than that for orthogonal distractors. Thus, more work will be needed to elucidate details of the underlying mechanisms.

The present findings challenge traditional contingent capture theory and reveal the critical role played by feature preferences of visual neurons in constraining the top-down selection of specific feature values. It remains to be seen why top-down selection for orientation is so profoundly affected by what appear to be a subset of visual neurons, and whether similar constraints affect attentional selection for attributes other than orientation.

Acknowledgment

The first author Feng Du is supported by grants from the National Natural Science Foundation of China (Grant No. 91124003) and the Scientific Foundation of Institute of Psychology, Chinese Academy of Sciences (Grant No. Y1CX212005).

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